Flexible energy systems Leveraging the Optimal
integration of EVs deployment Wave

Grant Agreement Nº: 101056730

Deliverable 1.3

Potential: Barriers & Services of Vehicle-Grid Integration

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Website FLOW

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Project funded by

Schweizerische Eidgenossenschaft
Confédération suisse
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Swiss Confederation

Federal Department of Economic Affairs,
Education and Research EAER
**State Secretariat for Education,
Research and Innovation SERI**

Document information Table

Project Data	
Project Acronym	FLOW
Project Title	Flexible energy system Leveraging the Optimal integration of EVs deployment Wave
Grant Agreement n.	101056730
Topic identifier	HORIZON-CL5-2021-D5-01-03
Funding Scheme	RIA
Project duration	48 months
Coordinator	Catalonia Institute for Energy Research
Website	https://www.theflowproject.eu
Deliverable Document Sheet	
Deliverable No.	1.3
Deliverable title	Potential: Barriers & Services of Vehicle-Grid Integration
Description	Task T1.3 provides a list of the challenges and potentials that the rest of FLOW addresses and explores, serving as an important point of synchronization between partners in the project. To establish the known barriers for full support of EV integration, it summarises the main barriers and links to the WPs which address them in FLOW, namely User requirements and acceptance (WP2), Cyber security, standardization, and Interoperability (WP3), Scalability of local solutions (WP4), Business models, grid codes and regulations for system integration (WP5). T1.3 also creates a shortlist service catalogue to provide an overview of applicable services for different market conditions and stakeholders. This provides a starting point to WP5.
WP No.	1
Related task	1.3
Lead beneficiary	DTU
Author(s)	Mattia Secchi, Peter Bach Andersen (DTU)
Contributor(s)	EGIN,AVE,BMW,R2M,ARE,AE,HEL,NUIM,TUD,IREC,RSE,EAT-IE,EAT-CH,EDSO, EDI, EDE,TER
Type	Report

Dissemination L.	Public		
Due Date	30-04-2023	Submission Date	03-05-2023

Version	Date	Author(s)	Organisation	Comments
V0.1	15/03/2023	M. Secchi, P. B. Andersen	DTU	Document creation
V0.2	31/03/2023	M. Secchi, P. B. Andersen	DTU	Table of contents
V0.3	14/04/2023	M. Secchi, P.B. Andersen	DTU	Draft version for revision
V0.4	28/04/2023	A. Siviero, A. Bonvento, C. Manaresi, V. Pioppini, M. Baron, D. De Michino, D. Davi, M. Pardo	TER/EDE/EGIN	Internally reviewed version
V1.0	29/04/2023	M. Secchi, P.B. Andersen	DTU	Version for submission

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List of Acronyms

Acronym	Meaning
AC	Alternating Current
AEV	All-Electric Vehicle
BEV	Battery Electric Vehicle
CPO	Charging Point Operator
DC	Direct Current
DER	Distributed Energy Resource
DSO	Distribution System Operator
EV	Electric Vehicle
EVSE	Electric Vehicle Supply Equipment
EMSP	Electro Mobility Service Provider
FCEV	Fuel-Cell Electric Vehicle
FHEV	Full-Hybrid Electric Vehicle
V1G/G2V/CC	Grid-to-vehicle / Unidirectional Controlled Charging
HEV	Hybrid Electric Vehicle
ICEV	Internal Combustion Engine Vehicle
MHEV	Mild Hybrid Electric Vehicle
PHEV	Plug-in Hybrid Vehicle
POD	Point of Distribution
SOC	State-of-charge
SOH	State-of-health
TSO	Transmission System Operator
UC	Uncoordinated Charging
UX	User Experience
V2B	Vehicle-to-building
V2G/BC	Vehicle-to-grid / Bi-directional Coordinated Charging
V2V	Vehicle-to-vehicle
VGI	Vehicle-Grid Integration
WP	Work Package

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Executive Summary

This deliverable outlines the main barriers and potential in vehicle-grid integration. The purpose is to create a systematic and consolidated view on both to be used throughout the activities of the FLOW project.

The specifics on how barriers are overcome, and services provided will be further explored throughout the project and reported by the respective work packages.

The barriers described here are specifically the ones limiting or preventing the exploitation of the EVs capabilities as a flexible demand and bi-directional power and energy resource, and then applying those capabilities towards the provision of grid services under the current legislation and market conditions. The generic barriers to EV diffusion in the society are not treated here.

With the term “flexibility services”, instead, we relate all those services EVs may offer to the prosumer, the distribution system, the transmission system, or the market, through demand-side flexibility (V1G and V2G) and energy supply (V2G).

The description of the flexibility services will focus on their core concepts and the value they provide, since specific market products vary significantly in name and requirement throughout Europe.

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1. Background and Objectives

The activities of WP1 provide a common knowledge baseline for FLOW, and in this deliverable, our attention is focused on:

1) the **barriers to vehicle-grid integration**, which are classified based on their type (technical, user, cost, regulation, market) and the severity of the challenge to be overcome.
2) the potential **flexibility services provided by EVs** connected to the power network, which are classified based on their domain (behind-the-meter/local/regional), the power flow directionality, the main benefits and beneficiary, and the type of operation (centralized/decentralized).

With this deliverable, we aim at investigating the barriers to VGI, but also to present the core concepts behind the VGI flexibility services.

The deliverable has met all the objectives described in the task description.

2. Barriers to VGI

In this chapter we will list the barriers which must be overcome in order to have EVs provide the flexibility services described in the second half of this deliverable.

First, we attempt to frame exactly what type of barriers we are interested in and why they are of interest to the FLOW project. Then, we also describe previous and related work from which we have drawn inspiration. Finally, we classify the barriers in five types: user, technology, cost, regulation, market.

2.1 Definition of barriers and related work

The barriers described in this document may hamper or prevent the use of electric vehicles properties as flexible demand (G2V) and bidirectional sources of power and energy (V2G).

Many barriers and possibilities rely on the specific characteristics of EVs:

- They are a distribute energy resource (DER).
- They can react very fast.
- They can both consume from and return power to the grid.
- They represent a limited energy resource, since the battery capacity is finite, and they cannot produce energy.
- They are stochastic in nature, due to user behavior.
- They display a “rebound” effect, i.e., a change in behavior “now” necessitates an opposite (and compensating) action at a later time.
- They provide services using a battery designed for propulsion, additional usage to provide grid services will influence the longevity of the battery.
- They might not have a fixed physical location (point of connection), e.g., during the holidays they might move from the cities to the coast or countryside.

The services that the EV may provide are either new or have previously been provided by other technologies with different characteristics, i.e., the traditional thermal plants for which the current

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market regulation was originally designed. In either case, an effort is needed to fully exploit the potential of using EVs in grid services.

The organizations and commercial actors which conducted investigations on VGI barriers include ENTSO-e, the International ZEV Alliance and ElaadNL.

Barriers have been investigated in many research projects. Example of such projects are national projects like Project Leo[1] and Parker [1]. The projects represent efforts in doing field demonstrations of V2G – providing new and better insights into the barriers of the technology.

On a European level, investigations are presently being conducted in fellow Horizon projects such as SCALE[2] and EV4EU[3]. These can exploit the national pilot projects which have been conducted so far as to solve barriers in a common effort across European partners.

Finally, many research organizations are engaged in VGI research and released publications detailing possible challenges relating to V1G and V2G.

The identified barriers are often classified as belonging to one or more aspects, i.e., market-, regulatory-, user-, cost- or technology-related. Some of the ongoing research focuses mainly on some of these aspects. For instance, the authors in [2] have done a comprehensive study on user barriers while other studies emphasise issues from the market [3] and regulatory side[4]. In this section we will try to include barriers covering all these aspects.

The barriers are also often described in terms of severity i.e., how big of a challenge they pose to the concept of VGI and how important it is to proactively solve them. This approach allows for the prioritization of barriers which should be solved first and towards which the most resources and attention should be directed.

Finally, some of the investigated publications propose solutions which may help overcoming each barrier. While solutions will not be presented in this deliverable, the FLOW project will help face several of the barriers listed below and present recommendations to help solving them.

2.2 List of barriers

In the following, we list all the identified barriers to VGI. Each barrier is described according to the aspect it relates to and whether it is relevant for V1G, V2G or both. The list is based on the literature described in the previous section, as well as the experience of the WP contributors.

The aspects used to classify the barriers are as follows:

User – barriers originating from the EV owner's perception, use and interaction with VGI

Technology - barriers tied to present limitations in the technology used in chargers, vehicles and the software and protocols used to connect and manage them.

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[1] V2G Barriers and Opportunities: a capability approach, Nick Banks, University of Oxford, 2021
[2] SCALE Project, https://scale-horizon.eu/
[3] EV4EU Project, https://ev4eu.eu/
[4] Regulatory barriers for Smart Charging of EVs and second life use of EV batteries, PWC, 2019

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Cost – barriers arising from all types of added monetary costs from implementing and supporting VGI.

Regulatory – barriers which either require new regulation or that existing regulation is improved or adjusted.

Market - barriers relating to the current setup of power and energy markets, including market products and service design and requirements.

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Table 1. Barriers to VGI classification.

Name	Description	Flow		Barrier type					Severity
		V1G	V2G	User	Tech.	Cost	Reg.	Market	
Additional battery degradation	Degradation of the EV battery due to additional cycling caused by V2G-based services.		X	X	X	X			Moderate
Concern on range adequacy	User concerns on whether adequate range is achieved when a third party is controlling the charging process of the vehicle.	X	X	X	X				Minor
Round-trip efficiency	The roundtrip efficiency of V2G is of great importance as the accumulated energy losses adds to the cost side of providing services.		X		X	X			Moderate
Service maturity and valuation	Several market and system services which can be provided though V1G and V2G are either not currently defined, or not very mature, and the savings/earnings which may be achieved are unknown.	X	X		X			X	Major
Charger cost	Smart charging capabilities and V2G add costs to the charging equipment. This is especially true for V2G chargers which are typically based on DC charging, which inherently has a higher cost.	X	X		X	X			Minor **(V1G)** Major **(V2G)**
V2G vehicle support and harmonization	There is a lack of EVs available that support V2G. Also, there is no consensus on whether AC- or DC based V2G will be the norm. Both approaches have merits and drawbacks.		X		X	X			Moderate **(V2G-DC)** Major **(V2G-AC)**
Two-way energy tariffs and taxation	When providing behind-the-meter V2G services there is a risk that the energy exchanged may be subject to taxes and fees multiple times. This is exacerbated in services such as frequency support, where energy is continuously fed back and forth through the meter.		X			X	X		Major
Market pre-qualification	New technical regulations must be introduced to allow pre-qualification for market access that cover aggregations of EVs. Also, such pre-qualifications may need to be kept simple as to deal with many small, individual units.	X	X		X	X	X	X	Moderate
Standard support and interoperability	Communication standards still do not support all the necessary information and control needed for either V1G or V2G. While ISO 15118-20 in theory allow support for V2G, the actual implementation by EVSE and EV OEMs is still limited. Standards updates and harmonization are required also at the wider energy system level (back-end operations, smart grids, billing and roaming inside the same country or at the EU level)	X	X		X		X		Moderate **(V1G)** Major **(V2G)**
Vehicle data availability	It is very limited how much information can be extracted from the vehicle through the EVSE. Especially for AC charging where only the vehicle state is communicated via the control pilot pin of the cable.	X	X		X		X		

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	While more information is available with DC charging, and potentially via ISO/IEC 15118, information on the vehicle battery, which is essential for charging management, is not readily available to actors except the OEMs.								
Ancillary services: Minimum bid sizes	For the provision of ancillary services there are often minimums for the bids provided to the markets. Depending on the market and service, large aggregations may be needed to meet such requirements.	X	X		X			X	**Minor**
Ancillary services: Duration requirements	For the provision of ancillary services there are minimums for the durations for which services must be delivered. This may be a challenge due to batteries being depleted or full.	X	X		X			X	**Moderate**
Aggregator models	There are still uncertainties around the conditions and requirements for aggregators acting on the market on behalf of an EV fleet. The role of the aggregator is not harmonized across Europe and existing portfolios include DERs which are fewer in number and larger in individual size than a single EVs. Finally, the role the aggregator has in connection with the operation of the TSO and DSO also needs clarification.	X	X				X	X	**Moderate**
Meters	Several VGI services depend on data from a meter measuring power and energy exchange of the charger. This meter can either be the integrated meter of the chargers – or a separate series meter installed at the charger. Regardless, this meter must meet accuracy and precision requirements based on the service, which is provided, and the requirements applied to settlement meters. This in turn adds costs and complexity.	X	X		X	X	X		**Moderate**
Procurement of flexibility services by grid operators	The services and mechanisms which would allow a grid operator to use the flexibility from EVs for grid investment deferral are still not mature. Whether the flexibility should be invoked through implicit or explicit price signals, bilaterally or through a market is still not settled. There is also still no clear and universal way for the EV owners to be incentivised for providing such services.	X	X				X	X	**Major**
User perception and acceptance	The user's willingness to commit their vehicles to VGI services depend both on having a sufficient understanding of the specific services (something which can be difficult for ancillary services, for example) and whether they will have sufficient trust in the third-party assuming responsibility for management of charging (V1G and V2G).	X	X	X					**Minor (V1G)** **Moderate (V2G)**
Flexibility supported by plug-in patterns	It is unknown if future charging patterns will allow for charging flexibility and the provision of VGI services. It may be necessary to convince EV owners to connect the vehicles more regularly than what is necessary to meet the energy demand for driving only. An exception could happen if new charging technologies automatically connect the EV to the grid and eliminate user involvement.	X	X	X	X				**Moderate**

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Coincidence factor – DSO vs TSO services	Future charging patterns may be increasingly synchronised due to price-based charging, or other VGI services aimed at the TSO level or market. This may have the adverse effect of creating secondary peaks which counteract the load levelling strategies pursued by DSOs.	X	X					X	**Major**
Bi-directional flow safety	It is necessary to address safety concerns when power is provided to the grid from behind-the-meter resources.		X		X		X		**Moderate**
Competitive solutions to V2G	Stationary storage may become more cost competitive with vehicles in providing storage-based services to the grid. Other, new technologies providing grid reserves and services may also disrupt the energy system and compete with V2G-based services.		X			X			**Moderate**
Availability of DC V2G chargers	If DC-based V2G should become the norm – a broader and cheaper selection of DC V2G chargers should be available. Such DC V2G chargers should match power levels and costs suitable for private and semi-public charging locations such as company parking lots and even domestic parking.		X		X	X		X	**Major**
		V1G	**V2G**	**User**	**Tech.**	**Cost**	**Reg.**	**Market**	

3. Electric Vehicle Services

3.1 Flexibility & V2G

As presented in FLOW's D1.2, the concept of "EV flexibility" entails a "power adjustment or curtailment, sustained by an EV, from a particular moment in time, for a certain duration, at a specific location" [4]. In this regard the EVs can be "flexibly" used to perform several tasks, leveraging the storage capacity of the battery they host.

In "unidirectional" smart EV charging, also called V1G or CC (controlled charging), the power required to charge the EV battery can be up- or down-regulated to peak shave the grid demand or improve the use of DERs. EVs flexibility can be further improved by including vehicle-to-everything (V2X) capabilities, performing what is usually called "bidirectional" smart charging, i.e., discharging the EV to provide backup power or peak shaving services, for example. Bidirectional charging enhances the value of many services**,** since any aggregator can "recover" the flexibility of a V2G charger even if the battery is full, just by injecting power into the grid. However, this is not mandatory to perform a specific service. This enhancement comes along with a number of additional costs for implementation.

In the following sections, we will try to classify the available EV flexibility services, explain the basic principle behind each one of them and provide an example to clarify that principle.

3.2 List of VGI Services

The following table classifies the flexibility services which can theoretically be provided by EVs, even if there may not be any available commercial offers for that. The classification is performed based on the type of operation (centralised/decentralised), who benefits from the service, and what's the value for the involved actors. Note that by "centralised" and "decentralised" here we try to describe which services require a centralised coordinator (such as an "aggregator") to elaborate the EV charging schedules and then send them to the vehicles (performing either "implicit" or "explicit" DSM), or if the schedule can also be decided the EV by itself, or a "local" optimising device. A deeper detail is provided from Section 3.3 onwards.

Table 2 - EV flexibility services catalogue.

Domain	Service	Operation	Who Benefits?	Which Benefits?
Behind-the-meter	Backup Power/Islanded Operation	Decentralised	EV Owners	Security of supply
	Improved DER Self-Consumption	Decentralised	EV Owners	Economic savings
	Improved Self-Sufficiency	Decentralised	EV Owners	Economic/Emissions savings
	Energy Arbitrage	Decentralised	EV Owners	Economic savings
Distribution/Local	Peer-to-peer Trading (Energy Communities)	Centralised	EV Owners	Economic/Emissions savings
	Congestion Management	Both	DSO/EV Owners	Reduced grid reinforcement/EV

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				owners' compensation
	Voltage Regulation	Both	DSO/EV Owners	Compliance with technical regulation/EV owners' compensation
	Voltage Phase Balancing	Both	DSO/EV Owners	Compliance with technical regulation
Transmission/Regional	Virtual Inertia/Synthetic Inertia	Centralised	TSO/EV Owners	Security of supply/EV owners' compensation
	Fast Frequency Reserve (FFR)/Frequency Containment Reserve (FCR)	Centralised	TSO/EV Owners	Security of supply/EV owners' compensation
	Frequency Restoration Reserve (FRR) / Replacement Reserve (RR)	Centralised	TSO/EV Owners	Security of supply/EV owners' compensation

Some considerations can be done:

1. **The larger the domain, the more the flexibility services become centralized**, i.e., there is generally a requirement for a central "coordinator" to gather information on the EV and elaborate the charging schedules to be applied to provide the service. This applies for local domain services, but does not for frequency-related services, which are based on a bidding process happening on the balancing services market. When working "behind the meter" instead, a single vehicle can optimize its charging to achieve a particular objective, generally without requiring a central coordination.
2. **The larger the domain, the higher the number of involved EVs**, hence the requirement for an "aggregator" to assemble a fleet and influence the power network. The benefits are shared between the EV owners (compensated for the services provision) and the system operators (who use the flexibility of EVs to improve the grid operation).

3.3 Behind-the-meter Services

“Behind-the-meter” services are generally offered by a physical or cloud-based optimiser which manages the load and production resources located behind the smart meter installed between a building and the electric distribution system. The operation of those devices is generically not “detected” by the power system, which only sees its effects on the energy balance. As such, these services are aimed at achieving energy autonomy and self-sufficiency, primarily for the benefit of the EV owner, and do not require a centralised operation, since every EV owner has its own optimiser.

3.3.1 Backup power/Islanded operation

Whenever any electricity provision service interruption occurs in a system with a large penetration of EVs, the storage capacity of their batteries can be used to provide an uninterruptible power source, and to ensure the service stability for houses [5], [6] or important infrastructure, such as data centres or hospitals.

The following two plots show how four cars with a different battery size, 30 (small)-100 (large) kWh, can contribute to the provision of electricity during a blackout, based on the same domestic consumption profile, with and without distributed PV generation. The plots show the net (load minus production) active power flow for the EV owner and the EV batteries SOC.

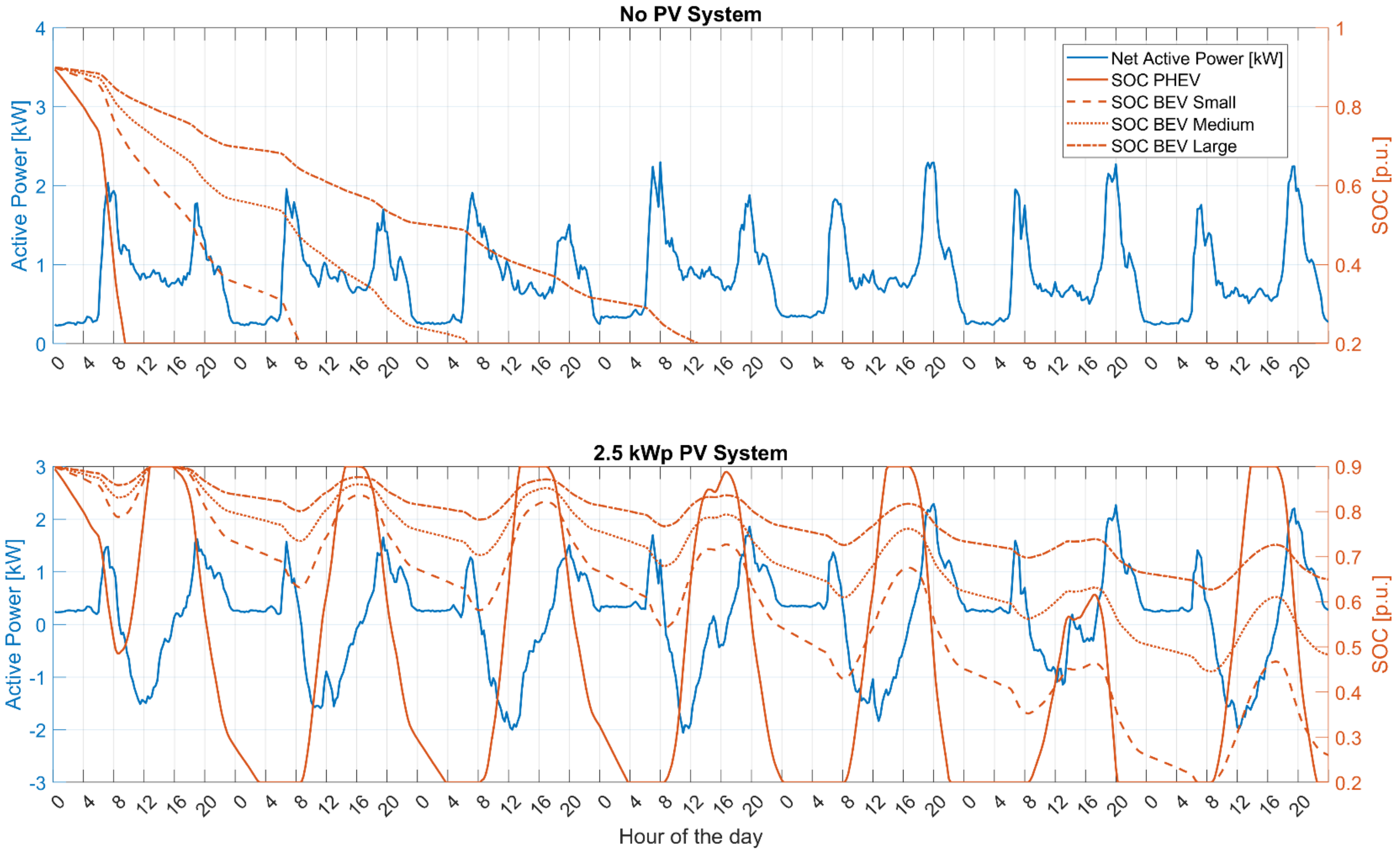

Figure 1 - Backup power provision from a parked EV with different battery

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As it can be seen, if no distributed generation is available, even the large BEV (100 kWh) cannot sustain the household for more than three days, i.e., the household consumes around 30 kWh per day, whereas the presence of a small 2.5 kWp PV system ensures the possibility of operating for 7 days in islanded mode with all types of BEVs. PHEVs instead, do not allow for more than one day of uninterrupted power, since they have a much smaller battery (12 kWh).

The balance between the daily PV production and the load consumption is crucial for this type of service since the consumed power should ideally be replenished completely during the central hours of the day. In case of a cloudy day, the energy deficit carries over to the following one, hence the user may start to experience supply interruption events. It must be noted, however, how 7 days is a very long-time span for the grid to be unavailable, and only happens in extraordinary circumstances, e.g., the Texas power system breakdown in 2022.

The provision of this service is subject to a number of additional technical and safety requirements, which need to be considered when feeding domestic loads with the electricity from the EV battery.

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3.3.2 Improved DER Self-Consumption

Unidirectional smart chargers can be used to modulate and shift the EV charging demand to improve the consumption of energy produced by DERs, e.g., PV [7][8]. From the grid perspective, this allows for a reduction in the occurrence of reverse power flows, i.e., situations in which the production is higher than the demand, and the power flows from the LV to the MV side. These occurrences must be limited since the electric equipment operation, especially protection relays, may be triggered.

Figure 2 shows an example of an EV improving the self-consumption of the energy produced by a 5 kWp PV system, installed at a single-family household with a maximum of 3 kWp contractual power.

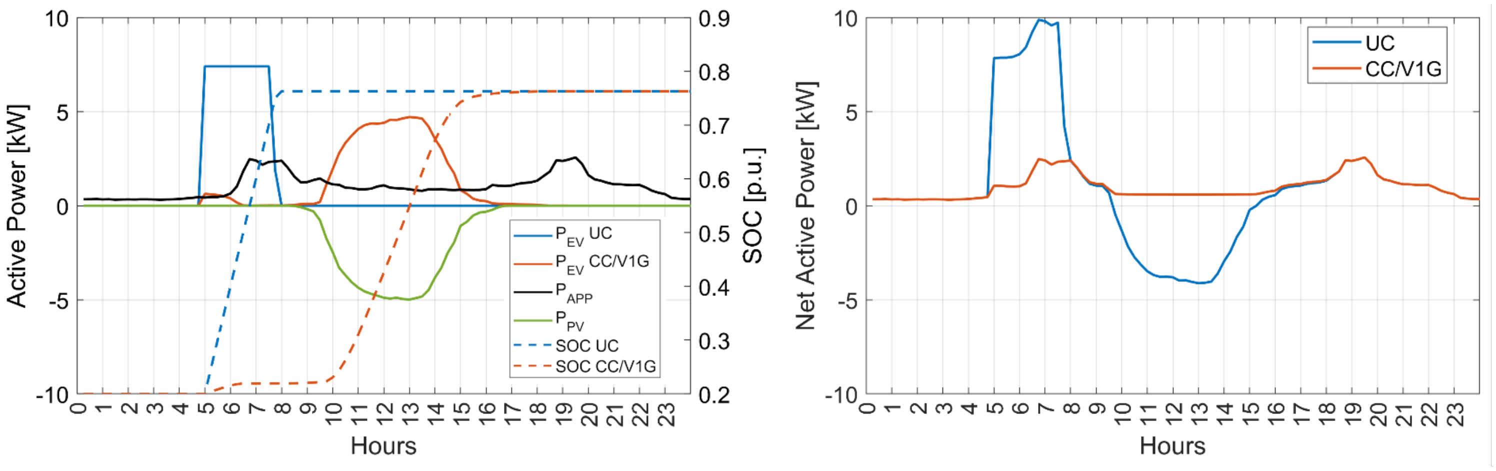

Figure 2 - Improved Self-Consumption for a 2.5 kWp PV System.

The EV would normally charge at a 7.4 kWp constant power (Mode 3, 32 A, 230 V, single-phase, 90% round trip charging/discharging efficiency) from 5 to 8 a.m. (P_{EV} UC and SOC UC curves), the part of the day when appliances reach their peak consumption value of 2.5 kWp (P_{APP} black curve). The PV system instead, starts producing at 9 a.m., and stops at 17 p.m (P_{PV} green curve). In "uncontrolled" EV charging, the PV production mostly goes to the grid (around 73%), and a peak of 9.5 kW consumption is detected at 7 a.m., when the EV is charging, and the appliances consumption peaks.

If the EV is parked from 5 a.m. to 16 p.m. and it is operated in CC/V1G mode, the charging is shifted to the central hours of the day (P_{EV} CC and SOC CC red curves), hence all the PV production is stored in the EV, and none goes to the grid. This not only allows for a reduction in the electricity bill of the consumer, since the EV is charged with self-produced energy, but has a positive effect on the grid as well, since its net-load profile (right plot in Figure 2, red plot) is smoothed out. All of this happens "behind the meter", hence the grid only sees a smoothed out active power profile.

It has to be noted how, in all of the following examples, we assume the EV owners to either increase their maximum consumable power to allow for EV charging through the household smart meter, or request a second point-of-distribution.

3.3.3 Improved Self-Sufficiency

As an upgrade to Improved PV Self-Consumption, EVs equipped with bidirectional chargers are also able to feed power back to the grid, to allow the user for an increased self-sufficiency, which leads to substantial economic benefits and emissions reduction [9], [10]. Figure 3 shows how the same EV we considered for improved self-consumption in Section 3.3.2 would react in a scenario where the energy demand for appliances is doubled, i.e., the peak is around 5 kW, and the EV smart charger is bidirectional.

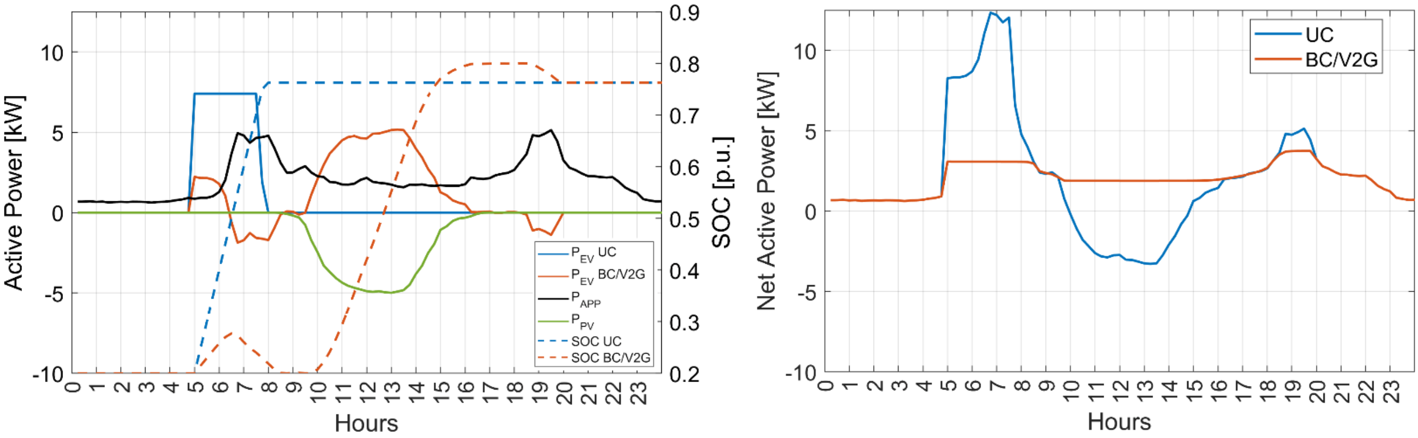

Figure 3 - Improved Self-Sufficiency for a household with a 2.5 kWp PV system.

A few key differences exist. Firstly, the EV is allowed to feed power back to the grid to peak-shave the active power demand from the appliances. As such, the EV is shortly discharged (P_{EV} BC) between 06:30 and 9 a.m. to smooth out the net active power curve. Then, it is charged and reaches 80% SOC at 16:00 p.m. Note how only 77% was reached in the previous scenario because that 3% SOC is used between 18:30 and 20:00 p.m. to peak shave the demand from the appliances, which was impossible to do in CC/V1G. The household self-sufficiency increases from 15 % in UC to 31 % in BC/V2G.

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3.3.4 Energy Arbitrage

The flexibility provided by an EV capable of modulating and delaying the charging sessions, together with the availability of dynamic time-of-use tariffs, e.g., at an hourly resolution, allows for energy arbitrage, i.e., buying when the prices are low (V1G and V2G), and selling when the prices are high (V2G only) [11], [12]. It must be noted that nowadays, it is not possible to perform this kind of service in most of the EU countries.

If hourly dynamic charging tariffs are available, a potential arbitrage service could be the one described in Figure 4, where a 7.4 kW EV charging station is used to charge a 60 kWh EV (medium size) between 16:00 and 19:00 p.m. (blue line in both the plots) for two consecutive days. The plotted price of electricity is the average cost in Italy in 2020 (before the 2021-2022 fluctuations) resulting from the day-ahead market bidding process, whereas the active power consumption for appliances (black line in the plots) is a standard 3 kW domestic consumption profile.

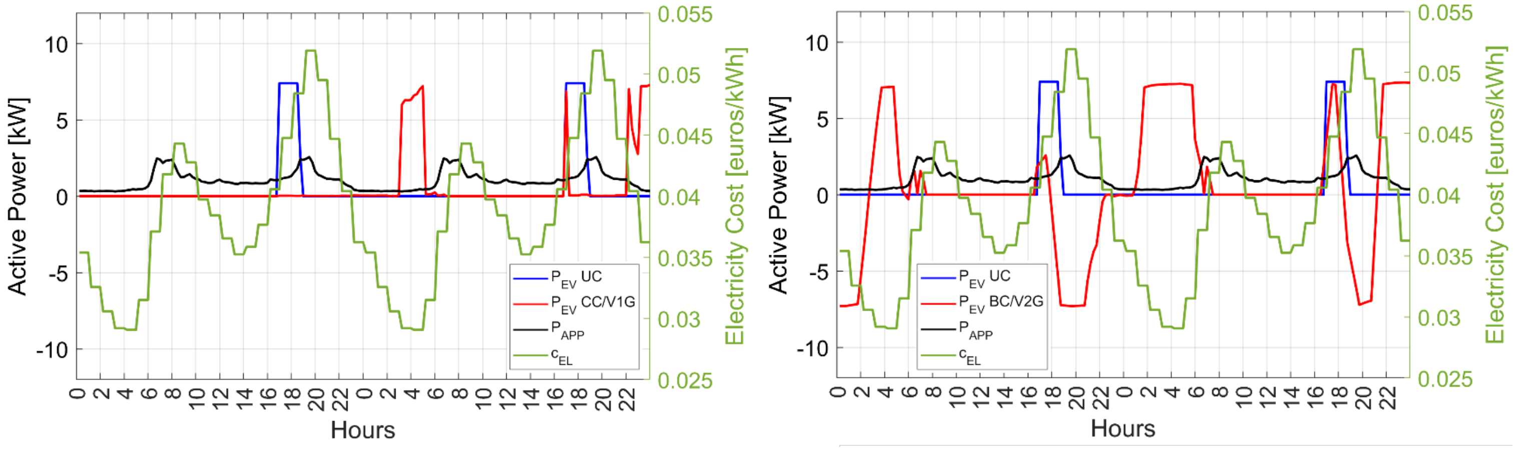

Figure 4 - Energy arbitrage via Controlled or Bidirectional Controlled

Even with V1G/CC (red line, left plot), it is possible to charge the EV between 03:00 and 05:00 a.m. (2 hours), when the cost of electricity is low, and thus save up to 60-65% of the daily charging costs. Moreover, if the EV is allowed to sell electricity back to the grid (red line, right plot), it will discharge from 17:00 to 22:00 p.m., to make money out of the high electricity costs, charging instead from 02:00 to 06:00 a.m. (4 hours), when the electricity cost is low. Note how the charging lasts twice as much in BC/V2G, since the EV was discharged to a lower SOC on the previous day. The economic savings are, in this last scenario, around 85%. This service has a great potential for economic savings when the electricity costs are high (e.g., between 2020 and 2022), because it leverages on the storage capacity and availability of the EV to generate profits.

A final remark should be made on the feasibility of this kind of service from the grid perspective. Indeed, if all the EV owners applied this charging strategy, the peak load demand from EV would simply be shifted from the early evening to the late night, possibly jeopardizing the electric grid stability.

3.4 Distribution Level/Local Services

Distribution level or “local” services can be provided by an EV fleet equipped with smart chargers that can respond to an external signal and modulate their demand to achieve a specific grid-related goal. The EV operation can either be decentralised or centralised, depending on the specific target, and can be either activated “implicitly” (via price signals/dynamic tariffs) or “explicitly” (direct control by an aggregator). Generally, both the DSO and the EV owners benefit from these kinds of services.

3.4.1 Peer-to-peer Trading (Energy Community)

If a group of EVs engages in “peer-to-peer” trading, it is possible to charge one EV by making use of the electricity stored in the other one [13], [14]. If the transaction is priced at a lower cost than the grid electricity purchase cost, or if the EV owner who shares his battery capacity is compensated for doing so (e.g., the “renewable energy communities” case [15]) a reduction of the yearly charging expenses is possible, because purchasing from a “peer” is either less expensive or more remunerative than buying from the grid. Figure 5 shows an example of peer-to-peer trading happening between two EVs which need to be charged at different times of the day.

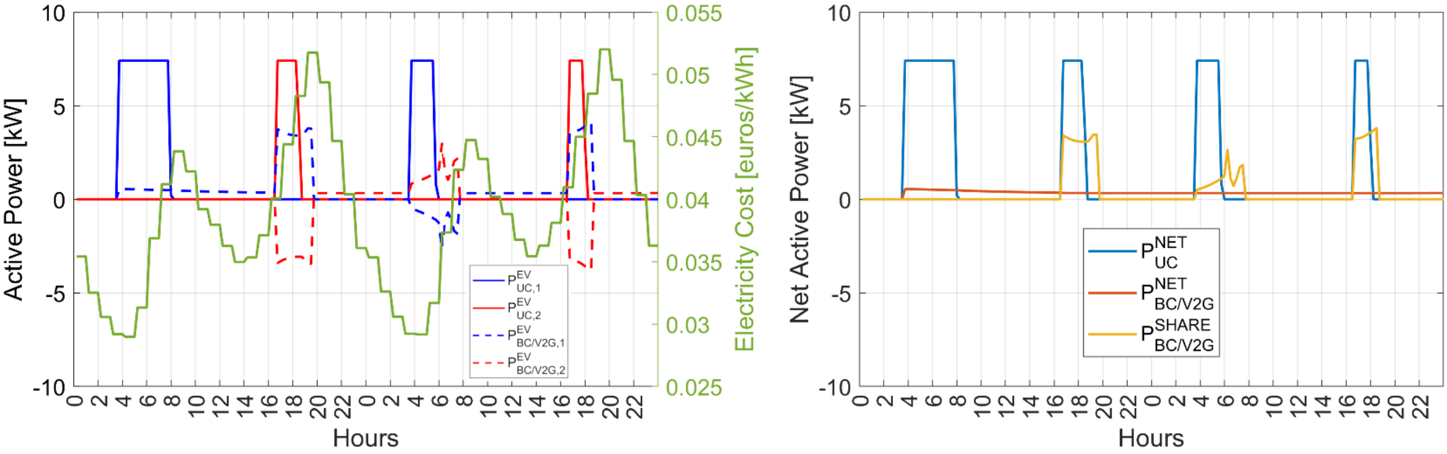

Figure 5 - Peer-to-peer trading between EV owners with no distributed generation or appliances load.

The first EV indeed, belonging to a night-shifts worker, is connected during the day, and needs to be charged between 04:00 and 08:00 a.m., right after coming back home from work. The second instead, is used to go to work between 08:00 a.m. and 16:00 p.m., hence it is normally charged between 16:00 and 18:00 p.m. If BC/V2G is allowed, the second EV (red) can charge the first in the morning, in case the battery SOC is high enough, while the first can charge the second in the evening. Once again, this allows the first EV to avoid charging in the early morning and the second in the early evening, the moments of the day when the electricity is more expensive. A possible environmental benefit is also attainable when the first EV, which is connected during the central hours of the day charges from a PV system, for example. An example of that can be seen in Figure 6.

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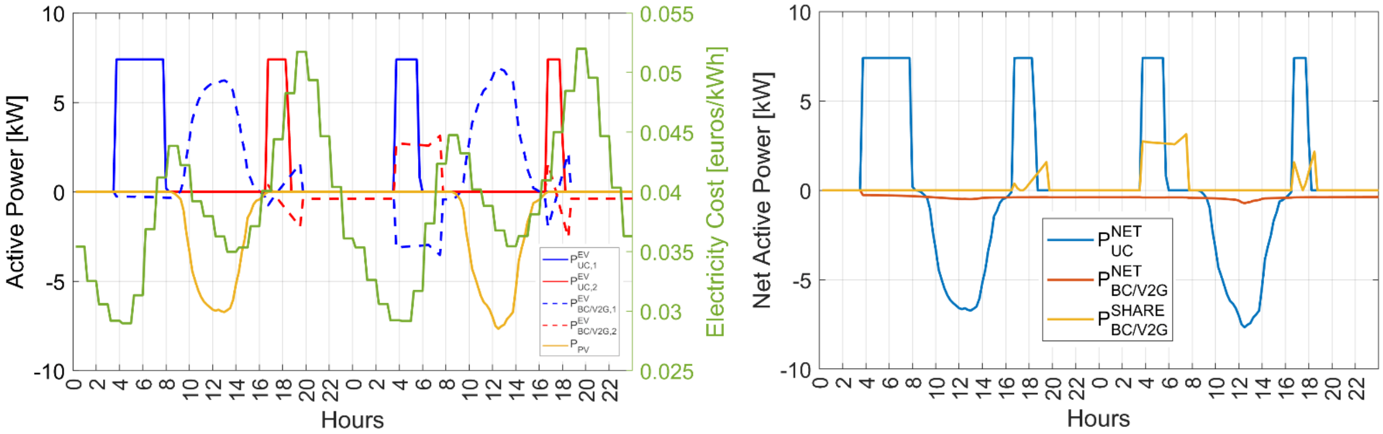

Figure 6 - Peer-to-peer trading between EV owners with a standard 2.5 kW appliances load, and 7 kWp PV system.

In this case, the first EV will mostly charge with its own PV production during the central hours of the day, allowing it to support the charging of the second EV the morning of the following day (04:00-08:00) by leveraging the energy still stored in the batteries.

Note how in both scenarios, the energy shared between the EVs covers a significant part of the charging process. In the context of a "Renewable Energy Community", the sharing would be compensated with a certain amount of money, depending on the national legislation on the topic. This would effectively be an additional revenue stream, to be added to the economic saving due to the reduced consumption from the power grid.

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3.4.2 Congestion Management

Congestion management is a type of flexibility services where the EVs modulate their energy demand and/or shift their usage patterns from high to low grid congestion moments of the day, to avoid transformer and lines overloading.

Different types of congestion management mechanisms can be identified:

- Peak-shaving: the EVs either reduce their load by delaying the charging sessions to a moment of the day when the grid load is lower (available both in V1G and V2G) or discharge their batteries to provide some of the load requested by the grid (only in V2G). An example of the first type can be seen in Figure 7, where EVs are used to peak-shave the grid load between 18:00 and 20:00 p.m. The second type is instead noticeable in Figure 8 and **Figure 9**, between 6 and 8 a.m., when the EVs are operated in BC/V2G and they feed energy to the grid to smooth out the net active power load curve.
- Valley-filling: the EVs either anticipate the charge to the central hours of the day, or delay it to the late night, to level the power request to the grid and homogenize the load demand to a predefined optimal value. An example can be seen again in Figure 7, where the charging is delayed from 18:00-20:00 p.m. to 20:00- 23:00 p.m.
- Improved RES Consumption: the EVs are used to consume the DER overproduction from PV systems, for example. This can be seen in Figure 8 between 08:00 a.m. to 18:00 p.m., where a reverse power flow happens if the PV production is not consumed by the EVs (negative active power). This doesn't happen if the EVs are operated in CC/V1G, as it is possible to see from the flatter net power curve. Even if BC/V2G is not a mandatory requirement for improved RES consumption, the overall efficiency of the flexibility service is improved, hence the additional net-load minimization in the plot.

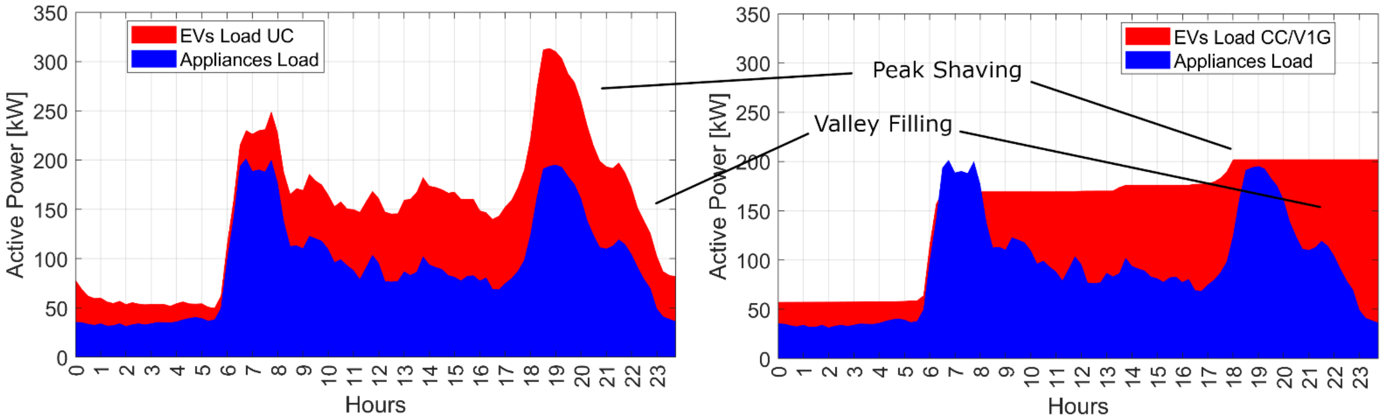

Figure 7 - Peak shaving and valley filling effect on the transformer active power flow when CC/V1G is applied.

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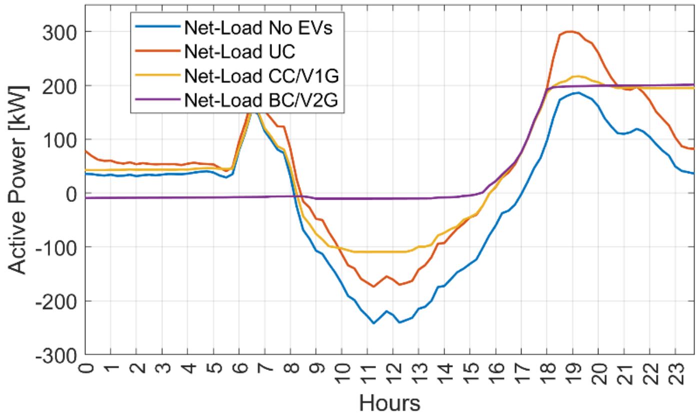

Figure 8 – Congestion management effect on the transformer active power flow when V1G and V2G are applied.

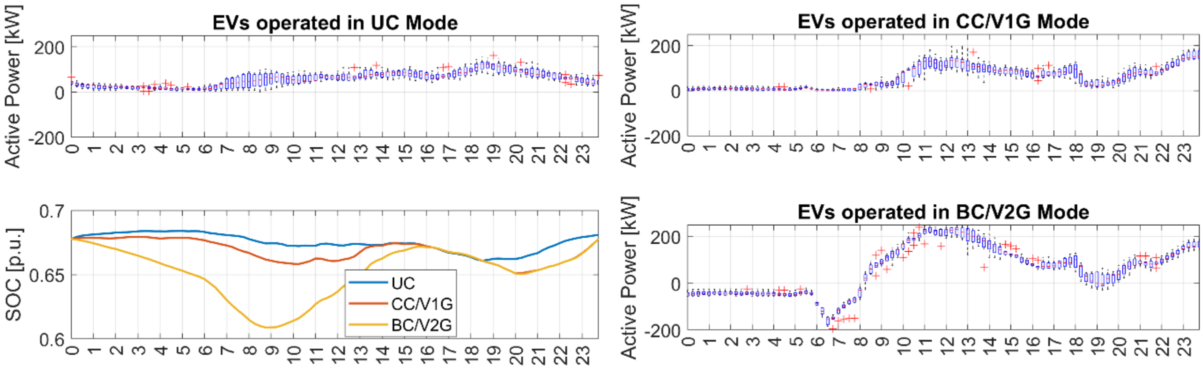

Figure 9 - EVs charging power and median cumulative SOC in UC, V1G, V2G modes.

As tertiary reserves, see chapter 3.5, are typically used in some markets for congestion resolution too on the HV grid, EV aggregates could potentially contribute to the purpose also at the transmission grid level, provided such aggregates meets the specific requirements (e.g., typically a MW-scale size, etc.).

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3.4.3 Voltage Regulation

The inverters located at the interface between each DER and the power network allow the EVs to balance both the active and reactive power exchange with the grid, with the possibility of stabilising the network voltage at the buses the EVs are connected to [16]. Since the voltage magnitude limits are regulated by EN 50160:2010, it is a pressing matter for DSOs to mitigate the impact of massive EV deployment on the network.

Figure 10, Figure 11, and Figure 12 show how it is possible to modify the voltage profile at the point of connection to the grid in different situations, depending on when the EV is available to perform active/reactive power balancing. All the presented plots consider a single-phase aluminium 4x50 mm^2 underground cable connecting two consecutive buses of a LV network, i.e., bus 1 and bus 2. The cable is 1 km long, has a resistance value of 0.391 ohm/km and a reactance of 0.079 ohm/km, and it is operated at 230 V line-to-ground. One EV is connected at terminal 2, charging at 7.4 kW max power (Mode 3, 32 A, 230 V, single-phase) through an 8 kVA inverter. A number of appliances are also connected to bus 2 in single-phase, with a maximum power of 3 kW.

In the **first scenario**, from Figure 10, the EV would normally charge from 17:00 to 19:00 p.m. in UC (blue line, left plot) and be connected in idling mode from 19 to midnight. Hence, the voltage lowers from 1 p.u. to 0.976 p.u. (blue line, right plot) because the peak appliances load corresponds to the EV charging period. If BC is applied, the active power is lowered during peak loading time, hence the voltage is stabilised at 0.992 p.u. (red line, right plot). Lowering the active power consumption frees up additional headspace for the bidirectional charger to inject reactive power, to further raise the voltage up to 0.995 p.u. again (yellow line, both plots). In this case, not only the EV does not lower the power network voltage, but the impact of the appliances load is also mitigated by the EV itself. Note how the PV production from the 5 kWp PV system raises the voltage at bus 2 up to 1.01 p.u., but since the EV is not connected during the day, the voltage raise cannot be mitigated.

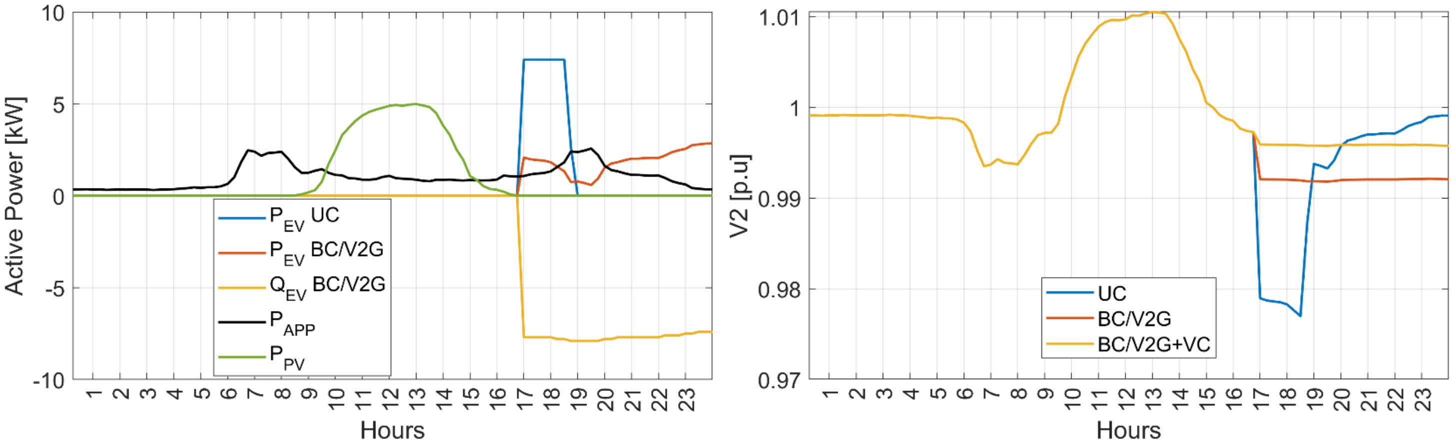

Figure 10 - Example of voltage regulation when the EV is charging in the early

In the **second scenario** instead, from Figure 11, the EV is connected from 08:00 a.m. to 16:00 p.m., and normally charges from 08:00 to 11:00 a.m. (blue line, left plot), meaning that voltage at bus 2 (V2) falls down to 0.976 p.u. in UC mode (blue line, right plot). If the EV is operated in BC instead, the charging lasts for the entire connection time, and the absorbed power follows the PV production curve (installed PV power is 3 kWp here), hence V2 is stabilised between 0.993 and 0.997 p.u. (red line, right plot). The EV also peak shaves the active power demand in the second connection period, from 18:30 to 20:00 p.m., and recovers the energy lost in the process from 20:00 p.m. to midnight. If voltage control is applied instead, V2 is stabilised at 1 p.u. by means of reactive power injection (yellow Q_{EV} line, right plot).

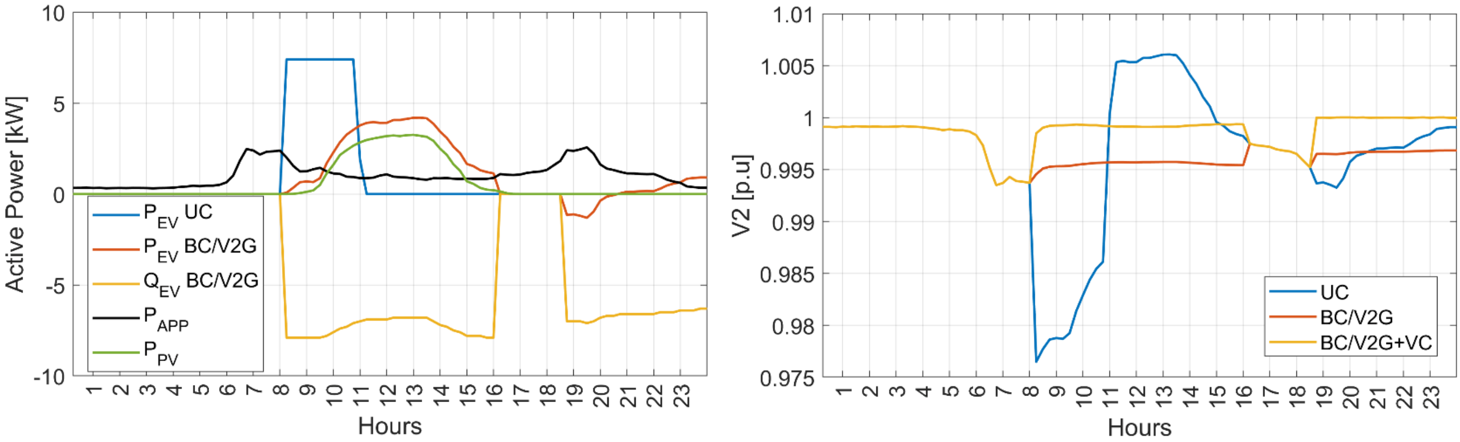

Figure 11 - Example of voltage regulation when the EV is charging in the central hours of the

In the **third scenario**, presented in Figure , the EV is connected from 05:00 a.m. to 20:00 p.m., and the installed PV power is increased up to 10 kWp, to show the overvoltage reduction capabilities of the connected EV. This scenario is similar to the previous one, but in this case the PV system raises the voltage to 1.023 p.u. (blue line, right plot), and the EV is incapable of mitigating the overvoltage just by means of active power consumption, since the battery fills up during the day. Indeed, at 12:30 the battery can absorb only 6 of the 10 kWp produced by the PV system (red line, left plot). Hence, the inverter operating in voltage control mode consumes reactive power (5 kVAr) to lower the voltage from to 1.005 p.u. when voltage control is applied (yellow line, right plot).

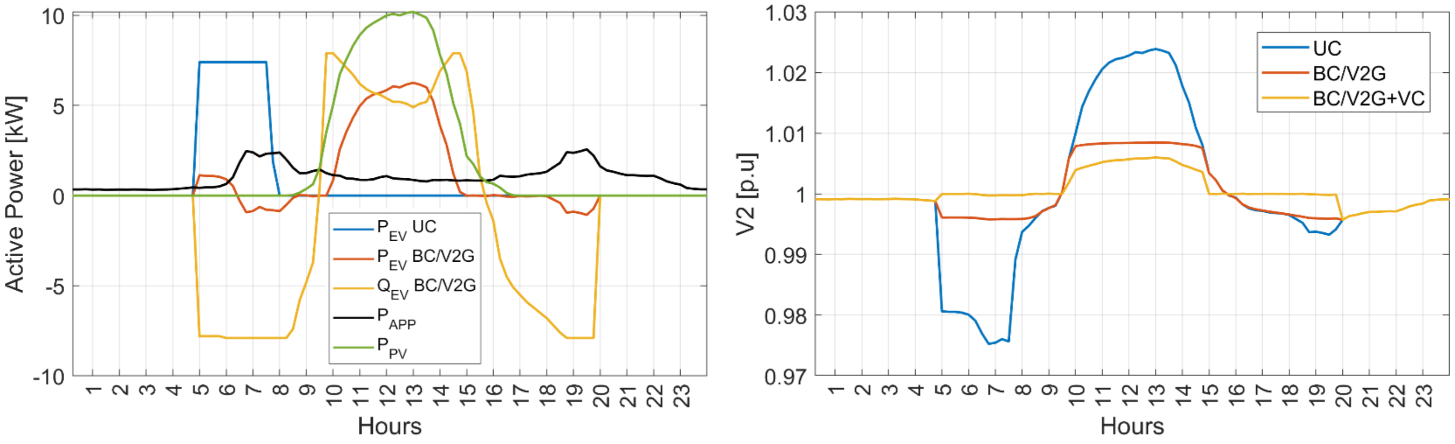

Figure 12 - Example of voltage regulation when the EV is available for most of the

It must be noted how, in all these examples, the EN 50160 thresholds of 0.9 and 1.1 p.u. are not trespassed, since the line is short (1 km) and there is a low number of load/production unit. With the increasing uptake of PV systems and EVs, the voltage stability problem will become more and more crucial to solve.

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3.4.4 Voltage Phase Balancing

A sizeable share of the EV models available on the market still charge in single-phase, with a maximum power of 3.7 kW (16 A) or 7.4 kW (32 A). Hence, both the impact of many EVs connected to a single phase, and the variability of the EV charging profiles with time, could create voltage unbalances along the three phases of a power system. In Europe, this is regulated, once again, in EN 50160:2010 by means of a limitation to the Voltage Unbalance Factor (VUF), expressing the ratio between the negative and positive-phase voltage magnitudes.

Some modern smart chargers can optimise the charging on the different phases to avoid creating voltage unbalances. In this case, modulating the power in CC/V1G or BC/V2G modes wouldn't be a mandatory requirement, but helps to balance out the load on the three-phase system [17], [18]. Figure 13 and Figure 14 show a possible example of voltage phase balancing performed by 12 EVs, charging at 3.7 kW (Mode 3, single-phase, 16 A), which are owned by 12 domestic households connected to a 230 V network. The considered electric system has the same characteristics of the one previously described for voltage control.

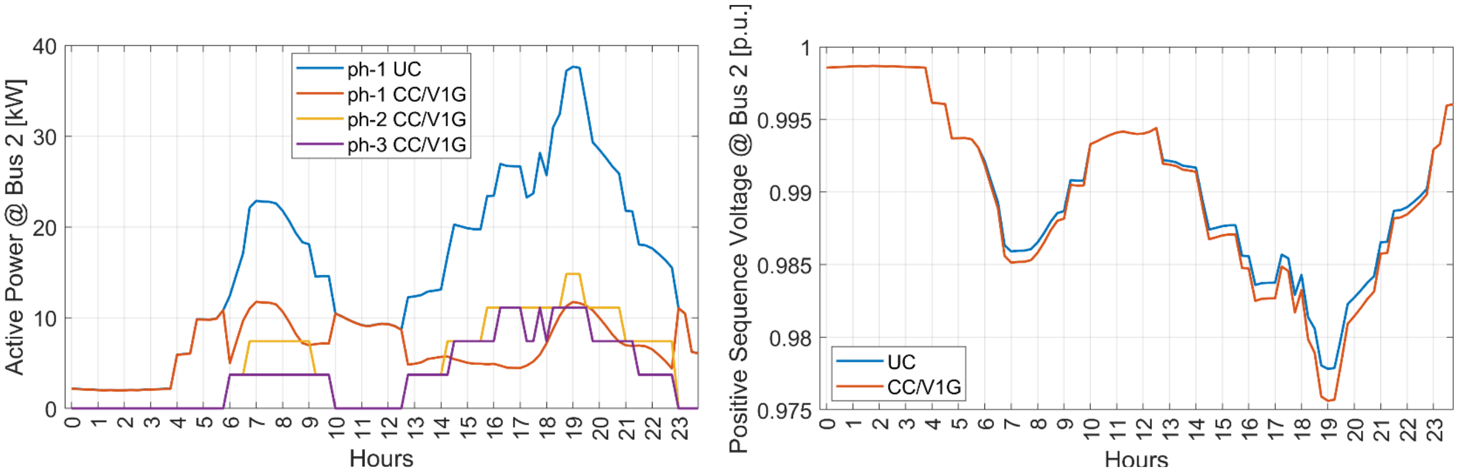

Figure 13 - Active power absorption and positive sequence voltage levels at EVs point-of-connection with and without voltage phase balancing.

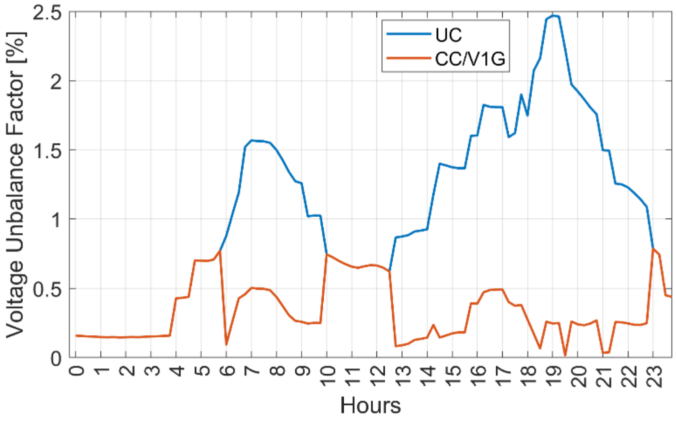

Figure 14 - Voltage Unbalance Factor with and without voltage phase balancing.

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Figure 13 shows that in UC mode, the appliances load and the EVs are all charging on phase 1, hence the system is highly unbalanced, even if this does not produce an undervoltage (right plot, voltage is lowering down to a minimum of 0.975 p.u.).

If CC/V1G mode is activated, the EVs can shift their charging to the 2nd and 3rd phases, as shown again in Figure 13, hence the active power flow is levelled and the VUF, shown in Figure 13, is kept under control. Note how the EN50160 regulation sets 2% as the VUF threshold to be respected.

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3.5 Transmission Level/Regional Services

At the "regional" scale, the power network becomes a high voltage one, and is managed by the TSO, which oversees the security of supply, and ensures the power balance between production and generation, guaranteeing that grid frequency and voltage remain in a predefined range around their nominal values.

The TSO must ensure the "security" of the electric system which can be defined as its capacity to withstand variations in its operational status. Those variations may be due to sudden disturbances and should not lead to any violation of the system limits. "Security" means the **electric grid** must be **robust**, i.e., able to maintain a stable voltage waveform after a perturbation, and **stable**, i.e., quick in responding to sudden disturbances that may cause frequency instabilities. A focus on frequency stability is given in the following.

When a perturbation of the active power balance happens, e.g., the loss of a production plant, the electric system enters a **transient phase** where the grid parameters oscillate around their nominal values. Grid inertia is the first to act in these cases. Electric AC systems possess a certain amount of **rotational inertia** which is directly proportional to the degree of interconnection of the system to others. The inertia is provided by the rotating generators that produce the AC current. A system with a lot of inertia requires a much higher variation in the active power production/consumption mismatch to produce a noticeable frequency fluctuation. This is a "passive" frequency stability feature that does not require any action by the TSO and acts in a timeframe of some milli-seconds after the disturbance occurs.

Following the perturbation event, frequency does not naturally return at its nominal value, but rather enters a **new stability phase**, different from the nominal one. In order to restore the normal operational conditions, automatic or manual actions are executed by the TSO. In particular, the TSO is responsible to procure the reserve capacity needed for frequency regulation actions such as **Frequency Containment Reserve (FCR)** or "primary" reserve, **Automatic Frequency Restoration Reserve (aFRR)** or "secondary" reserve, **Manual Frequency Restoration Reserve (mFRR)** or "tertiary" reserve, as detailed in Table 2. Such services, going under the name of "ancillary services" are procured by the TSOs on the ancillary services/balancing markets, through which the energy operators are paid to reserve and modify in real time their energy production to meet the demand. These services are presently mostly provided by traditional thermoelectric plants, due to their response quickness/duration, ramping and load-following capabilities.

The energy transition entails a **radical change in the electric systems**, especially due to the rise in installed RES capacity, and the dismissal of conventional power plants:

- The system is moving from a **"few to many"** model, where large thermoelectric plants produce the energy consumed by the many users connected to the power network, to a **"many to many"** one, where energy supply is strongly distributed and naturally localized where the RESs are available. The localization mismatch between renewable energy plants and loads can contribute to a growth in grid congestions. Moreover, EVs can be displaced between several physical locations during the same day, weeks. Even if some technologies, such as PV systems, reduce the usage of the grid, a growth in congestion events could happen, since **the grid still needs to be used** to transfer electricity from the production sites to the consumption ones.

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- The growth of inverter-based generation and the phase-out of traditional synchronous-converter plants is **reducing the system inertia and frequency stability**, while also contributing to a reduction in the short-circuit power of the system.
- The non-programmability of RES plants affects the **daily residual evening load**: as the sun goes down and the load increases, additional thermoelectric plants may need to be switched on. If a lower number of thermoelectric plants are available in the system, its capacity to cover peak loads, which may happen during low RES production moments, is reduced as well.

Hence, the evolution of the context requires an expansion of the number of resources providing flexibility to the electric system. Indeed, in the past few years, a general trend towards opening ancillary services markets to DERs has been observed throughout Europe[5].

EVs could be among the resources providing these services and contributing to grid support, while creating new economic opportunities for the actors in the value chain, including the EV owners.

The participation of EV owners to an ancillary services market **requires EVs to be aggregated**, e.g., in a fleet. Such aggregates are usually managed by an aggregator and, according to its characteristics (be it operated in CC/V1G or BC/V2G) it might be available to provide different typologies of service.

In this scenario, **dynamic charging tariffs are not mandatory, but a higher degree of centralisation is**, since influencing the frequency of an interconnected system entails a high number of participating EVs, which need to be either explicitly or implicitly coordinated.

3.5.1 Frequency Services Classification

Figure 14 splits the frequency services in periods, depending on the objectives and the activation time requirements:

- Arresting Period: frequency stabilization starts in milli-**seconds**, and the main goal is to slow down the frequency fluctuation by **reducing the rate of change of frequency** (RoCoF), to prevent the activation of protection systems. The frequency “nadir”, i.e., the minimum/maximum frequency reached by the system during the event, should be delayed as much as possible. Besides rotational inertia, new services in this period are still being defined, since many challenges exist in providing such a fast response to the perturbation event (e.g., the measurement and communication delays).
- Rebound Period: frequency stabilization reserves are activated in **seconds to minutes**, and their goal is to **completely arrest the frequency fluctuation** and avoid a “critical” frequency nadir that can trigger protection devices. A new “steady state” should be reached, hence there needs to be a balance between the active power generation and consumption, even if the frequency might still be lower than the nominal one.
- Recovery Period: the frequency stabilization resources are activated in **minutes to hours**, and their goal is to restore the reserves previously activated and **restore the normal grid operation** by reaching the nominal 50 Hz system frequency.

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[5] smarten Map of Ancillary Services in Europe: https://smarten.eu/wp-content/uploads/2022/12/the_smarten_map_2022_DIGITAL-2.pdf

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It must be noted that the different grid codes created by the national TSOs set specific requirements not only for the activation time, but also for the minimum duration the reserves must be available/operated.

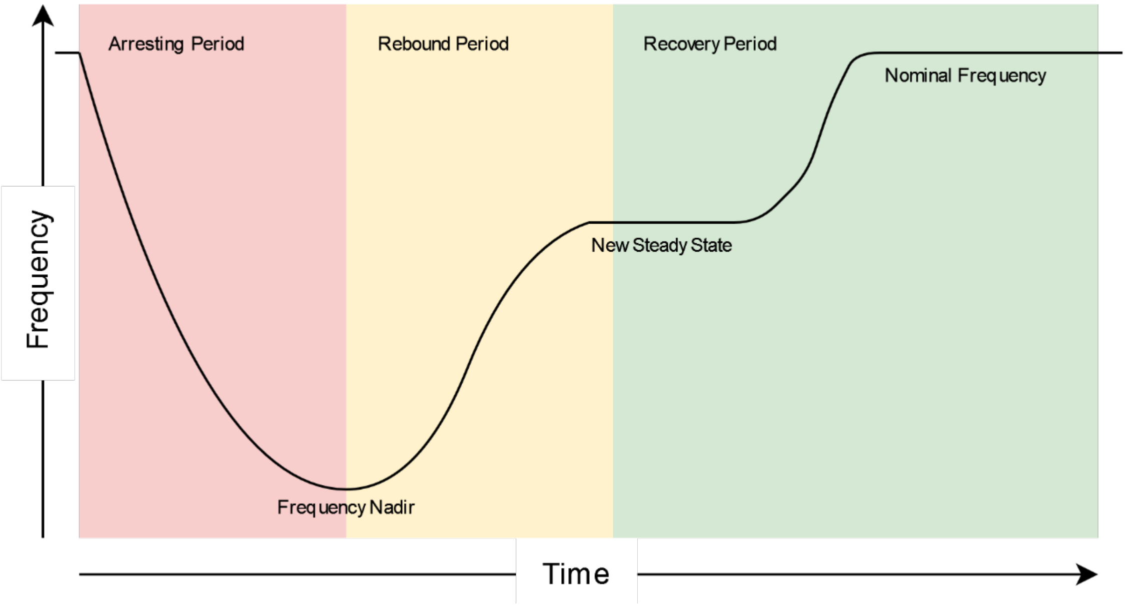

Figure 15 – Qualitative timeline of frequency services classification, based on the required response time and service objectives.

The following table classifies the services the EVs can potentially provide into the different "periods", provides a short description of their core concept, and indicates whether these services are already procured on the market by EVs.

Table 3 - Frequency services summary table.

Virtual Inertia	Arresting	Electrical torque response from a grid-forming converter (<400 ms activation time), able to generate its own waveform rather than following the grid, hence not requiring a measurement of the grid frequency or RoCoF fluctuation to start the mitigating action [19].	Research Only [20]. Service definition and implementation still on-going.
Synthetic Inertia	Arresting	Electrical torque contribution of a unit which proportionally responds to a change in the RoCoF at the unit's terminals. This response can be provided by grid following converters (<700 ms activation time) that require to measure the variation in the RoCoF before starting the mitigating action [21].	Research Only [22][23]. Service definition and implementation still on-going.

Fast Frequency Reserve (FFR)	Arresting	Electrical torque contribution of a unit which responds quickly (< 2s) to changes in frequency, to mitigate the reduced inertial response of the system. The contribution is expected to be maintained for a timespan defined by the grid code (between 5 and 30 s in Denmark, for example). A measurement and a detection of the frequency fluctuation is required before the reserves are activated.[21]	Commercial and Research [24] Provision of this service is currently limited to specific EV use-cases (such as specialised EV fleets), so that very short response times can be guaranteed.
Frequency Containment Reserve (FCR)	Rebound	"Primary" operating reserves, necessary for the containment of frequency deviations from the nominal value, in order to constantly maintain the power balance in the whole synchronously interconnected system. The activation of these reserves results in a restored power balance at a frequency deviating from nominal value. This category includes operating reserves with an activation time typically of 30 s, depending on the specific requirements of the grid code. Operating reserves of this category are usually activated automatically and locally. [25]	Commercial and Research [26][27] Service has been proven on a theoretical and practical base (research projects), and EVs are authorised to provide it.
Frequency Restoration Reserve (aFRR/mFRR)	Rebound/Recovery	Operating reserves necessary to restore frequency to the nominal value and the power balance to the scheduled value after a sudden system imbalance occurred. The activation time is typically up to 15 minutes, depending on the specific requirements of the regulator. Operating reserves of this category are typically centrally managed and can either be automatically (aFRR) or manually (mFRR) activated.[25]	Commercial and Research [28][29] Service has been proven on a theoretical and practical base (research projects), and EVs are authorised to provide it.
Replacement Reserve (RR)	Recovery	Replacement reserves are operating reserves manually activated in a time frame from 15 minutes to a few hours, to restore the required level of operating reserves and be prepared for a further system imbalance following the first one. These reserves can also be used to anticipate on expected imbalances, and their activation time, duration, and quantity highly depends on the national market design.[25]	Commercial and Research [30] Service has been proven on a theoretical and practical base (research projects), and EVs are authorised to provide it.

The common underlying aspect to any type of frequency service provided by EVs is that, in order to balance the active power flow in an interconnected system, a large number of EVs is required, hence the presence of an aggregator, which can participate in the "balancing" market, becomes very relevant.

The analysis of the flexibility services presented in the last sections highlights, once more, how EVs are not only a possible threat to the power system, but also a huge opportunity to create a smart and more flexible power network, allowing for a deeper decarbonization of the energy system.

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3.6 EV Charging Tariffs

Time-of-use (ToU) tariffs are specific electricity cost profiles designed to send customers price signals that reflect some market or system conditions. They can be used to influence the EV owners charging behaviour, such as the case of “implicit demand side management”, thus enabling the provision of some EV flexibility services.

The most common tariff schemes, which can also be applied to EVs, are:

1. **Static Tariffs:** prices are determined in advance and remain constant for a fixed period. They can reflect on and off-peak hours or the seasonality, which is particularly relevant in a highly RES-penetrated system. Examples: Pinergy (Ireland), Flower (Sweden)
2. **Real Time Pricing/Simple Dynamic Tariffs:** prices are determined close to real-time consumption of electricity and are based on wholesale electricity prices, plus a supplier margin. They should be determined at least on an hourly basis, and they allow the EVs to be charged whenever the electricity cost is the lowest. Examples: Agile by Octopus Energy (UK), PVPC (Spain), Monta Dynamic Pricing (DK)
3. **Variable Peak Pricing:** hybrid between static and real time, the different periods for pricing are defined in advance, but the price during on-peak periods is determined by the market conditions.
4. **Critical Peak Pricing:** hybrid between static and real time, they include a substantial increase in the tariffs for some specific days of the year, usually when the wholesale prices are the highest.

With the transition to electric mobility, there is a need for *specific EV-targeted charging tariffs, able to guide the EVs towards the fulfilment of a specific goal*.

ToU tariffs are nowadays applied to EV charging in Europe only in the Scandinavian, Baltic countries, and in Spain [31], while the rest of the EU is rapidly following their example. Among those countries, only Norway and Denmark already implemented different types of dynamic ones.

In addition to the mentioned pricing schemes, some more tariff schemes can be defined, based on how much they consider other inputs, such as the carbon intensity of the electricity mix, or the network conditions:

1. **Advanced Dynamic Tariffs:** tariffs which also keep into account different inputs, e.g., the carbon intensity of the electricity mix of the country, based on national-level forecasts of renewable energy production. Examples: Green Caravan (UK), WhenToPlugIn (UK), GenGame (UK)
2. **Transmission Network Balancing Tariffs:** allowing the EVs to participate to the “grid balancing market”, following an input signal coming from the regional TSO. Examples: OvoEnergy (UK)
3. **Local Network Balancing Tariffs:** allowing the EVs to stabilize the distribution grid in multiple ways, following the input signal coming from a local DSO. Examples: ev.energy (UK)

Even if the EVs impact will probably be stronger at the distribution level [31], very few of the currently available tariffs in the EU consider the power network as one of the determining factors contributing to the final electricity price.

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This first classification of the charging tariffs, which is going to be expanded in other FLOW work packages, highlights a lack of commercial offers for local network management services, which will need to be addressed to fully tap into the flexibility potential of VGI.

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4. Conclusions

A number of barriers still exist to the development of VGI, the vast majority of which are still technological, closely followed by cost and energy market related ones.

The regulation also needs to be constantly developed to allow for the provision of EV flexibility services, so barriers that are not visible nowadays may arise in the future.

EV owners as well, need to be aware that the shift to electro-mobility will not only impact the cost of owning a car, but also their life habits, hence social barriers may be expected to arise in the future as well.

V2G is expected to improve the efficiency of the flexibility services, by allowing aggregators to recover the EV battery capacity, even after it was completely charged. However, this additional flexibility influences the number and severity of the barriers to VGI, for example the battery degradation, the safety requirements on a bi-directional power flow, the availability of DC V2G chargers, the V2G harmonization, and the tariff design that must account for selling electricity to the grid as well.

Regardless of these barriers, there are a number of flexibility services the EV could be providing, both behind-the-meter, and at the distribution/transmission levels. Indeed, EVs can be used to provide backup power in case of outages, or to improve the self-sufficiency of EV owners who installed a generating unit (e.g., a PV system). They can also be used for energy arbitrage, leveraging the fluctuations of the wholesale electricity market prices to profit.

Moreover, the DSOs could try to stabilise the grid and avoid expensive grid reinforcements, by leveraging the flexibility of the EV resources. For example, EV owners could be engaging in congestion management services, voltage regulation, or voltage phase balancing. At the regional scale instead, provided EVs are authorized to participate in the balancing market, the TSOs could perform frequency balancing services, down to the FCR and FFR timeframe at the moment.

The work from this deliverable will be enhanced and completed by WP5, where a particular focus will be placed on the design of optimal strategies to deploy and manage flexibility services provided by EVs.

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