



# Ancillary services and electric vehicles: An overview from charging clusters and chargers technology perspectives

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## ABSTRACT

The transformation towards a sustainable power system calls for new ways of operating the network. In that regard, electric vehicles (EVs) with their charging infrastructure qualify as a flexible resource. This paper interconnects ancillary services and EV flexibility to help system operators (SOs) and flexibility providers understand the role and localize EV-chargers in the power system. First, the focus is on SOs. The manuscript reviews ancillary services based on power system operational challenges. The ancillary services are differentiated between 8 frequency and 32 flexibility services. These are then subdivided depending on the management control: the first group includes inertia, primary, and secondary/tertiary frequency control, while the second includes congestion management, voltage regulation, power quality, grid stability, and emission management. Of all the different services, the ones that can be provided by EV-charger are highlighted and classified into 12 geo-electrical charging clusters. Second, the focus is moved to the flexibility providers. Independently from location, to provide ancillary services with EVs, multiple actors are recognized: the end-user, the charging site operator (CSO), the charging point operator (CPO), the aggregator, the energy community, the distribution system operator (DSO), and the transmission system operator (TSO). The collaboration between the actors is today carried out by making alliances, to help exchange knowledge and gain confidence in ancillary services provision. In conclusion, the literature review presents the characteristics of 27 slow (up to 50 kW) smart chargers, the common flexibility features being scheduling (100%), modulation (89%), and phase switching (10%).

## 1. Introduction

The conventional grid planning process requires the decision of the grid components capable of covering the maximum demand of the system and generally have a useful life between 25 and 50 years [1,2]. However, grid sizing and normal operation are challenged by the increasing penetration of intermittent renewable energy resources (RESs) and new distributed technologies [3]. For instance, the EVs rapid growth has an adverse instantaneous power delivery effect; the simultaneous charging can potentially harm the grid or require large grid upgrade investments [4,5]. Therefore, power system flexibility (PSF) is a possible solution to the sustainable power system paradigm [6]. For example, the authors of [7] highlight how PSF can substitute unnecessary grid upgrade or support the grid infrastructure. Fundamental work on flexibility in the power system has been presented in [8–14]. Authors agree when defining flexibility according to (i) type of flexibility resource (ii) duration and (iii) incentives for activation. In addition, authors of [15,16] emphasize the importance of relating flexibility with geographic granularity, system operators, and market interoperability.

Thus, a flexibility solution is the combination of flexible resources, which can be further categorized on (i) demand, (ii) supply and (iii) grid-operation flexibility [8,10], with market enablers [11,12] on a predefined time and space domain [14,15]. Hence, highlighting the need for new markets, regulations, and codes of practices to harvest the flexibility value proposition. Furthermore, the authors of [17] define the flexibility value proposition on current markets and systems, while the authors of [18,19] suggest that the network can become more cost-effective by incorporating flexibility into the grid planning phase.

### 1.1. Motivation and research gap

The first step in a successful implementation of PSF is to agree on a definition of PSF. The authors of [6,9] have provided a historical background for the flexibility term used in the context of power systems and have underlined the lack of clarity in reviews of the literature. Our manuscript agrees with the PSF definition proposed by authors of [9],

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### List of Abbreviations

AGC	Automatic generation control
BRP	Balancing responsible party
CPO	Charging point operator
CSO	Charging site operator
DER	Distributed energy resource
DSM	Demand side management
DSO	Distribution system operator
EV	Electric vehicle
FCR	Frequency containment reserve
FFR	Fast frequency reserve
FRR	Frequency restoration reserve
HAN	Home area network
OCPP	Open charge point protocol
PSF	Power system flexibility
RES	Renewable energy resource
RoCoF	Rate of change of frequency
RR	Replacement reserve
SO	System operator
ToU	Time of use
TSO	Transmission system operator
TyoU	Type of use
V1G	Unidirectional smart charger
V2G	Vehicle-to-grid

where PSF is strictly connected with the ancillary services and reads as follows:

*“The ability of power system operation, power system assets, loads, energy storage assets and generators, to change or modify their routine operation for a limited duration, and responding to external service request signals, without inducing unplanned disruptions”.*

The British PAS1879 code of practice [20] provides a standardized control for the power of domestic smart appliances subject to consumer consent. In Denmark, instead, the flexibility services procurement guidance [21] displays a market structure that exploits the current infrastructure for data management, monitoring, and validation. This guide, heavily based on the findings of the EcoGrid 2.0 research project [22], aims to stimulate DSOs to procure flexibility services instead of grid reinforcement without compromising their radial network N-1 spare operational capacity. Taking inspiration from such British and Danish initiatives, the rich PSF literature, and the integration of EVs in the power system [23,24], the entire process of delivering a flexibility solution should incorporate five principles:

1. Interoperability—consumers should have the possibility to choose from different flexibility providers [20,25].
2. Data privacy—personal data should be used under clear consent agreements and remain secured/encrypted on flexibility providers [11,12].
3. Cyber security—confidentiality and control services of smart appliances should never be breached by an unauthorized user [13, 26].
4. Grid stability—each flexibility service activation should not compromise grid stability and resilience [8,27].
5. Transparency and fairness—system operators and market enablers should provide standardized guidelines for all participating actors [21].

The study investigates the issue of grid stability and acknowledges the missing link between PSF and ancillary services. Previous review

articles have a wide scope regarding flexibility assets [9,12] and flexibility actions such as demand side management (DSM) [16], energy efficiency and network reconfiguration [26,27], without looking at practical ancillary services. Others review market concepts [11,12]. A more narrow scope on flexibility assets is followed from [23,24], looking at EVs, probably the most influencing up-coming technology. However, authors of [23] are discussing a conceptual framework for EVs grid integration starting from technical to economical and regulatory aspects, without analyzing ancillary service provision. Further, authors of [24] look into ancillary services from EVs, but focusing on optimization techniques. Lastly, the lack of technical and geographical connection between ancillary services and EVs, is also highlighted in [28]. The manuscript analyzes such research gap with two major ancillary services subgroups: frequency and flexibility services. The distinction between the two is needed to investigate such services specifically for EVs.

### 1.2. Contributions

By looking at the power system operation challenges, first ancillary services are presented in this article. These are distinguished between frequency and flexibility services. Second, ancillary services that EVs can provide are presented. Third, the ancillary services are reflected in the charging clusters and charger technology available today. The objective of the article is to help SOs and flexibility providers better understand the role of the EV charger in the power system and what the EVs charger can and cannot do. The main contributions can be summarized as follows:

1. Frequency and flexibility service review with highlights of services delivered from EVs.
2. Distinction of geo-electrical charging clusters to identify where and what services from EVs can be offered.
3. Identification of EV flexibility alliances and stakeholders helping ancillary services provision.
4. Smart charger definition and review of 27 slow (up to 50 kW) smart chargers present in the market today.

The rest of the paper is structured as follows. Section 2 describes the paper methodology and the conducted review workflow. Further, Section 3 introduces frequency and flexibility services, which Section 4 utilizes to sketch the framework of the services. Section 5 classifies the current smart chargers' state-of-the-art technology and Section 6 concludes the article with the main findings.

## 2. Methodology

The methodology and workflow are presented in Fig. 1. The goal of the paper is to link ancillary services provision with electric vehicles. To do so, two parallel workflows are performed (Steps 1–4 and 5–9). Starting with the literature review, ancillary services (step one) and EV grid integration (step five) are the keywords used on the Google Scholar and IEEE Xplore search platforms. The introduction of the EU Electricity Market Directive (2019) [29], the British PAS1879 code of practice, and the Danish flexibility procurement guidance are important directives to gain confidence in ancillary services provisions. Hence, the ancillary services literature screening process (step two) benefits from the chosen eligibility criteria and limiting the scope to European ground. Similarly for the EV grid integration literature, the eligibility criteria (step six) is the charging behavior studies and notations followed from the IEA. On the one hand, ancillary services are classified on frequency and flexibility services (step three). On the other hand, charging behaviors are classified on the basis of charging locations as electrical and geographical charging clusters (step seven).

Step four analysis the ancillary services by highlighting services delivered from EVs. Additionally, based on market platforms proposed from demonstration projects, the paper recommends a flexibility supply

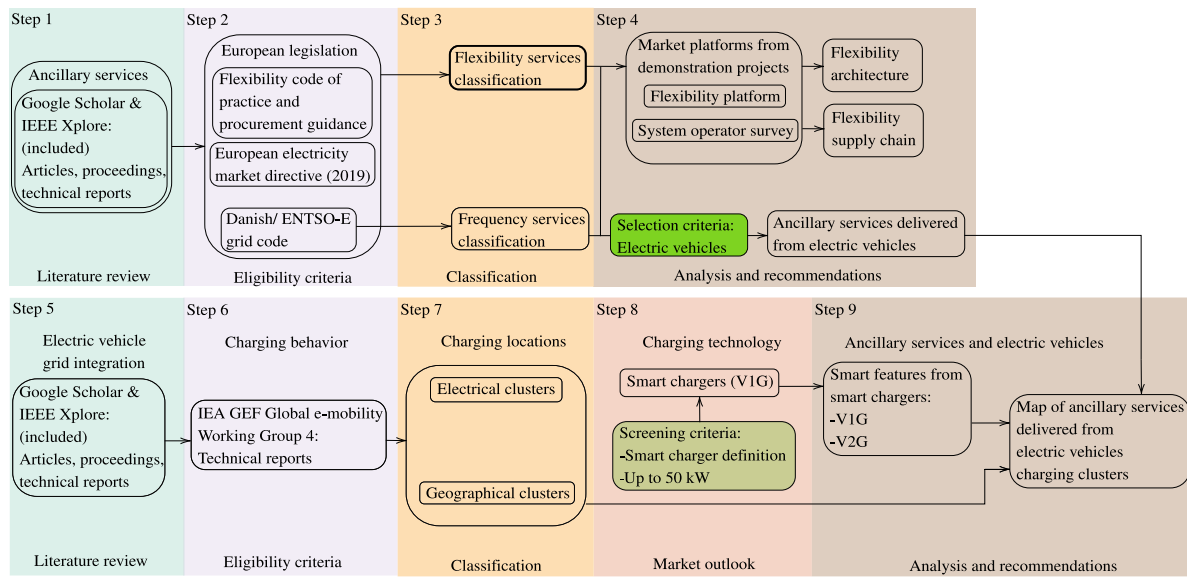


Fig. 1. Description of the methodology and the work-flow performed in this paper.

chain and architecture. Here, a recent market-based flexibility survey among Nordic DSOs [30] expected flexibility to have growing importance. However, Nordic DSOs lacked confidence in participating in or creating such markets. Furthermore, looking at European EVs market operators and research projects, we identify flexibility supply chain actors and the latest formed EV alliances.

In contrast, before analyzing the charging clusters (Fig. 1 step nine), the study conducts an European charging technology market outlook (step eight) based on a smart charger definition and charging power up to 50 kW. Such infrastructure is needed to link the charging clusters with the ability to provide ancillary services from EVs. Therefore, the last step sketches a map of potential ancillary services to be offered from the EVs charging clusters.

### 3. Ancillary services and electric vehicles grid integration

#### 3.1. Electric vehicles potential

Authors of [31] quantify the demand response flexibility potential for two European system scenarios. By 2050, there is a flexibility potential from EVs of 878 out of 1648 GW for the centralized system scenario and 260.7 out of 370 GW for the decentralized system scenario. Thus, by acknowledging even the large potential of economical savings from smart charging [23,32], this article focuses on EVs charging operation. Flexibility from EV and charging station is dependent on user constraints, time availability, charging location, etc. [33]. In particular, the residential and workplace charging environment top the parking period, while it remains dominated by slow charging, commonly below 50 kW charging power [34]. To perform EV ancillary services, a smart charger (unidirectional (V1G) or bidirectional (V2G)) is required [23, 35]. Unidirectional smart chargers (V1Gs) can only draw power from the grid, while vehicle-to-grid (V2G) chargers can also inject power to the grid. This study focuses on V1Gs, which are reviewed in Section 5. The V2G technology, previously discussed in [23,36], will become more attractive when future vehicles are equipped with on-board bidirectional chargers, or the price of V2G chargers decreases significantly [37].

Further, the recent update on the Danish grid code has included the V2G technology part of the same group with battery energy storage [38]. Depending on the storage size (kWh), different groups are present in the Danish grid code. These different groups mandate which ancillary services should the V2G technology provide. To the authors'

knowledge, ancillary services from EVs have been discussed in the literature without a full comprehension of all services. On top of that, the literature is missing a geographical localization of ancillary services from EVs.

#### 3.2. Ancillary services

Under the new sustainable power sector paradigm, the operational needs of the power system can be grouped into three pillars: (i) Adequacy and security of supply (having enough generation to cover peak demand at any time) [39], (ii) Power system stability (the ability of the power system to regain the operating equilibrium state after experiencing a physical disturbance, for a given initial state without violating system variables, hence the system remaining intact) [40,41], and (iii) Power system resilience (ability of the system to react to extreme, or catastrophic events) [42]. The conventional way to cover such requirements is through grid codes, wholesale/retail energy markets and ancillary services markets, more specifically balancing markets [43,44]. However, these services have limitations on the upcoming decentralized grid, because they were initially developed for the centralized one [45]. Therefore, extensive research is conducted on complementary services [46,47]. The entirety of the services required from the power system perspective falls under ancillary services [48]. Those account for all services offered in the balancing and flexibility markets. Frequency services maintain the system-wide frequency characteristic, while the flexibility services assist local challenges.

#### 3.3. Frequency services

The conventional method for controlling the system frequency depends on inertia, primary, secondary, and tertiary frequency control [44]. This section describes the frequency stability and services first, and then it highlights the services that can be delivered by EVs.

##### 3.3.1. Frequency stability conundrum

First, the integration of converter-based generation, phase-out of thermal units lead to the reduction of system inertia [49,50]. The system inertia and rotating load-damping effect are further challenged by the growth of high voltage direct current connections [51] and the uptake of load frequency drivers [52], respectively. Second, the increased penetration of RESs and the phase-out campaigns of polluting thermal units reduce the number of generators able to provide reserve

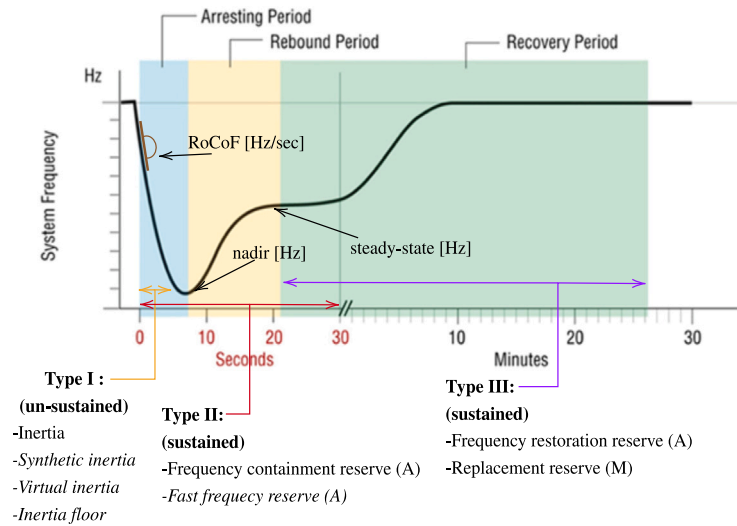


Fig. 2. Frequency services timeline extended from [47,60,65]. The service in *italic* describes novel services. “A” is automatic activation, while “M” is manual activation.

power for primary (containment reserve) and secondary (restoration reserve) frequency control [53]. On top of that, the frequency stability is threatened by both the loss event of generating units [40] and the ill generation forecast of RESs [48]. Hence, due to the low-inertia in the system, even mild disturbances would cause a large enough rate of change of frequency (RoCoF) to activate defense plans [54], such as under/over-frequency schemes [55]. In addition, a large RoCoF can activate protection relays, resulting in cascaded trips and leading to system collapse [56]. Acknowledging such challenges, the Nordic TSOs have proposed three low-inertia mitigation measures [57,58]: (i) restricting the dimensioning incident; (ii) assessing the minimum systems’ inertia; and (iii) dispatching faster active power reserves that supplement the primary frequency control. Such measures also address the participation of converter-connected RESs in frequency services [59–61]. Similarly recommendations are followed-up in North America [62, 63], Australia, United Kingdom [53,64], and Ireland [53,65]. These measures try to arrest RoCoF, avoid a low frequency nadir, and help the system land at a desired steady-state frequency, which is affected by the size of the contingency, systems’ inertia [66], speed, and magnitude of injected active power response from generators [62].

### 3.3.2. Conventional and novel frequency services

Fig. 2 describes frequency regulation services by timeline and distinguishes between conventional and novel services (supporting a low-inertia system). Frequency services are divided into activation periods and service types. The periods are the arresting, rebound, and recovery period [60], while the types are I (un-sustained), II (sustained), and III (sustained) [53,67]. The nomenclature in Fig. 2 is adopted from ENTSO-E [68].

After a mismatch between production and consumption, a sharp increase/decrease of the frequency is experienced. Here, the frequency-arresting period is the most critical. Multiple varieties of the system inertia are automatically and instantaneously activated. However, such measures are not sustained, hence, those are complemented by the governor/droop-based control of frequency containment reserves (FCRs), and the novel fast frequency reserves (FFRs). The latter one does not intend to replace FCRs rather support them [57]. From the observed implementations and their respective requirements, two FFRs activation approaches exist. Nordic TSOs and ERCOT are dispatching FFRs after the FCRs [63,69], while EirGrid and NG ESO are dispatching the FFRs before the FCRs [65,70]. Another difference is the hard constraints of delivering FFRs. The NG ESO and ERCOT require full delivery below 1 s, while EirGrid and Nordics TSOs require full delivery below 2 s. On the one hand, this hard time constraint is a reason that

conventional steam and hydro turbines are unable or do not desire to participate in such reserves [58]. On the other hand, converter-connected resources and frequency-responsive demand response cope well with such constraints, and those might dominate the FFRs [58].

After experiencing the minimum frequency (frequency nadir), there is the rebound period, which goal is to land the frequency in a steady-state. The amount of time and the frequency deviation from the nominal value are subject to the speed and the magnitude of injected power response (type II reserves) [68]. After reaching the frequency steady-state, the power system requires automatic generation control (AGC) to clear the frequency deviation by activating frequency restoration reserves (FRRs). Hereafter, the system is entering the recovery period where the frequency should adhere towards the normal operation. Once the AGC is provoked, the type II reserves are automatically deactivated. Further, the replacement reserves (RRs) replace the FRRs, and the FRRs can be restored for a new event [67].

Frequency control techniques are out of the scope of this paper, however, for a detailed review it is recommended to refer to: (i) photovoltaics [85,86]; (ii) wind [67,86]; (iii) battery energy storage system [47,76] and (iv) different energy resources [62,87]. The characterization of the frequency services depending on the type is presented in Table 1. This characterization per type is based on three reasons: (i) the goal of the service (reduce RoCoF, delay and prevent critical frequency nadir, clear frequency deviation), (ii) the stretch on the frequency excursion period (arrest, rebound, and recovery period) and (iii) the activation topology (RoCoF or frequency-based). The table summarizes the services presenting type and criteria. According to ENTSO-E, frequency service providers can be generators or loads [88]. The table also highlights in bold and \* the five services that can be provided by EVs and their V1G or V2G chargers. Examples of how frequency services can be provided are as follows: (i) phase-locked loop (PLL) to measure RoCoF and a proportional-based control deploys synthetic inertia [89], (ii) virtual synchronous machine [90], and virtual oscillator control [91] methods to deploy virtual inertia from grid forming inverters [92], (iii) droop-based control for deploying FFR, or FCR [78], and (iv) the AGC which is a proportional integral-based control for deploying FRR or RR [82].

These services have already been validated in research; however, fast delivery services such as synthetic inertia, virtual inertia, and FFR are not commercially available. The main reason for this is the requirement to deliver such services with response time below 1 s. Of the rest of commercially proven services, due to economic feasibility, only FCR is applied in the field, i.e., droop-based control in Denmark [78]. FRR and RR have only been applied in pilot projects. The



**Table 1**

Frequency services classification. \* marks services that can be delivered from EVs via **uni/bi-directional smart chargers (V1G and V2G)**, or only *bidirectional chargers (V2G)*.

Type	Explanation	Design stage
<i>Type I: un-sustained Arrest period RoCoF-based activation</i>	Goal: Should reduce the RoCoF (prevent triggering RoCoF relays) and delay the frequency nadir.	
1. Inertia [59,61,71]	1. Natural feature of rotating generators from which benefits the frequency stability.	1. -
2. <b>Synthetic inertia*</b> [72–75]	2. Capability of converters to try reducing RoCoF by injecting power into the system. Also known to be related to grid following converters.	2. Research proven
3. <b>Virtual inertia*</b> [74,76]	3. Capability of converters to try reducing or improving RoCoF by injecting power into the system. Also known to be related to grid forming converters.	3. Research proven
4. Inertia floor [59,72,77]	4. Requesting rotating inertia to maintain or improve optimal system's inertia, which mitigates frequency excursions.	4. -
<i>Type II: sustained Arrest-rebound-recovery period Frequency-based activation</i>	Goal: Should arrest the frequency excursion by preventing a critical frequency nadir that can trigger defence schemes.	
5. <b>Fast frequency reserve*</b> [58,78]	5. Requesting a power injection with a very fast delivery period, typically less than 2 s, to be maintained for a predefined time span accordingly to the grid-code.	5. Research proven
6. <b>Frequency containment reserve*</b> [79,80]	6. Requesting a power injection with a fast delivery period, typically less than 15 sec, to be maintained for a predefined time span accordingly to the grid-code.	6. Research proven Commercial proven
<i>Type III: sustained Recovery period Frequency-based activation</i>	Goal: Should replace the generation loss and restore normal operation.	
7. <b>Frequency restoration reserve*</b> [81,82]	7. Requesting a power delivery to restore the frequency deviation to the nominal operating point.	7. Research proven Commercial proven
8. <b>Replacement reserve*</b> [83,84]	8. Requesting a power delivery (generator rescheduling) to fully clear the frequency deviation.	8. Research proven Commercial proven

increase penetration of EVs can mature (reduce the cost) the charging technology, and the rising electricity spot-prices could make FRR and RR economically viable very soon.

### 3.4. Flexibility services

Frequency regulation is a system-wide characteristic that cannot be contained locally. On the contrary, flexibility services reflect a local problem. Thus, flexibility services are, among others, linked to reactive power support, congestion management, power quality, power smoothing, and post-fault restoration services [93].

#### 3.4.1. Flexibility services definition

Moving forward, this study lists the flexibility services that can be provided from EVs. While for frequency services there is an available market framework [94], the flexibility services are lacking, or rather are on the first steps of the implementation of such markets. For example, the authors of [95] discuss how flexibility products can be delivered, as ramp or energy, whereas in [6] a capacity allocation product is discussed. Recalling from the aforementioned literature [9,24], they agree on the allocation of flexibility services based on five features: resource type, duration, incentives, location, and enablers. Therefore, the authors propose the following definition for flexibility services:

*Flexibility service refers to scheduling and/or modulation of the collective/single consumption or generation of electrical appliances or distributed technologies, in agreement with the customer (consumer or generator) or mandated in the grid code, after responding to signals from market enablers, to increase network reliability and efficiency on a predefined time and location.*

#### 3.4.2. Flexibility services classification

Based on the aforementioned pillars of power systems operational needs and on the Danish flexibility services procurement guidance, this paper characterizes the flexibility services into three categories: natural, scheduled, and conditional. Natural flexibility services refer to actions actively enabled by the SO without the need for a procurement process, namely demand response programs, control of network components and grid code requirements. Scheduled services account for measures procured by the SOs to not jeopardize system safety operation or counteract N-1 situations. Conditional flexibility services are activated to restore system stability or increase power system efficiency. The difference between conditional and scheduled services is the activation type. For conditional services the activation is post-event, whereas for scheduled services it is a pre-event or during event activation. Natural flexibility comes first, it is a tool only based on the agreement with the user, and it potentially reaches the highest number of flexibility providers, along the timeline. If natural flexibility is not enough, scheduled flexibility is used by SO in a dedicated area, with a specific timeline and fewer providers. Similarly, conditional flexibility is the last resource to avoid further escalation of the problem or help the system recover. In addition, what may sound important to the reader are the steps SO takes to acquire flexibility services (Table 2 and Figs. A.8, A.9): first, exhaust the available (natural) services and then use the market ones (scheduled or conditional). Table 2 categorizes the flexibility services by type – natural, scheduled, and conditional –, by area DSO or TSO and by topic. Also, the table gives a short description of the services and highlights the services that can be delivered by EVs by bold style and \*. Here, 26 and 20 out of 32 flexibility services can be delivered via V2G and V1G, respectively. The extra services that can be provided through V2G refer to the possibility of injecting power into the grid and providing reactive power support.

Further, the V1G can deliver flexibility services via scheduling or modulating the charging process. These features are fully investigated

**Table 2**

Flexibility services classification based on type, enabler and grid location. \* marks services that can be delivered from EVs via both **unidirectional and bidirectional smart chargers (V1G and V2G)**, or only *bidirectional chargers (V2G)*.

Type	DSO area	Explanation	TSO area	Explanation
Natural and w/o procurement	Congestion management (DSO) via non-dispatchable demand response programs such as [96–100]: <b>1. Time of Use (ToU)*</b> <b>2. Dynamic pricing (DP)*</b> <b>3. Critical peak pricing (CPP)*</b> <b>4. Peak-time rebate (PTR)*</b> <b>5. Extreme day pricing (EDP)*</b> <b>6. Inclining block rate (IBR)*</b> <b>7. Peak upgrade*</b>	It provides an economic incentive for consumers to reduce their consumption.  1. Putting an extra flat fee on particular hours. 2. Putting an extra dynamic fee. 3. Putting an extra fee on energy used during peak time. 4. Offering payments for those who reduce consumption during peak time. 5. Increasing DSO fees on a high loading day. 6. Increasing the electricity price rate with the end-user consumption rate. 7. Proposing an end-user peak value and peak time-span (forcing an infrastructure upgrade if the time spent on the peak is met).	Emission management [101]: <b>1. Type of Use (TyoU)*</b>	It intends to reduce consumption from polluting generators.  1. Inducing an extra fee related to grid carbon intensity.
	Congestion management (DSO) via network components [102,103]: <b>8. Network reconfiguration</b>	8. Remote control of radial networks components to better manage their loading.		
	Grid stability (DSO) via network components [104–106]: <b>1. Low-voltage ride through*</b> <b>3. Fault ride through*</b> <b>3. Power factor control (TSO)*</b> <b>4. Anti-islanding*</b>	It mandates capability features from the grid code to assist system stability.  1. Requesting to withstand a low-voltage event in the network (high Q consumption nearby). 2. Requesting to withstand a voltage-dip (grid fault) for a defined time, as stated in the grid code. 3. Requesting reactive power control proportionately (determined by the droop) to active power in the point of connection. 4. Requesting from grid connected inverters to be able to recognize islanding events and prevent them.	Grid stability (TSO) via network components [38,105]: <b>1. Low-voltage ride through*</b> <b>2. Fault ride through *</b> <b>3. Power factor control (TSO)*</b> <b>4. Anti-islanding*</b>	It mandates capability features from the grid code to assist system stability.  1. Requesting to withstand a low-voltage event in the network (high Q consumption nearby). 2. Requesting to withstand a voltage-dip (grid fault) for a defined time, as stated in the grid code. 3. Requesting reactive power control proportionately (determined by the droop) to active power in the point of connection. 4. Requesting from grid connected inverters to be able to recognize islanding events and prevent it.
	Voltage regulation (DSO) via network components [103,107]: <b>1. Tap-changers</b> <b>2. Static VAR compensators</b>	It tackles voltage unbalances, under and over-voltage challenges.  1. Remote control of transformers tap-changer to help tackle voltage stability. 2. Remote control of reactive compensator to mitigate voltage unbalanced networks.	Voltage regulation (TSO) via network components [108–110]: <b>1. FACTS</b> <b>2. Reactive power support*</b>	It tackles under and over-voltage network challenges.  1. Remote control of power electronic devices located in substations to maintain voltage stability. 2. Requesting reactive power support for weak grids. Capability curves are mandated in the grid code.
Scheduled and subject to procurement	Congestion management (DSO) [111,112]: <b>9. Valley-filling (DSO)*</b>	It demands a load curtailment or induced power to reduce loading stress on network components.  9. Requesting a load shift in time from the consumers.	Congestion management (TSO) [113]: <b>1. Valley-filling (TSO)*</b>	It dictates a load reduction or induced power to manage high-voltage network loading.  1. Requesting a load shift or delay in time from the consumers.
	Voltage regulation (DSO) [114,115]: <b>3. Under/over voltage regulation*</b>	3. Requesting active or reactive power support for under and over-voltage networks.		

(continued on next page)

in Section 5. Five major topics are recognized: congestion management, voltage regulation, power quality, grid stability, and emission (CO<sub>2</sub>) management.

*Congestion management* refers to measures taken from SO to maintain the desired loading on their network components, such as transformers and electric lines. The reasons for doing so are twofold: (i) high overloading of a grid component will instantly damage the component [135] and (ii) moderate overloading will produce heat higher than normal from the current flowing through the device. With time,

extra heat shortens the lifetime of the device, requiring earlier maintenance [136]. In *Appendix A* a Danish city distribution network [137] named Frederiksberg is taken as example to present the provision of congestion management.

*Voltage regulation* refers to measures taken from SO to maintain voltage stability and overcome short-circuit scenarios. Here, the paper distinguishes between voltage and reactive power support. In the former, both active and reactive power play a role, while the latter is more related to reactive power support with a focus on weak grids [138]. The cause of voltage instability derives from the fact that the power network

Table 2 (continued).

Type	DSO area	Explanation	TSO area	Explanation
Conditional and subject to procurement	Power quality [116–119]: 1. DER power-smoothing* 2. Damping harmonics* 3. Power factor control*	It tackles grid losses and improving supply quality:  1. Mitigate power flickering effects from the highly volatile nature of renewable sources. 2. Requesting to filter the harmonics via filters or inverters. 3. Requesting to correct the power factor of a customer (capacitive or inductive).	Grid stability (TSO) [120–125]: 1. RES power smoothing* 2. Emergency power* 3. Black start capability* 4. Energy arbitrage* 5. Seasonal balancing *	It tries to improve or backup the network's power stability.  1. Requesting to smooth power variations from RES. 2. Requesting to energize critical infrastructure during emergencies. 3. Requesting to generate active power to energize lines or start-up larger power plants. 4. Requesting to fill the mismatch absent from BRP commitment, by reducing the load. 5. Requesting to store large renewable energy surplus and deliver it back on low renewable season production.
	Voltage regulation (DSO) [126–128]: 4. Voltage unbalance mitigation* 5. Reactive power support*	4. Requesting to alleviate voltage asymmetries by better balancing the phase loading. 5. Requesting reactive power support for weak grids.		
	Grid stability (DSO) [129,130]: 3. Intentional islanding* 4. Emergency power (DSO)*	3. Requesting to maintain frequency/voltage stability after the isolation of a part of the grid . 4. Requesting to energize local loads during emergencies.		
	Congestion management (DSO) [112,131,132]: 10. Peak-shaving (DSO)* 11. DER power matching* 12. Phase balancing*	10. Requesting a load reduction or maintaining a predefined load baseline during peak time. 11. Requesting to absorb surplus renewable energy production to prevent negative power flow congestion (from 5-min to a couple of hours). 12. Requesting a transfer of the load to less loaded phases.	Congestion management (TSO) [133,134]: 2. Peak shaving (TSO)* 3. RES power matching*	2. Requesting a load decrease or sustaining a predefined load baseline during peak time. 3. Requesting to absorb excess renewable energy production.

is operated close to stability limits and different load characteristics trigger it [139]. In Appendix A the provision of voltage regulation is illustrated from the perspective of DSO.

*Power quality* refers to the measures taken from DSO to improve supply quality and reduce grid operational losses. Here, the voltage regulation service is distinguished from the power quality service because it belongs to both DSO and TSO. In contrast, the latter belongs to the DSO. Besides, voltage regulation itself has become quite important; hence, it deserves to be mentioned separately. Power quality is focused on the fast dynamics of switching of electronic devices [140], the mitigation of distributed energy resources (DERs) power flickers [116,121], and the control of the end-user power factor [141].

*Grid stability* services cover the power system stability, adequacy, and security of supply outside of the wholesale electricity and balancing markets and are operated by DSO and TSO. Services such as low-voltage/fault ride through, power factor control and anti-islanding are generally capabilities mandated in the grid code. In a high integration scenario of RESs, RESs power smoothing services might be required to operate the system safely and preserve frequency power reserves [121]. Similarly, energy arbitrage and seasonal balancing are believed to be necessary services to cope with the unpredictability of RESs [142, 143]. Additionally, emergency power and black-start capability are programmed for blackouts (according to ENTSO-E) [144], or to provide emergency power to areas affected by local emergencies [130].

As the name suggests, *emission management* relates to a demand response service type of use (TyOU) that intends to avoid RESs spilling and reduce consumption from polluting generators. The TyOU induces fees for the carbon intensity depending on the generation mix. Higher fees correlate with high polluting generators.

Flexibility services are provided in the active and reactive power domains. For both domains, Table 2 noted flexibility services that are, on a dominant majority, at least research proven. Acknowledging the recommendations from [30] and the novel applications of commercial

flexibility [20,21], stakeholders are only looking at active power services, mainly congestion management (refer to Table 2). In the short term, possible commercial flexibility services are demand response programs, TyOU, valley-filling and peak-shaving actions. In the long term, with large penetrations of EVs other flexibility services such as phase-balancing, power matching, and voltage regulation actions could be required.

#### 4. Flexibility framework

##### 4.1. Flexibility architecture and clustering

Another important step towards full activation of flexibility markets is the design of flexibility market platforms [145]. This has been researched and demonstrated through pioneer projects such as Piclo, Enera, Flex, GOPACS, NODES [30,146] and EcoGrid 2.0 [22]. The goal of such platforms is to couple flexibility providers with buyers of flexibility. Buyers of flexibility are SOs and providers of flexibility are aggregators or energy communities. Such aggregating entities utilize in an agreement the end-costumer flexibility (flexibility resource) and provide a flexibility offer to the flexibility platform. The flexibility platform decides for the winning bids. Taking advantage of the learning from these projects a stylized illustration of such platforms is displayed in Fig. 3.

##### 4.1.1. Clustering

One important step before matching the flexibility services is clustering the EV owners based on their charging behavior. The results can be biased to early movers [147] as the industry is still in the early stages. However, by looking at different databases and clustering investigations, in Figs. 4 and 5(a), we first cluster according to the grid connection (low, medium or high-voltage) [148] and second based on the charging behavior. Here, a complete picture of the available

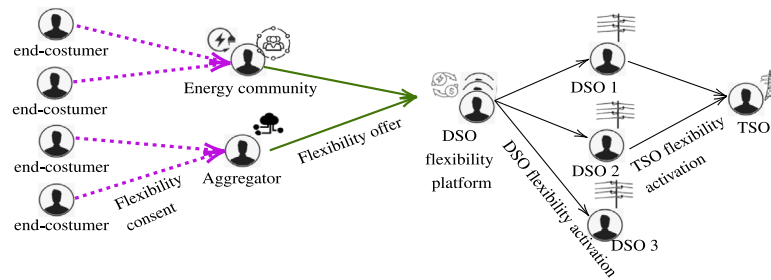


Fig. 3. Converged proposal for the DSO flexibility platform.

Charging clusters	Spread quantity [no of chargers]	Single site capacity [kW per site]	Single chargers's capacity	Type	Sites
CSO-LV.1			3.6-22 kW	Destination charging	(Semi) detached houses
CSO-LV.2			3.6-22 kW	Charging destination	Curbside parking
CSO-LV.3			3.6-50 kW	Destination charging	Education/workplace car parks
CSO-LV.4			3.6-50 kW	Destination charging	Housing associations, Flat blocks, Apartments
CSO-LV.5			3.6-50 kW	Destination charging	Supermarkets, Shops, Small shopping centers, Restaurants, Gyms, Cinemas Cafes
CSO-LV.6			3.6-150 kW	Charging destination	Transport companies park sites
CSO-MV.1			3.6-150 kW	Destination charging	Large organizations headquarters, campuses or shopping malls
CSO-MV.2			50-350 kW	Destination charging	Motorway service stations
CSO-MV.3			3.6-350 kW	Charging destination	Stadium and large entertainments (sport palace, zoo, pool, concert halls) parking lots
CSO-MV.4			3.6-350 kW	Charging destination	Charging forecourts
CSO-MV.5			3.6-350 kW	Destination charging	Airport, train parking sites
CSO-HV			50-1000 kW	Charging destination	Dedicated charging hubs

Fig. 4. The CSOs site characteristics. The column “type” extends from [154].

charging data sets can be found in [149], while for charging behavior, it is recommended [150,151], and for infrastructure deployment, it is recommended [152,153].

The literature review distinguishes between destination charging and charging destination. In the first, charging is complementary to other user needs, such as going to the supermarket, in the second charging drives the choice of the user needs. Furthermore, charging behaviors are reflected at different charging sites: (i) home [155,156] and public residential charging [157,158]; (ii) curbside [159–161] and semi-public charging [162,163]; (iii) workplace charging [164]; (iv) fleet charging [165]; (v) large semi-public charging [166]; (vi) fast(en route) charging [167,168]; (vii) special semi-public charging [169, 170]; (viii) charging forecourts [171,172]; (ix) semi-private charging [173] and (x) charging hubs [174]. Although it is still quite early for the clusters to mature, the charging clusters derived from the review are in line with the clusters used in the Working Group 4 of the IEA GEF Global e-mobility program [175,176].

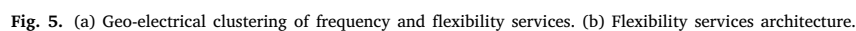
Accordingly, Fig. 4 illustrates with examples the CSO, which is the representative of the cluster. The CSO can incorporate one charger, in the case of a home charger or include multiple chargers such as the charging forecourts. The higher the site hierarchy, the fewer chargers

there are, while the site connection capacity increases. Furthermore, it is a challenging task to estimate the number of chargers in each cluster. This factor is one of the current limitations on forecasting flexibility of charging clusters. In addition, the charging technology needs to be mature before trying any estimation. For example, most slow chargers today are single outlet; however, to increase utilization efficiency, dual outlet options are investigated. After identifying the charging clusters or CSOs, Fig. 5(a) matches the charging clusters with their grid location (low/medium/high voltage). Besides, it couples CSOs with possible delivery of flexibility and frequency services. This is achieved by matching the previously discussed ancillary services depending on V1G or V2G. The V1G represents a smart load, while V2G (converter technology) is similar to the battery energy storage. Further, the drawing in Fig. 5(a) pairs each CSOs with the charging technology (AC and DC smart chargers) and with different EVs ownership types (passenger cars, taxis and fleets, autonomous vehicles, shuttles, and public transport buses) [175,176].

#### 4.1.2. Flexibility architecture

Based on the generalized flexibility architecture and clustering above displayed (Fig. 3), in this subsection we intend to provide an





else. Here, the CPOs concept is introduced, which can control (back-end control) the charging infrastructure. Further, it is recently observed alliances between CPOs and charger manufacturers. Hence, these alliances are made to offer a complete charging infrastructure package to the end-users and CSOs. A CPO can fully control one or multiple CSOs accordingly to the CSO desires. On the one hand, the CPO can deliver bilateral flexibility service to the SO. On the other hand, CPO can delegate front-end control (API interface) to an aggregator [177]

or an energy community to participate in the flexibility market [178]. In this case, a larger entity is created, and CPO can help the process by providing flexibility forecasts of their sites to the aggregator or energy communities. Subsequently, the aggregator or energy communities bid a flexibility offer in the flexibility platform related to the DSOs or TSO network. The platform decides the winning bids and activates the flexibility service. Lastly, in Fig. 5(b) a summary of flexibility services from the aggregating entity is presented. Further, a novel aggregator-free approach is investigated from Danish ACDC and FUSE research projects [179,180]. Both projects investigate the bilateral flexibility services CPO-DSO.

#### 4.2. Electric vehicles flexibility alliances

To participate in electricity markets an entity must become a balancing responsible party (BRP) and fulfill size, market, and grid requirements. Barriers such as size and market requirements can be overcome by forming alliances between SOs, and CPOs. To recall from above, CPOs are already forming alliances with charger manufacturers. Thus, different stakeholders are bypassing such barriers by offering full charging services package that include charging infrastructure and smart charging incentives (among others, smart charging is comprised of flexibility and frequency services).

Fig. 6 illustrates the supply chain of flexibility services provided by EVs, including examples from the Nordic countries. CPO can offer a bilateral flexibility service to SO, with the consent of CSO through centralized or distributed control of smart chargers [181]. A typical example is Powerloop, a project implemented in the United Kingdom between Wallbox, Octopus EV, and UK Power Networks [182]. Wallbox supplies a V2G technology to Octopus EV (the commercial name of the charger is Quasar). Octopus EV provides congestion management services to UK Power Networks (DSO) in agreement with end users. Similarly, the FUSE research project aims to combine Zaptec, Spirii, and Radius to simplify the development of flexibility services [180]. Zaptec supplies a state-of-the-art V1G to Spirii, which is the CPO. Spirii offers to its customers the possibility to participate in congestion management services. Radius, a Danish DSO will utilize the Spirii infrastructure to their benefits. Additionally, a more ambitious aggregator and CPO-free path is followed from the ACDC project [179]. The project aims to deliver an autonomously controlled distributed smart charger. The charger developed from Circle consult couples the DSO (TREFOR El-Net Øst) directly to the CSOs.

## 5. Smart chargers

After considering what services SOs require to maintain fully operational grids and highlighting which services can be delivered from the EVs charging cluster, this section reviews the slow smart charger technology. The charging infrastructure plays a central role in supporting EV adoption, and smart chargers are a promising distributed infrastructure coupling power system with the transport sector [143]. Therefore, first, we provide a definition for the smart charger, which will facilitate the correlation between ancillary services and EVs. Second, we review the current state-of-the-art of slow smart charger technology.

#### 5.1. Dumb and smart charger comparison

International charging standards are well covered in the literature [35,36]. In this paper we focus on IEC 61851 [183], and based on it we define the differences between a dumb and a smart charger, as shown in Fig. 7. A *dumb charger* is a device comprised of circuit breakers, relays, and voltage oscillator, which maintains a constant control pilot duty cycle to charge the EV. The scheduling devices outside the dumb charger (on the grid and EV side) can turn on or off charging process. In addition, it illustrates a smart behavior from the user side, even though users own a dumb charger.

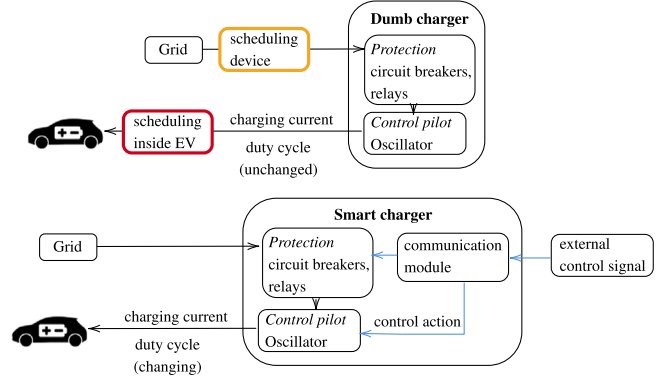


Fig. 7. Smart charger and dumb charger comparison.

A *smart charger* contains a communication module and can control the control pilot duty cycle, thus modulating or scheduling the charging

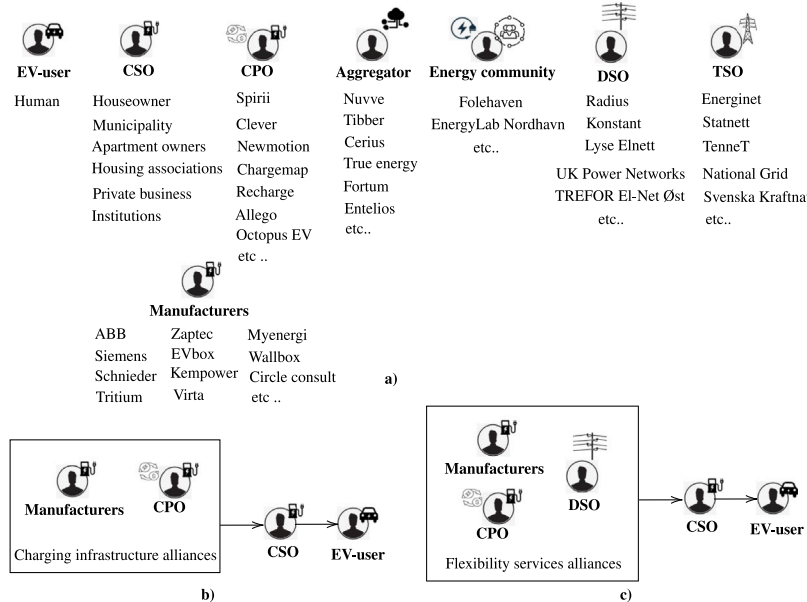


Fig. 6. (a) The EVs flexibility supply chain. (b) Charging infrastructure alliances. (c) Flexibility services alliances. Examples are provided for the Nordic countries cases.

process. Scheduling refers to turning on–off the charging process. Modulating refers to controlling the charging current through the control pilot. An optional action of smart chargers is the ability to control the open-closure of the relays, which allows a three-phase capable EV to perform a switch from three-to-one phase charging [184], hence, curtailing two of the phases. Here, it should be underlined that those chargers which can control their relays also offer the 0 Amp current option. This means that they can keep the EV on-board charger awake without drawing any current for the charging process.

Therefore, a smart charger is a device providing protection, communication, at least scheduling and at most modulation and phase curtailment (3 to 1-phase switch) for the EV charging process.

## 5.2. Control architecture

The control approaches of smart chargers can be divided into centralized, decentralized, and distributed. Table 3 merges the findings from authors of [5,185–189] regarding advantages and drawbacks of each control approach. So far, smart chargers have followed in a large majority the centralized control approach, mainly due to simplicity of implementation and a more mature architecture [190]. Besides that, recent initiatives are exploiting the distributed control approach [181, 191]. The main difference is the location of the intelligence. In the centralized case, the intelligence resides on the cloud, while in the distributed one, it is spread among the cloud and the virtual aggregator (local intelligence).

## 5.3. Flexibility services and smart chargers

EVs can benefit the power system providing as a large flexible energy resource. Nevertheless, such services are one side of the charging process decision-making. The other side relies on infrastructure owner's economic benefits and user's comfort. The authors of [192] highlight the EV multi-use or optimal designed strategies that combine different value streams for EVs. Here we argue the difference between flexibility services and smart charging strategies. The charging process can be scheduled or modulated. Smart chargers can offer both scheduling and modulation, while dumb chargers can provide scheduling via external interference.

Smart charging strategies aim at increasing consumer acceptance and satisfaction rate. Further, coordination is required to deliver a smart charging strategy. Examples of strategies are (i) scheduling-based control, the simplest smart charging strategy that can be performed from both dumb (with external help) and smart chargers [193], and (ii) modulation-based control, the exclusive feature of smart chargers. Smart charging strategies combine technical grid requirements with the economical benefits of owners and user comfort. Other examples of such strategies can be found in [192,194].

As discussed previously in Section 3, flexibility services aim to increase the reliability and efficiency of the grid. Flexibility services are key elements for designing smart-charging strategies that are beneficial for the power system and can be enabled from SO. Examples of such strategies comprising only flexibility services can be found in [195,196]. This means that smart-charging strategies can: (i) be beneficial to the grid or not and (ii) involve different flexibility services or none at all. Here, it is relevant to underline the importance of designing well-thought strategies due to the risk of causing grid avalanche effects [197]. For example, a smart charging strategy synchronized only with electricity spot prices can result in overloading of grid components [133]. Therefore, to limit the potential danger, the smart-charging strategies development should include more variables and account for possible rebound effects [198,199]. One example is the bill optimization strategy for a residential consumer, which can comprise of stacked services such as spot-price, time of use (ToU), avoid peak upgrade, offer valley-filling (DSO) and TyoU among others.

## 5.4. Smart chargers state-of-the-art overview

Smart charger technology is crucial for scaling up the charging infrastructure. To the authors knowledge a review of available smart chargers in the market is missing in the literature. In [200,201] the authors investigated the incompatibility of EVs chargers on a large scale. This study focuses on slow smart chargers, and it offers, for the first time, a market technological overview of 27 smart chargers. Based on [190], Tables B.1 and B.2 present a full picture of the current smart-chargers state-of-the-art technology up to 50 kW, which have controllable features. These will be referred to as “slow smart chargers” in the following. Smart charger characteristics are divided into user interaction, charging status information displayed in the physical device, charging and construction data, communication protocols, incorporated smart features, and flexibility features.

Regarding user interaction, the majority of smart chargers are RFID (26/27 that means 26 out of 27) and mobile application (27/27) friendly, while a physical key (9/27) or pin code (5/27) is less spread. Similarly, LED lights that display the charging status are more often adopted (25/27) compared to physical displays (11/27). From this observation it seems that the future trend for user's interaction with smart chargers will be RFID and mobile applications, while for physical charging status, it will be LEDs. The latter one makes sense economically when comparing LEDs with physical displays.

Each single-phase charger has a 3-phase twin. Currently, the 22 kW charging power dominates over the 11 kW option (21 options for 22 kW towards 8 options for 11 kW). Although most of the chargers found are AC chargers (22/27), few DC chargers examples are also given (5/27).

Regarding the construction of physical chargers, charger manufactures are currently competing to make the chargers as light and as

**Table 3**  
Advantages and drawbacks of EV chargers control approaches.

Control approach	Advantages	Drawbacks
Centralized	Vulnerable to cloud aggregator malfunction being spread on all chargers. System wide observation. Easier implementations of optimization algorithms.	Need of a backup server system. Heavy communication and computation when scaled-up. Subject to cyber-attacks and possible data privacy violation.
Decentralized	Diverts data privacy challenges. Low communications and computation capabilities when scaled-up. Low sensitivity to errors and cyber-attacks, thus high system robustness. High deployment scalability. Low communication delays.	Lack of grid observability. Immature control architecture. Risk of avalanche effects. Difficult to reach optimal solutions from optimization algorithms.
Distributed	High scalability and autonomy. System wide observation. Low sensitivity to errors, thus high system robustness. Diverts data privacy challenges. Possibility of plug and play protocols. Low communication delays.	Novel control architecture, thus not mature. Prone to cyber-attacks. High complexity on charger design.

small as possible. Although the lightest AC charger is 1 kg, the DC one is minimum 47 kg. For further details, refer to Table B.1. The minimum observed enclosure rating standard is IP54 and in six other charger alternatives, an improved standard followed (four options stick to IP55 and two options keep IP65). Further, 3 out of 27 chargers include cooling options, while all chargers embody DC current leakage protection and third category surge protection.

All the chargers presented in Table B.1 are controllable. According to the description of Open Charge Alliance, open charge point protocol (OCPP) is an open protocol that allows CPO to control the smart charger. Here, the smart chargers observed tend to converge to the OCPP 1.6 protocol that allows smart charging features [202]. Nevertheless, to be future-proof some manufactures have or are ready to implement OCPP 2.0, since the protocol was made available in April 2018. The OCPP 2.0 is designed to be flexibility friendly [203] and it offers improved functionalities such as device management, transaction handling, security, smart charging functionalities, ISO 15118 support, display and messaging support. Furthermore, five options are observed to be used to communicate and be integrated with external devices, namely 4G (24/27), WiFi (22/27), Ethernet (20/27), Bluetooth (11/27), and RS485 (10/27). The last two are range-limited alternatives. The typical example for such implementation is a local controller communication as displayed from Schneider EVlink smart charging controller [204].

Furthermore, the smart features section incorporated in Table B.2 attempts to distinguish the inputs each charger can receive and use in a decision-making process. First, the power set point (27/27) is a user or CPO reference input to follow. Second, the smart charger can receive consumption measurements from the energy meter (16/27), or otherwise, the charger has its own meter that closes the control loop. The home area network (HAN) protocol allows smart chargers to become part of a larger smart infrastructure. A majority (17/27) of chargers are HAN friendly meaning that they are able to communicate with other smart home devices. In addition, smart charging options can be provided, such as price-based charging (21/27) or power-sharing between devices or using local generation (14/27).

Lastly, flexibility features of the chargers are also provided, to recognize what flexibility capability each of the smart chargers offers. The scheduling feature is the minimum feature a charger needs to be called smart charger. In addition, 24 out of 27 chargers can modulate the charging current, while only three out of 27 can make the three to one phase charging switch.

## 6. Conclusions

By looking at the future of the power system, this study reviewed how smart chargers can be used to provide flexibility and what is the technology status at today. First, the ancillary services available in the power system are presented, by distinguishing between frequency and flexibility services. Then, these were discussed in terms of the type of action, namely frequency regulation, congestion management, voltage regulation, power quality, grid stability, and emission management. Five out of eight frequency services and 26 out of 32 flexibility services can be derived by EVs. However, only three out of eight frequency services the charging technology is on a commercial stage. Similarly for flexibility services, mainly congestion management services are being further developed for commercial applications. Furthermore, the study recommends that SOs should exhaust available non-market flexibility services before purchasing market-based flexibility.

In this sense, it is necessary to understand how EVs can provide these services. Thus, the supply chain of flexibility services from EVs is presented. Seven actors are identified: the end-user, the CSO, the CPO, the aggregator, the energy community, the DSO, and the TSO. The end-user is the main actor due to its large influence (charging behavior) on supply chain decisions. To link charging behavior and charging location clusters, 12 geo-electrical charging clusters (CSOs)

are proposed. Additionally, the frequency and flexibility services are coupled with CSOs, and are matched with their grid location (low, medium, or high voltage).

To provide such services, CSOs can delegate their control to CPOs. CPOs can be further aggregated into energy communities or aggregators, and become a BRP to participate in electricity markets. However, to encourage the growth of the new technology/service provision, CPOs, charger manufacturers, and DSOs are forming alliances offering complete charging packages to the CSOs. Such packages include smart charging infrastructure and incentives to participate in ancillary services while bypassing current technological and market barriers.

Although, to perform ancillary services smart charger infrastructure is needed. Thus, this article provides an overview of current market available slow smart chargers with up to 50 kW. Three main flexibility features were observed to be commonly provided by the chargers: scheduling, modulation and switching from three-to-one phase during charging. All observed smart chargers can schedule, while 89% can also modulate. Only 10% can switch the charging from three-to-one phase.

Regarding future work, having a map of ancillary services coupled with EVs charging clusters opens up the door on one side for full exploitation of smart charging strategies and on the other side for different stakeholders to better understand their roles. Further, the available flexibility of each charging clusters needs to be quantified and proper smart charging strategies should be investigated to avoid avalanche or rebound effects. The Nordic case highlight the need for simple regulations to attract flexibility providers, looking primarily at congestion management actions. Novel approaches, such as flexibility alliances, bypass market barriers and bid size to help SOs gain confidence in flexibility service provisions. For example, Dansk Energi, an organization representing the Danish energy companies, is proposing a bid size of 10 kW, however, such approaches are still in the early stages. Lastly, smart charging infrastructure is developing rapidly. Most of the modern smart chargers are cloud-based and with a single outlet. To improve utilization factor and reduce the cost of smart chargers, double or quadruple outlets are being developed. In addition, new distributed controlled chargers are being investigated to tackle possible cyberattacks leading to a massive infrastructure being compromised.

## CRedit authorship contribution statement

**Kristian Sevdari:** Conceptualization, Methodology, Investigation, Writing – original draft, Visualization, Formal analysis. **Lisa Calearo:** Conceptualization, Methodology, Investigation, Writing – review & editing, Formal analysis. **Peter Bach Andersen:** Conceptualization, Methodology, Writing – review & editing, Supervision, Investigation, Project administration, Funding acquisition. **Mattia Marinelli:** Conceptualization, Methodology, Writing – review & editing, Supervision, Investigation, Project administration, Funding acquisition.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Examples of DSO flexibility services provision.

### A.1. Congestion management

Fig. A.8(a) reflects the location and size domain, while Fig. A.8(b) reflects the time and size domain. The Frederiksberg distribution



network comprises of three separate 10 kV networks supplied by a medium voltage transformer each [137]. The DSO congestion management can be first achieved from demand response programs, like ToU,

or network reconfiguration on a wide area. For instance at Fig. A.8(a), ToU is activated but one of the three transformers, transformer X.5, is still overloaded, as shown in Fig. A.8(b). Thus on a second step,

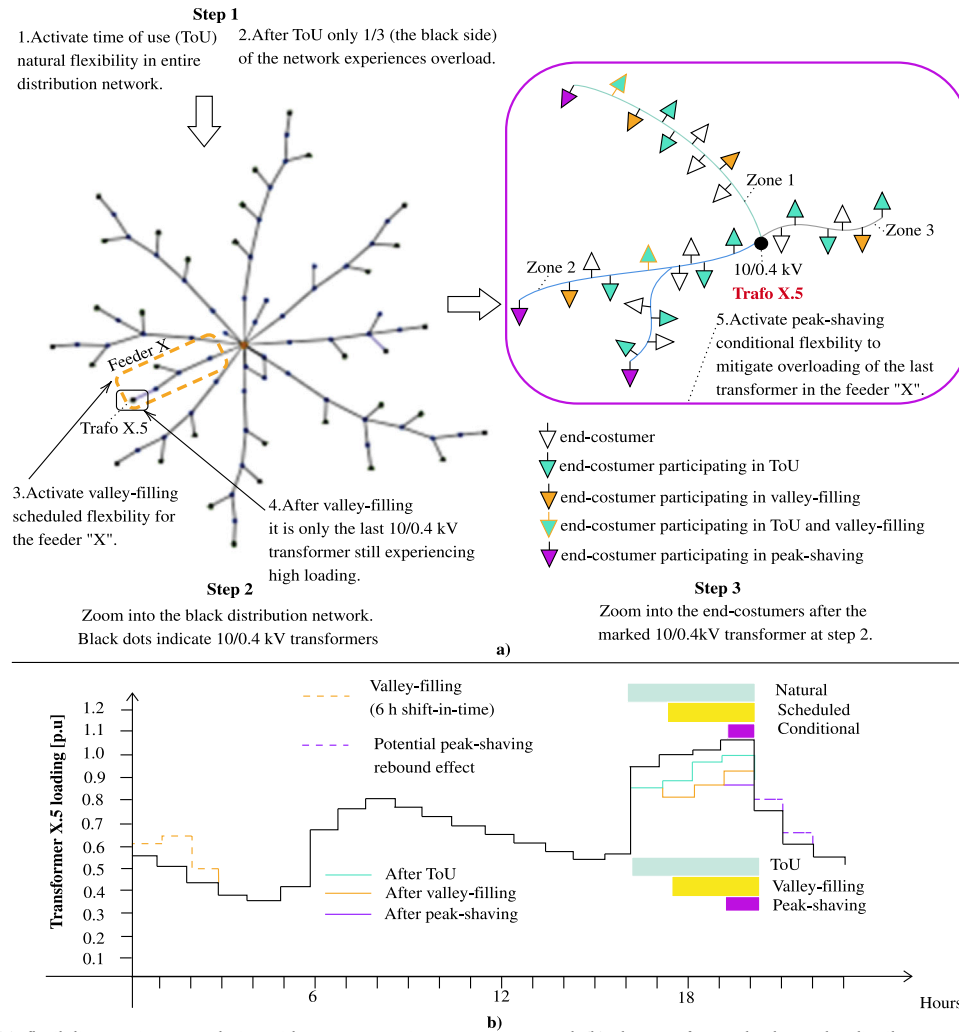


Fig. A.8. Illustration of (a) flexibility services granularity with DSO congestion management and (b) the transformer loading. The distribution network map is adapted with permission from [137].

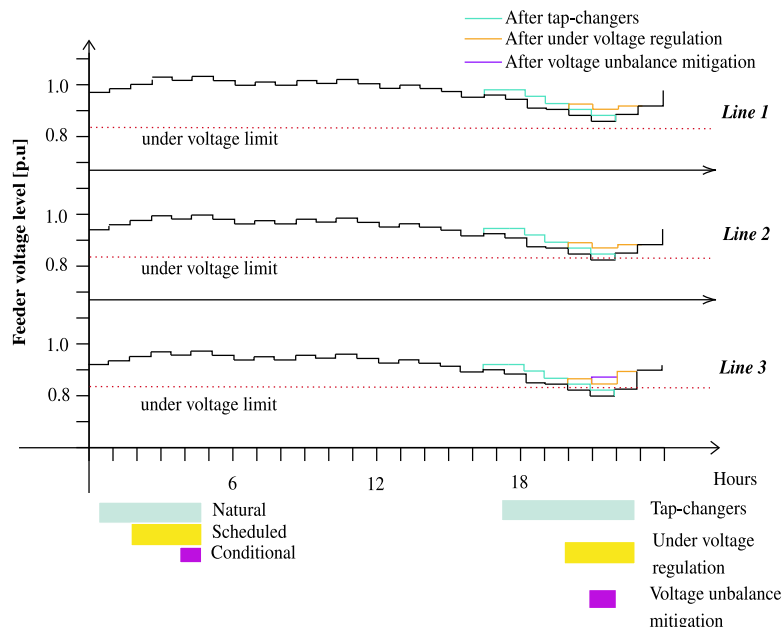


Fig. A.9. Illustration of flexibility services (voltage regulation) implementation from the DSO.



the DSO activates the procured services for feeder X, such as valley-filling. Transformer X.5 is still highly loaded, thus the activation of peak-shaving services closer to the location is required. Each flexibility service activation reflects a loading reduction. Nevertheless, the load reduction of each service is highly case dependent, so it is difficult to quantify before-hand. Further, the activation of the services could also cause rebound effects which should be carefully considered when designing these services [197].

## A.2. Voltage regulation

Similarly, for an illustrative purpose in Fig. A.9, it is shown the voltage regulation activation. The DSO can activate voltage regulation in three steps. First, the DSO can remotely control the transformers' tap-changers. Second, the DSO can acquire market-based voltage regulation services like under-voltage regulation for the local area. Finally, if a more severe voltage unbalance is experienced the DSO can procure voltage unbalance mitigation services to recover the affected lines.

## Appendix B. Overview of slow electric vehicles (EVs) smart chargers

See Tables B.1 and B.2.

Table B.1

Part 1 of the smart chargers technology overview. "Y" means yes, "N" means no and "NA" means the information is not available.

No	Type	Brand	Charger's name	User interaction				Status information			Power [kW]	Max current [A]	Phases	Voltage	Mode	Weight [kg]	Dimensions H × W × D [mm]	Enclosure rating
				RFID	App	Key	Pin code	LED	Display	AC(1) DC(0)								
1	V1G	ABB	Lunic	Y	Y	Y	N	Y	Y	1	4 to 22	16 and 32	1 and 3	240 and 400	3	NA	320 × 195 × 110	IP54
2	V1G	ABB	Terra AC wallbox	Y	Y	N	N	Y	N	1	7.4	32	1	240	3	2	320 × 195 × 110	IP54
3	V1G	ABB	Terra AC wallbox	Y	Y	N	N	Y	N	1	22	32	3	400	3	3.5	320 × 195 × 110	IP54
4	V1G	ABB	Terra DC wallbox	Y	Y	Y	Y	Y	Y	0	24	40	1	240	4	60	770 × 584 × 294	IP54
5	V1G	ABB	Terra DC wallbox	Y	Y	Y	Y	Y	Y	0	24	40	3	400	4	60	770 × 584 × 294	IP54
6	V1G	GHP	CP4100	Y	Y	Y	N	Y	Y	1	3.7 to 22.17	16 and 32	1 and 3	240 and 400	3	NA	491 × 189 × 189	IP54
7	V1G	Delta	Mini AC	Y	Y	N	N	Y	N	1	7.4	32	1	240	3	2	260 × 320 × 115	IP54
8	V1G	Delta	Wallbox	Y	Y	Y	N	Y	Y	0	7.4 and 22.17	32	1 and 3	240 and 400	4	47	680 × 430 × 230	IP54
9	V1G	EVBox	Elvi	Y	Y	Y	N	Y	N	1	3.7 and 7.4	16 and 32	1	230	3	3	186 × 328 × 161	IP55
10	V1G	EVBox	Elvi	Y	Y	Y	N	Y	N	1	11 and 22	16 and 32	3	400	3	6	186 × 328 × 161	IP55
11	V1G	EVBox	Business	Y	Y	N	N	Y	N	1	7.4	32	1	230	3	10	600 × 255 × 410	IP55
12	V1G	EVBox	Business	Y	Y	N	N	Y	N	1	11 and 22	16 and 32	3	400	3	12	600 × 255 × 410	IP55
13	V1G	Kempower	T500-DC	Y	Y	N	N	Y	Y	0	40	63	3	400	4	120	670 × 640 × 1220	IP54
14	V1G	Kempower	T800-DC	Y	Y	N	N	Y	Y	0	40	63	3	400	4	120	670 × 640 × 1220	IP54
15	V1G	Myenergi	Zappi	Y	Y	N	Y	Y	Y	1	7.4	32	1	230	3	NA	439 × 282 × 122	IP65
16	V1G	Myenergi	Zappi	Y	Y	N	Y	Y	Y	1	22	32	3	400	3	NA	439 × 282 × 122	IP65
17	V1G	Schneider	EVlink	Y	Y	Y	N	N	N	1	7.4	32	1	230	3	NA	157 × 150 × 46	IP54
18	V1G	Schneider	EVlink	Y	Y	Y	N	N	N	1	22	32	3	400	3	NA	157 × 150 × 46	IP54
19	V1G	Siemens	VersiCharge	Y	Y	N	N	Y	N	1	7.4	16	1	230	2	7.7	410 × 180 × 100	IP54
20	V1G	Siemens	VersiCharge	Y	Y	N	N	Y	N	1	11 and 22	16 and 32	3	400	2	7.7	410 × 180 × 100	IP54
21	V1G	Zaptec	Pro	Y	Y	N	N	Y	N	1	7.4 and 22	32	1 and 3	230 and 400	3	5	392 × 258 × 112	IP54
22	V1G	Zaptec	Go	Y	Y	N	N	Y	N	1	7.4 and 22	32	1 and 3	230 and 400	3	1.3	242 × 180 × 75	IP54
23	V1G	Virta	Single	Y	Y	N	N	Y	Y	1	7.4 and 22	32	1 and 3	230 and 400	3	NA	370 × 240 × 130	IP54
24	V1G	Wallbox	Pulsar plus	N	Y	N	N	Y	N	1	7.4 and 22	32	1 and 3	230 and 400	3	1	166 × 163 × 88	IP54
25	V1G	Wallbox	Copper SB	Y	Y	N	N	Y	N	1	7.4 and 22	32	1 and 3	230 and 400	3	2	260 × 192 × 113	IP54
26	V1G	Wallbox	Commander 2	Y	Y	N	Y	Y	Y	1	7.4 and 22	32	1 and 3	230 and 400	3	24	221 × 152 × 115	IP54
27	V1G	Fronius	Wattpilot	Y	Y	N	N	Y	N	1	3.7 and 11	16	1 and 3	230 and 400	3	1.9	251 × 146 × 96	IP54

Table B.2

Part 2 of the smart chargers technology overview. "Y" means yes, "N" means no and "NA" means the information is not available. To the reader please keep track with Table 3 via the corresponding charger number.

No	Controllable Yes/No	OCP	Communication							Surge category	Leakage protection	Incorporated smart features					Flexibility feature		
			4G	Wifi	Ethernet (RJ45)	Bluetooth	RS485	Cooling Yes/No	Power setpoint			Data from energy-meter	HAN friendly	Price based	Power share	Scheduling	Modulation	3 to 1 phase switch	
1	Y	1.6	Y	N	Y	N	N	N	3	Y	Y	N	N	N	N	Y	Y	N	
2	Y	1.6	Y	Y	Y	Y	Y	N	3	Y	Y	N	N	N	N	Y	Y	N	
3	Y	1.6	Y	Y	Y	Y	Y	N	3	Y	Y	N	N	N	N	Y	Y	N	
4	Y	1.5/1.6/2.0	Y	N	Y	N	N	N	3	Y	Y	Y	Y	Y	N	Y	Y	N	
5	Y	1.5/1.6/2.0	Y	N	Y	N	N	N	3	Y	Y	Y	Y	Y	N	Y	Y	N	
6	Y	1.6	Y	N	N	N	N	N	3	Y	Y	N	N	N	Y	Y	Y	N	
7	Y	1.5	Y	N	Y	N	N	N	3	Y	Y	N	N	N	N	Y	Y	N	
8	Y	1.5	Y	Y	Y	N	N	Y	3	Y	Y	N	N	N	N	Y	N	N	
9	Y	1.5 S/1.6 J	N	Y	N	Y	Y	N	3	Y	Y	Y	Y	Y	N	Y	Y	N	
10	Y	1.5 S/1.6 J	N	Y	N	Y	Y	N	3	Y	Y	Y	Y	Y	N	Y	Y	N	
11	Y	1.5S/ 1.6S/1.6J	Y	Y	N	Y	N	N	3	Y	Y	N	N	Y	N	Y	Y	N	
12	Y	1.6	Y	Y	N	Y	N	N	3	Y	Y	N	N	Y	N	Y	Y	N	
13	Y	1.6	Y	Y	Y	N	N	Y	3	Y	Y	Y	Y	Y	N	Y	N	N	
14	Y	1.6	Y	Y	Y	N	N	Y	3	Y	Y	Y	Y	Y	N	Y	N	N	
15	Y	1.6	Y	Y	Y	N	N	N	3	Y	Y	Y	Y	Y	Y	Y	Y	N	
16	Y	1.6	Y	Y	Y	N	N	N	3	Y	Y	Y	Y	Y	Y	Y	Y	N	
17	Y	1.5/1.6 J	Y	Y	Y	N	Y	N	3	Y	Y	Y	Y	Y	Y	Y	Y	N	
18	Y	1.5/1.6 J	Y	Y	Y	N	Y	N	3	Y	Y	Y	Y	Y	Y	Y	Y	N	
19	Y	1.6	Y	Y	Y	N	Y	N	3	Y	Y	Y	Y	Y	Y	Y	Y	N	
20	Y	1.6	Y	Y	Y	N	Y	N	3	Y	Y	Y	Y	Y	Y	Y	Y	N	
21	Y	1.6 J	Y	Y	Y	Y	Y	N	3	Y	Y	Y	Y	Y	Y	Y	Y	Y	
22	Y	1.6 J	Y	Y	Y	Y	Y	N	3	Y	Y	Y	Y	Y	Y	Y	Y	Y	
23	Y	1.6	Y	Y	N	N	N	N	3	Y	Y	N	N	Y	Y	Y	Y	N	
24	Y	1.6	N	Y	N	Y	N	N	3	Y	Y	N	N	N	Y	Y	Y	N	
25	Y	1.6	Y	Y	Y	Y	N	N	3	Y	Y	N	Y	Y	Y	Y	Y	N	
26	Y	1.6	Y	Y	Y	Y	N	N	3	Y	Y	Y	Y	Y	Y	Y	Y	N	
27	Y	1.6	Y	Y	Y	N	N	N	3	Y	Y	Y	Y	Y	Y	Y	Y	Y	

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