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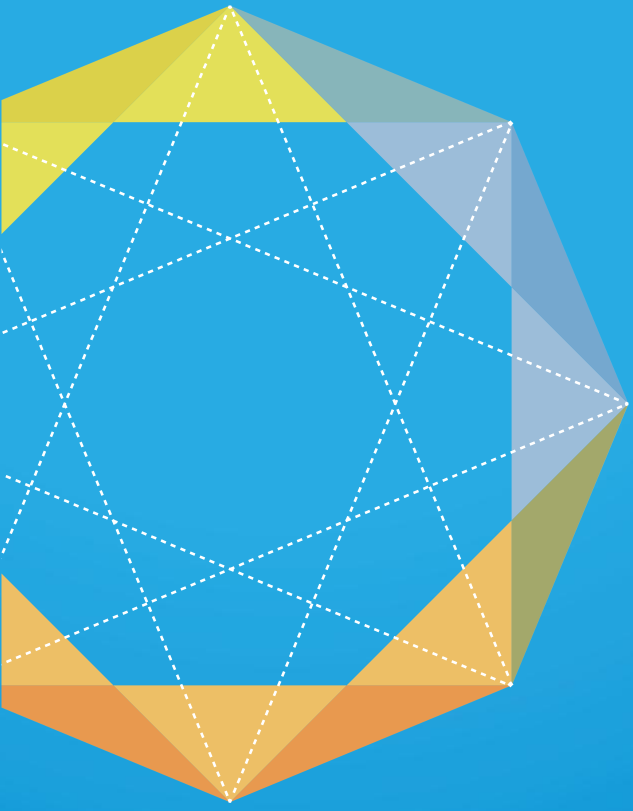
Grid integration of sustainable transport



ETIP SNET

European Technology and Innovation Platform
Smart Networks for Energy Transition

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Grid integration of sustainable transport

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1 EXECUTIVE SUMMARY

Growing concerns about the environmental sustainability of transport require the promotion of new electrified solutions, supported by the integration and coordination of the energy and transport sectors. Coordinated infrastructure planning and significant investments in grid adaptation are essential for the cost-effective decarbonisation of mobility. At the same time, charging processes must be tailored to acceptable use cases for customers, with new tariff schemes and greater standardisation to achieve new flexibility mechanisms.

2 INTRODUCTION

2.1 Sustainable mobility integration into the grid as a potent strategy to reduce greenhouse gas emissions

The optimal integration between sustainable transport and the energy sector remains of utmost importance considering the rapid evolution of both sectors. According to the European Commission[1], achieving sustainable transport means putting users first and providing them with more affordable, accessible, healthier and cleaner alternatives to their current mobility habits. The present document explores this statement from the perspective of ETIP SNET[2], highlighting its mission to establish a clear vision for research, development and innovation in smart networks for the energy transition. It considers aspects such as the main functionalities, quality and efficiency of the electricity system and the benefits of its integration with electromobility, which constitutes the main topic of ETIP SNET Working Group 1. Working Group 2 provides the perspective of the technological and market developments related to the innovative adoption of storage solutions, including their direct interaction with the transportation sector. The work in this field of the two working groups connects very well with relevant aspects of ETIP SNET Vision 2050[3]. On the one hand, it highlights the need for a coordinated approach to developing sustainable fuels for transportation applications that rely heavily on liquid hydro-carbon fuels, such as heavy-duty long-distance road transport. On the other hand, it fosters the circular economy to mitigate environmental impacts and to minimise energy losses and anticipate possible raw material shortages.

The 2Zero partnership[4] aligns with the Green Deal by identifying the research needs to achieve the targets set out in European transport, energy and environmental policies. Its contribution is, therefore, highly relevant to these European objectives and for this reason its participation in this paper has great value. Sustainable transport requires that its specific needs are met and electricity networks are available when and where they are required. Affordability and price transparency are crucial to ensure that mobility users are not penalised for using the network for transportation. Additionally, grid operators are required to act in an unbiased and non-discriminatory manner, both as operators of the entire power system grid and as key facilitators of optimal integration between the transport and the energy sectors in a sustainable way.

With the aim of sharing the insights from this document with relevant stakeholders and the general public, ETIP SNET took advantage of the Northern Europe Regional Workshop to present the topic "Sustainable transport integration in the grids". The event, held on April 8, brought together speakers addressing the challenges and opportunities of integrating electric mobility into distribution networks, particularly in northern Europe. Some of the main takeaways from the workshop are mentioned in this document. The workshop brought together a diverse audience, including European Commission representatives, energy technology providers, system operators (SOs), technology providers, utilities, research organisations, and regulators from across Northern Europe, in particular from Norway, Sweden, Finland, Estonia, Latvia, Lithuania, and Denmark.

This document aims to provide the ETIP SNET perspective on the new high-level initiatives to be developed concerning the integration of sustainable transport with electricity networks. The most relevant are the Sustainable Transport Investment Plan, the Grid Package and the Electrification Action Plan, as announced in the new Industrial Action Plan for the European automotive sector[5].

2.2 Previous related papers

The most recent ETIP SNET paper on the transportation sector was “E-mobility deployment and impact on grids. Impact of EV and charging

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[1] The European Green Deal, COM(2019) 640, December 2019.

[2] https://smart-networks-energy-transition.ec.europa.eu/

[3] ETIP SNET Vision 2050

[4] https://www.2zeroemission.eu/

[5] https://transport.ec.europa.eu/document/download/89b3143e-09b6-4ae6-a826-932b90ed0816_en?filename=Communication%20-%20Action%20Plan.pdf

infrastructure on European T&D grids – Innovation needs"[6], released in 2022. This paper presents a holistic overview and framework to better understand the needs of the involved stakeholders from traditionally separated sectors and foster cooperation among them. These stakeholders include vehicle manufacturers, battery producers, the electronics and automation industries, technology companies, data platform providers, mobility service providers, transport and urban planning authorities, electricity market aggregators, grid operators, consumers, and prosumers. It serves as a reference since its analysis highlights key relevant concepts that will be further explained in the present paper. Building on the previous publication, this new paper proposes a more in-depth analysis of the contribution of storage and the perspective of the electric vehicle manufacturing industry, represented by the 2Zero Partnership. It aims to enhance the overall vision and take the deployment of sustainable transport through electricity grid integration.

Regarding the HORIZON EUROPE co-programmed partnership 2Zero[7], its global objective is to contribute to achieving a carbon-neutral road transport system in Europe by 2050. Among its four pillars associated with the partnership's specific objectives, the second aims to "develop affordable, user-friendly charging infrastructure concepts and technologies that include vehicle and grid interaction"[8]. Several calls of the Work Programme, therefore, feature topics addressing grid-integrated charging solutions supporting smart charging as well as bidirectional charging that can be considered stress-mitigating measures for the existing grid infrastructure, including rather demanding aspects like megawatt charging stations that are necessary to support electric heavy-duty transport in long-haul applications. For the next multi-annual financial framework starting in 2028, ERTRAC[9] and the partnerships 2Zero and CCAM[10] (Connected Cooperative Automated Mobility) call for a strong collaborative pre-competitive research initiative supporting a cross-sector collaboration between, among others, transport and infrastructure[11] to continue the integration of the transport system with energy and information networks.

3 SCOPE AND TARGET

3.1 Context

The growing concern about environmental sustainability is driving the electrification of mobility as a key priority in developing a climate-neutral European road transport system. With the overarching goal of accelerating this necessary transition, sustainable mobility integration into the grid is a potent strategy to reduce greenhouse gas emissions, paving the way towards a zero-emissions energy ecosystem. Considering this initial premise, additional benefits can be achieved for both the transport and energy sectors through effective and appropriate integration and coordination. Thus, the coordinated planning of the location, capacity and types of charging stations, taking into account the different possibilities of electric mobility and the necessary mitigation measures, reduces their impact on the power system (see Chapter 5.1). More precisely, one of the buildings blocks of ETIP SNET Vision 2050 is to enhance the integration of the different energy networks at any scale, considering the most cost-effective way and using new infrastructures for mobility. This coordinated planning includes the development of the electricity network and ad hoc storage technologies to support power needs (e.g. flywheel, supercapacitors, batteries) (see Chapter 5.2). Another topic of interest is the charging and discharging processes of electric vehicles (EVs), which can provide flexibility to the electricity system where technologies such as smart charging and vehicle to grid (V2G) should be adopted to enable this synergy (see Chapter 5.3).

Placing users in the centre of the equation should not be perceived as an added complication since the very rapid evolution of smart grids acts as an additional revenue stream for end users and supplements existing grid reinforcement strategies. Drivers for this are the increased monitoring of charging points (e.g. availability of smart meters and greater granularity of information), V2G technologies, the upcoming related regulation (e.g. demand response network code) and the new possibilities to provide flexibility services. This will result in a more cost-effective grid planning and will ensure equitable benefits for all parties involved.

Finally, this paper identifies the research, innovation, and regulatory efforts needed to advance the integration of sustainable transport and the electricity network. It emphasises optimising local resource use, managing energy flows, and maximising the benefits for end users.

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[6] https://op.europa.eu/en/publication-detail/-/publication/01169b6b-540d-11ed-92ed-01aa75ed71a1

[7] https://www.2zeroemission.eu/, retrieved 2025-02-13

[8] "Strategic Research and Innovation Agenda 2021-2027", 2Zero Partnership, https://www.2zeroemission.eu/wp-content/uploads/2024/03/SRIA-2024-webversion_compressed.pdf, retrieved 2025-02-13

[9] https://www.ertrac.org/, retrieved 2025-02-13

[10] https://www.ccam.eu/, retrieved 2025-02-13

[11] "Joint ERTRAC-2Zero-CCAM Position Paper on Road Transport Research", December 2024, ERTRAC, 2Zero, CCAM, https://www.ertrac.org/wp-content/uploads/2024/12/Joint-Position-Paper-for-Road-Transport-Research-in-FP10-2024-12.pdf, retrieved 2025-02-13

3.2 Benefits of a proper integration of power and transportation sectors

Several opportunities exist to optimise the utilisation of EVs, each having different aims and beneficiaries, and stacking these processes can maximise overall benefits. Regarding the benefits for the energy system, smart charging can support the integration of a larger share of renewable energy source (RES) generation[12] by reshaping the power demand curve, supporting generation fleet adequacy, and optimising system costs and CO_2 emissions. In addition, system operators will be able to improve their system management, both in terms of ancillary services and grid congestions, using the flexibility that the charging process of EVs can provide. To this end, developing spatial-temporal management strategies and procurement mechanisms is crucial for leveraging and remunerating flexibility at the distribution level. It will help manage the high energy demand of electric vehicles (e.g. smart charging could be a valid tool to avoid grid congestion) and facilitate the integration of distributed renewable energy sources, supporting the transition to green energy.

From the users' point of view, it is necessary to explore innovative coordination strategies and remuneration mechanisms that promote the integration of sustainable transport modes into the electricity grid and to consider optimised planning efforts bringing together diverse viewpoints. For example, considering affordability and efficiency criteria in investment needs while maintaining the main functionalities of the electricity system means that EV users will also benefit from lower charging energy costs and more reliable services. A common design benefiting both sectors requires synergies between grid planning and charging point (CP) location strategies. This approach ensures sustainable electricity and charging network developments, alongside integrating new information and communication technologies to increase the usability and efficiency of electric vehicles (e.g., new digital tools linked to charging points and the service provision)

At the 2025 ETIP SNET Northern Europe Regional Workshop, the iFlex[13] project presented its research into implicit demand flexibility (demand response) in Norwegian households. Their conclusions showed that dynamic electricity pricing contracts are an effective tool for leveraging demand response; also that automatic smart charging contributes to significant short-term demand response. The project has also demonstrated that benefits to the electricity system include more stable energy prices and lower peak demand on the grid.

Technological and market advancements in energy storage solutions directly applied to transportation solutions, such as onboard batteries and charging processes, can mitigate risks and enhance the integration between electromobility and the electricity system. In this context, battery degradation must be thoroughly addressed and analysed from a holistic system perspective, as discussed in the following section.

3.3 Storage technologies that provide a better integration between sectors

3.3.1 The charging process

The analysis of integration between the transport and energy sectors often fails to consider the impact that storage technologies can have as facilitators in improving charging and discharging processes. Specific solutions, can even extend battery life under controlled conditions, proving the importance of incorporating storage considerations into decision-making. These solutions include using storage devices to smoothen the exchange of electricity with the grid and smart charging combined or not with the previous.

Among storage technologies, battery energy storage systems (BESS), including V2G integration and stationary batteries (such as second-life batteries), provide the most effective integration between the transport and energy sectors. Practical applications of these technologies are further illustrated in Chapter 6.

Flexibility solutions enabling smart charging and discharging, allows EVs to act as decentralised storage units that balance supply and demand on the grid. This dual functionality reduces grid congestion and stabilises renewable energy integration, which is crucial for decarbonisation. Future V2G applications will improve this capability by allowing EV batteries to supply power back to the grid during peak demand, fostering a bidirectional energy flow that enhances grid resilience and reliability. Additionally, stationary batteries amplify these benefits by providing cost-effective solutions for integrating renewable energy and charging infrastructure, supporting the grid when it is needed. The alternative of stationary second-life batteries promotes a circular economy while addressing energy storage challenges, in line with specific challenges and opportunities outlined in the ETIP SNET Vision 2050. These systems excel in short-term energy management, real-time grid stabilisation, and aligning renewable energy production with consumption, making them indispensable for sector coupling.

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[12] Regulation (EU) 2023/1804 of the European Parliament and of the Council of 13 September 2023 on the deployment of alternative fuels infrastructure, and repealing Directive 2014/94/EU (AFI Regulation).

[13] https://www.iflex-project.eu/

One concrete future integration use case has been evaluated in a study[14] that shows that V2G will make the decisions about energy flow easier and more effective (when to store, when to import and when to export). When people return home from their daily activities often coincides with peak electricity demand, as households use appliances, lighting, heating, and charging electric vehicles (EVs) simultaneously. This behaviour can strain the grid and increase energy costs and reliance on non-renewable energy sources. While smart charging helps to efficiently manage EV charging demand, V2G also enables releasing energy stored during off-peak times. Households can benefit from reduced costs, as the discharging process allows EV owners to sell surplus energy back to the grid if required by SOs and, in some cases, power their homes directly. Additionally, it supports greater integration of renewable energy by compensating for mismatches between generation and demand.

In summary, by turning EVs into mobile energy storage assets, V2G can help to reduce grid congestion, lower energy costs, and enhance the sustainability of the energy system.

3.3.2 Stationary energy storage systems

The integration of stationary energy storage systems (ESS) into the charging station infrastructure, especially for fast charging, has been analysed in relevant studies[15][16][17][18]. Maximisation of ESS retribution scheme, resilience to power outages, reduction of peak load and optimisation of PV supporting generation are the main reason behind its implementation. The lithium-ion batteries dominate the energy storage market and stationary applications. However, other storage technologies can be used, especially for power applications, such as when there is a need to mitigate the power demand from fast-charging stations. For instance, flywheel storage offers a comparable power density to batteries, and its implementation and integration into the charging station infrastructure is currently requiring much attention[19]. Other storage technologies such as redox flow batteries and supercapacitors[20] may be considered. However, considering energy investment costs, lifetime, and space requirements, the cost effectiveness of these alternatives to lithium-ion batteries must be equally explored. On the other hand, integrating flywheels or supercapacitors with the ESS could provide an additional revenue stream for charging station operators. If permitted and remunerated by the national grid regulatory framework, these technologies could provide short-term flexibility, ancillary services, or frequency stabilisation services.

4 BUILDING BLOCKS

Three pillars constitute the ecosystem this paper attempts to present: electricity grids, users and storage technologies. While each has its own unique characteristics, understanding and leveraging their interactions represents a significant opportunity for the integration of these sectors. This chapter describes their specificities, while Chapter 5 explores the challenges and opportunities of this integration.

Finally, and considering the importance of the political and social context in the development of new proposals, a review of the most relevant regulations and initiatives has been included here.

4.1 Electricity grids and charging infrastructure

As the energy transition progresses, system operators need to modify their network operations to meet a higher instantaneous (peak) capacity demand from the increasing electromobility needs. The electric mobility load is expected to grow faster, mainly affecting the low voltage (LV) network in the short term (the limiting factor for the LV grid is the capacity of cables, transformers

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[14] Bilal AMGHAR, Khelil SIDI IBRAHIM & Toufik AZIB ; Smart Charging and V2G Solutions : Optimizing Energy Demand Management with Grid Integration for EVs" 11th International Conference on Energy and City of the Future, Les Mureaux, France, 21-22 November 2024 ESTACA Lab, France

[15] Datta, U., Kalam, A., & Shi, J. (2020). Smart control of BESS in PV integrated EV charging station for reducing transformer overloading and providing battery-to-grid service. Journal of Energy Storage, 28, 101224. https://doi.org/10.1016/j.est.2020.101224

[16] Meiers, J., & Frey, G. (2024). A Case Study of the Use of Smart EV Charging for Peak Shaving in Local Area Grids. Energies, 17(1), Article 1. https://doi.org/10.3390/en17010047

[17] Lappalainen, K., & Kleissl, J. (2023). Sizing of stationary energy storage systems for electric vehicle charging plazas. Applied Energy, 347, 121496. https://doi.org/10.1016/j.apenergy.2023.121496

[18] Hussain, A., Bui, V.-H., & Kim, H.-M. (2020). Optimal Sizing of Battery Energy Storage System in a Fast EV Charging Station Considering Power Outages. IEEE Transactions on Transportation Electrification, 6(2), 453-463. IEEE Transactions on Transportation Electrification. https://doi.org/10.1109/TTE.2020.2980744

[19] Mouratidis, P. (2024). Augmenting electric vehicle fast charging stations with battery-flywheel energy storage. Journal of Energy Storage, 97, 112957. https://doi.org/10.1016/j.est.2024.112957

[20] Buchajczyk, M., Korjani, S., Duranti, M., & Macchi, E. G. (2024). Techno-Economic Analysis and Sizing of RFB and Supercapacitor-Based HESS for an EV Charging Station. 2024 AEIT International Annual Conference (AEIT), 1-6. https://doi.org/10.23919/AEIT63317.2024.10736734

and other parameters such as voltage levels or asymmetry). In the medium and long term, the impact is expected to extend to the medium voltage (MV) and eventually to the high voltage (HV) networks. Most of the charging will be performed at the low-voltage levels, although medium and high voltage networks will also be affected in terms of aggregation and connection of hyperchargers.

The planning and operation of electricity networks must also align with the requirements for charging infrastructure for electric mobility[21]. Consequently, grid reinforcement and anticipatory investments require a comprehensive assessment that accounts for other upstream load increases to evaluate the overall impact on the network. These parameters relate to the characteristics of the electricity network in areas under consideration and the expected future load requirements (accounting for the chargers' location and power capacity requirements). The exact location of the charging points, the requested power capacity for the chargers and the capacity of power lines and power transformers in the given area are some factors that can be considered for that purpose[22].

In conclusion, successful network planning should consider the total number of EVs already in use, their type, the forecasted density of charging points, and their power requirements. This assessment varies based on the availability of ultrafast/fast/slow chargers and the information on utilisation rates of charging stations, based on behavioural patterns of the drivers such as charging location (e.g. home or public charging) and the use of smart charging solutions and dynamic electricity prices. Other relevant factors are the timing and magnitude of EV charging power.

4.2 User behaviour and business cases

As described in the previous section, the integration of electromobility with the electricity grid promises to help accelerate the decarbonisation of the energy used for transportation as it enables the storing of a temporary surplus of renewable energy for transportation or, as V2G application, for covering peak demand.

Previous and ongoing EU projects in the European Green Vehicle Initiative[23] (EGVI, the H2020 predecessor of 2Zero) and in 2Zero[24] interviewed end users about their attitude to V1G and V2G. Researchers concluded that a common concern of all users is that a third party takes control of their hardware in the first place, next to the uncertainty of having the required energy stored in their batteries when wanting to use their vehicles perhaps earlier than initially planned. Among bidirectional connections, users were more likely to accept a vehicle-to-home (V2H) connection than a vehicle-to-grid integration. In particular, for the latter, concerns of premature battery degradation resulting from an increased number of cycles constitute a major resistance, though financial incentives could improve V2G acceptance. The intensity and frequency of use could also be further increased in the interest of providing demand response services. The project SCALE presented the corresponding results[25] during the RTR2024 Conference[26] and by XL-CONNECT[27] during the RTR2025 Conference[28].

On a complementary note, other research works[29] analyse different scenarios of network expansion versus cross-system solutions to address electricity network challenges, such as EV penetration and its charging infrastructure. The study tries to compare various solutions with the traditional grid investment and network expansion. Implementation timeline, CAPEX, OPEX, and the lifetime of the required assets are the main constraints and will determine the costs of the solution. Demand-side flexibility and storage assets are one of the proposed cross-system solutions, especially in circumstances where the network reinforcement is in the process of completion. In this context, different stakeholders may be involved, and besides the traditional system operators, figures such as aggregators, charging station owners, and energy storage owners prove to be essential in all the interactions within this particular ecosystem. Successful business cases require that all stakeholders create, capture, deliver and share values, which will determine how these costs impact consumers and society. When EV users adapt their behaviour and decide to charge or discharge EVs using smart charging, they can generate extra revenue by charging when electricity prices are low and discharging when prices are high. According to some studies, those revenues can represent 7-13% of their charging costs[30]. In parallel, adequate regulations, remuneration schemes and availability of business collaborative platforms are essential to build a robust business case (Venizelou

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[21] Grids, the missing link - An EU Action Plan for Grids, COM(2023) 757, European Commission, November 2023.

[22] Debunking the myth of the grid as a barrier to e-mobility. Eurelectric, April 2021.

[23] E.g., projects under the topic LC-GV-03-2019, https://cordis.europa.eu/programme/id/H2020_LC-GV-03-2019/en

[24] E.g., HORIZON-CL5-2021-D5-01-03 (https://cordis.europa.eu/programme/id/HORIZON_HORIZON-CL5-2021-D5-01-03/en)

[25] https://cordis.europa.eu/project/id/101056874

[26] https://www.2zeroemission.eu/wp-content/uploads/2024/04/RTR2024-Summary-Reports-final.pdf, retrieved 2025-02-13

[27] https://cordis.europa.eu/project/id/101056756

[28] https://rtrconference.eu/, public report pending, retrieved 2025-02-13

[29] Ansarin, M., Bene, C., Kralli, A., Gorenstein Dedecca, J., & van Nuffel, L. (2024). Advancing cross-system solutions to address electricity network challenges. Final report, (European Union Agency for the Cooperation of Energy Regulators—Trinomics B.V.).

[30] Unlocking EV smart charging to reduce grid congestion - lessons from the Netherlands, Strategy&/ElaadNL, March 2024.

et al., 2023)[31].

Passenger cars with low annual mileage benefit the most from smart charging. For these, a lifetime-optimised charging strategy can extend the battery life over the vehicle lifetime in some cases and create a “surplus” not used for driving purposes. This surplus can be used for vehicle-to-everything (V2X) services. However, some vehicle types, e.g. public transport buses, have limited V2X potential due to their intensive use. They also do not benefit significantly from an increase in life expectancy through smart charging.

Another interesting use case is pooling batteries via service providers, which offers additional advantages as it provides further degrees of freedom in battery charge and discharge individual profiles that can be effectively decoupled from the most grid-friendly aggregate profile.

The basic statements and recommendations are valid for plugin hybrid electric vehicles, too. However, the comparatively small battery capacities of PHEVsreduce the V2X potential, which makes it more difficult to amortize the charging infrastructure costs that may be necessary.

4.3 Storage technologies

The integration of storage technologies into the transportation and energy sectors offers significant advantages, particularly in increasing the efficiency of electricity exchanges with the grid. These solutions play a crucial role in smoothing such exchanges by acting together as buffers that absorb excess energy during periods of low demand and release it during peak usage times. They also stabilise the grid and prevent fluctuations that can lead to inefficiencies or outages. For example, systems that consider an integrated solution of EV chargers and an attached storage solution could be placed in parts of the grid, where capacity is limited, with storage providing direct support to the charger when grid resources are scarce.

Specific studies and years of experience with battery systems in the field and in the laboratory show that the implementation of smart charging practices positively improves battery longevity[32], provided dedicated BMS (battery management system) functions have control over the state and rates of charge and can coordinate this with the requests from the grid operator. By managing charging scheduling and optimising charging/discharging profiles, these practices[33] not only reduce costs for EV users due to an increased duration of storage components, they also contribute to a more resilient energy system by reducing the impact that grid constraints and related episodes have on users following those charging patterns.

V2G technologies, combined with an understanding of battery degradation, will play a pivotal role in achieving smooth grid integration and advancing sustainable transportation. Those technologies enable EVs to engage in bidirectional energy flow., Furthermore, a better understanding and monitoring of battery degradation are crucial, as they directly impact the longevity and efficiency of EV batteries.

Battery degradation is due to complex chemical and physical mechanisms. Factors such as temperature and charge cycles significantly influence battery health[34], and strategies that mitigate these effects can extend operational life.. This not only reduces the economic burden of frequent battery replacements, making EV ownership more cost-effective, it also allows longer-lasting batteries to contribute to grid stability over extended periods, solidifying their role in renewable energy integration. The chemistry of lithium-ion batteries must also be considered when managing them. A recent study[35] presents the parameters that affect the economic performance of energy storage systems, lithium-ion batteries and flywheels coupled with a fast-charging station. The authors conclude that the combination of flywheel and battery storage technologies provides the best economic performance, leveraging the strengths of both systems to improve return on investment (ROI) and reduce costs. Flywheel storage is ideal for high-power, short duration charging, while battery storage supports bulk peak loads. Notably, battery performance and degradation vary significantly across chemistries: lithium iron phosphate (LFP) offers better thermal stability and longer cycle life, while nickel

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[31] Venizelou, V., Tsolakis, A. C., Evagorou, D., Patsonakis, C., Koskinas, I., Therapontos, P., Zyglakis, L., Ioannidis, D., Makrides, G., & Tzovaras, D. (2023). DSO-Aggregator Demand Response Cooperation Framework towards Reliable, Fair and Secure Flexibility Dispatch. Energies, 16(6), 2815. https://www.mdpi.com/1996-1073/16/6/2815

[32] Nájera, Jorge, Arribas, Jaime R., de Castro, Rosa M. and Mendonça, Hugo "Analysis of Electric Vehicles Battery Ageing Associated to Smart Charging Controls" 8th International Electric Vehicle Conference (EVC 2023), https://doi.org/10.1016/j.trpro.2023.11.031

[33] F. Naseri and C. Barbu and T. Sarikurt ”Optimal sizing of hybrid high-energy/high-power battery energy storage systems to improve battery cycle life and charging power in electric vehicle applications”, Journal of Energy Storage, 2022, https://doi.org/10.1016/j.est.2022.105768

[34] Sang, V.T.D.; Duong, Q.H.; Zhou, L.; Arranz, C.F.A. Electric Vehicle Battery Technologies and Capacity Prediction: A Comprehensive Literature Review of Trends and Influencing Factors. *Batteries* 2024, *10*, 451. https://doi.org/10.3390/batteries10120451

[35] Mouratidis, P. (2024). Augmenting electric vehicle fast charging stations with battery-flywheel energy storage. *Journal of Energy Storage*, *97*, 112957. https://doi.org/10.1016/j.est.2024.112957

manganese cobalt (NMC) provides higher energy density but degrades faster under high-power cycling[36]. A **dual-chemistry battery configuration (see HELIOS in section 6),** combining two different types of battery chemistries in a single system, can significantly enhance the performance, lifespan, and cost effectiveness of energy storage, especially in fast-charging applications. For example, pairing **LFP** cells, with **NMC** cells, allows the system to balance power and energy needs more efficiently. The LFP cells can manage frequent, high-power charge/discharge cycles, protecting the more energy-dense NMC cells from rapid degradation.

Although all energy storage options are sensitive to cost and operational uncertainties, including these chemistry-specific traits, the study finds that even single-technology solutions carry relatively low investment risks, making them suitable for integration into fast-charging stations.

The synergy between V2G technology and insights into battery degradation fosters a sustainable ecosystem where renewable energy utilisation is maximised, greenhouse gas emissions are minimised, and economic incentives for EV owners are enhanced. Second-life batteries (see HELIOS use case in Chapter 6), retired from electric vehicles or other applications, further contribute to this framework by serving as stationary energy storage solutions[37] that balance supply and demand. These batteries can store excess energy generated during low-demand periods and release it during peak times, enhancing grid reliability and providing ancillary services like frequency regulation to the transmission system operators (TSO). Their deployment at EV charging stations helps manage load and prevent grid congestion, while synergies with V2G systems enhance energy management capabilities. The use of second-life batteries combined with the aforementioned strategy for improving grid stability and efficiency, ultimately informs better infrastructure planning that aligns with actual usage patterns and establishes a more efficient and sustainable grid integration.

ENTSO-e is currently preparing a study with the support based on laboratory testing experiences. The study, soon to be published, has found that, regardless of the vehicle type, smart charging extends the battery life compared to uncontrolled charging, mainly thanks to increased calendar ageing that occurs after the uncontrolled charging step because the battery remains for a longer period at higher State of Charge (SOC), usually in the range of 100 %. The SOC-swings (also called depth of charge and discharge) is one of the main contributors of battery cyclic ageing. The SOC-swing represents the absolute difference between the maximum and minimum SOC of a closed charge or discharge part of the cycle. The general rule for lithium-ion batteries is that a lower swing causes less degradation. The C-rate, which measures the speed of charge/discharge (instantaneous current flow in relation to battery capacity) accelerates degradation only in “fast-charging”. Residential charging wall boxes will generally not reach power levels sufficiently high to accelerate the battery degradation. For V2X services, it is therefore advisable to carry out small SOC-swing cycles more frequently rather than larger ones less often.

4.4 Existing regulation

This section gives a brief review of the regulatory framework and high-level policies relevant to the paper’s topic and, therefore, guides the direction of the discussion and the proposed recommendations in Chapter 7.

- **Revised Alternative Fuels Infrastructure Regulation (EU) 2023/1804**[38]. It establishes a common framework of measures for deploying alternative fuels and sets public EV charging infrastructure targets for EVs and bidirectional charging.

- **Revised Renewable Energy Directive (EU) 2023/2413**[39]. Electric vehicles must be able to participate in congestion management markets and provide flexibility services, including through aggregation. Vehicle manufacturers must provide real-time data on battery state of charge, capacity and, where appropriate, the EV location to EV owners/users and authorised third parties.

- **Recast Energy Performance of Buildings Regulation (EU) 2024**/1275[40]. It includes the roll-out of recharging points for electric vehicles in buildings, removing barriers to their installation, enabling smart charging and introducing measures for bike parking in buildings.

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[36] Evro, S., Ajumobi, A., Mayon, D., & Tomomewo, O. S. (2024). Navigating battery choices: A comparative study of lithium iron phosphate and nickel manganese cobalt battery technologies. Future Batteries, 4, 100007. https://doi.org/10.1016/j.fub.2024.100007

[37] Hassan, Ali, Shahid Aziz Khan, Rongheng Li, Wencong Su, Xuan Zhou, Mengqi Wang, and Bin Wang. 2023. "Second-Life Batteries: A Review on Power Grid Applications, Degradation Mechanisms, and Power Electronics Interface Architectures" *Batteries* 9, no. 12: 571. https://doi.org/10.3390/batteries9120571

[38] https://eur-lex.europa.eu/eli/reg/2023/1804/oj/eng

[39] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:L_202302413

[40] https://eur-lex.europa.eu/eli/dir/2024/1275/oj/eng

- **Clean Vehicle Directive (EU) 2019/1161**[41]. It focuses on emission reduction and aiming to promote the procurement of low- and zero-emission road vehicles in the public sector by setting minimum targets for new purchases. In addition to purchasing, the directive also includes leasing, renting or hiring purchase options. Quota for passenger/light-duty vehicles: 38.5%; for heavy-duty vehicles: 10% (until 2025), 15% (as of 2026); for buses: 45% (until 2025), 65% (as of 2026).

- **EU Action Plan for Grids**[42]. It recommends improving long-term grid planning for a higher share of renewables and increased electrification, promoting the integration of smart and bidirectional recharging has a substantial impact on the electricity grids.

- **Directive (EU) 2019/944[43] and Regulation (EU) 2019/943**[44] on common rules for the internal electricity market (recast in 2024). They include provisions on demand response and the use of flexibility by system operators.

- **Communication of the European Commission on an Industrial Action Plan for the European automotive sector, COM(2025) 95, March 2025**[45]. Its main goal is to enhance the competitiveness of European automotive manufacturers by promoting greater collaboration and improving overall enabling conditions, including targeted financing and regulatory simplification. The Action Plan aims to make electric vehicle battery cells and components produced in the EU cost-competitive in the short term.

- **Commission Regulation (EU) 2016/631 of establishing a network code on requirements for grid connection of generators (RfG)[46]**. Currently under review.

- **Commission Regulation (EU) 2016/1388 establishing a Network Code on Demand Connection (DCC)[47]**. Currently under review

5 CHALLENGES AND OPPORTUNITIES

5.1 Planning coordination of the location, capacity, and types of charging stations

5.1.1 Coordinated planning of EV charging network and electricity grid

Without any doubt, planning the location of charging points, with their appropriate voltage and power levels, represents one of the most relevant challenges for integrating electric mobility into electricity networks and, consequently, for the electrification of transport in general. It is not only about having a sufficient and well-distributed network of charging points: they must also be of the required type and power. The exercise of planning the appropriate network involves a set of interacting actors, forming an ecosystem that must be effectively coordinated[48], and in which EV users are at the centre, and system operators have to ensure that the system is capable of meeting the new demand. In this sense, to carry out a correct implementation, it is first necessary to use the existing regulation as a reference for setting the main objectives.

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[41] https://eur-lex.europa.eu/eli/dir/2019/1161/oj

[42] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2023%3A757%3AFIN&qid=1701167355682

[43] https://eur-lex.europa.eu/eli/dir/2019/944/oj/eng

[44] https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=celex:32019R0943

[45] https://transport.ec.europa.eu/document/download/89b3143e-09b6-4ae6-a826-932b90ed0816_en?filename=Communication%20-%20Action%20Plan.pdf

[46] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ:JOL_2016_112_R_0001

[47] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2016.223.01.0010.01.ENG&toc=OJ:L:2016:223:TOC

[48] Gallego Amores, Santiago, et al. The interaction of electromobility with the power grids, Electra CIGRE, 2022.

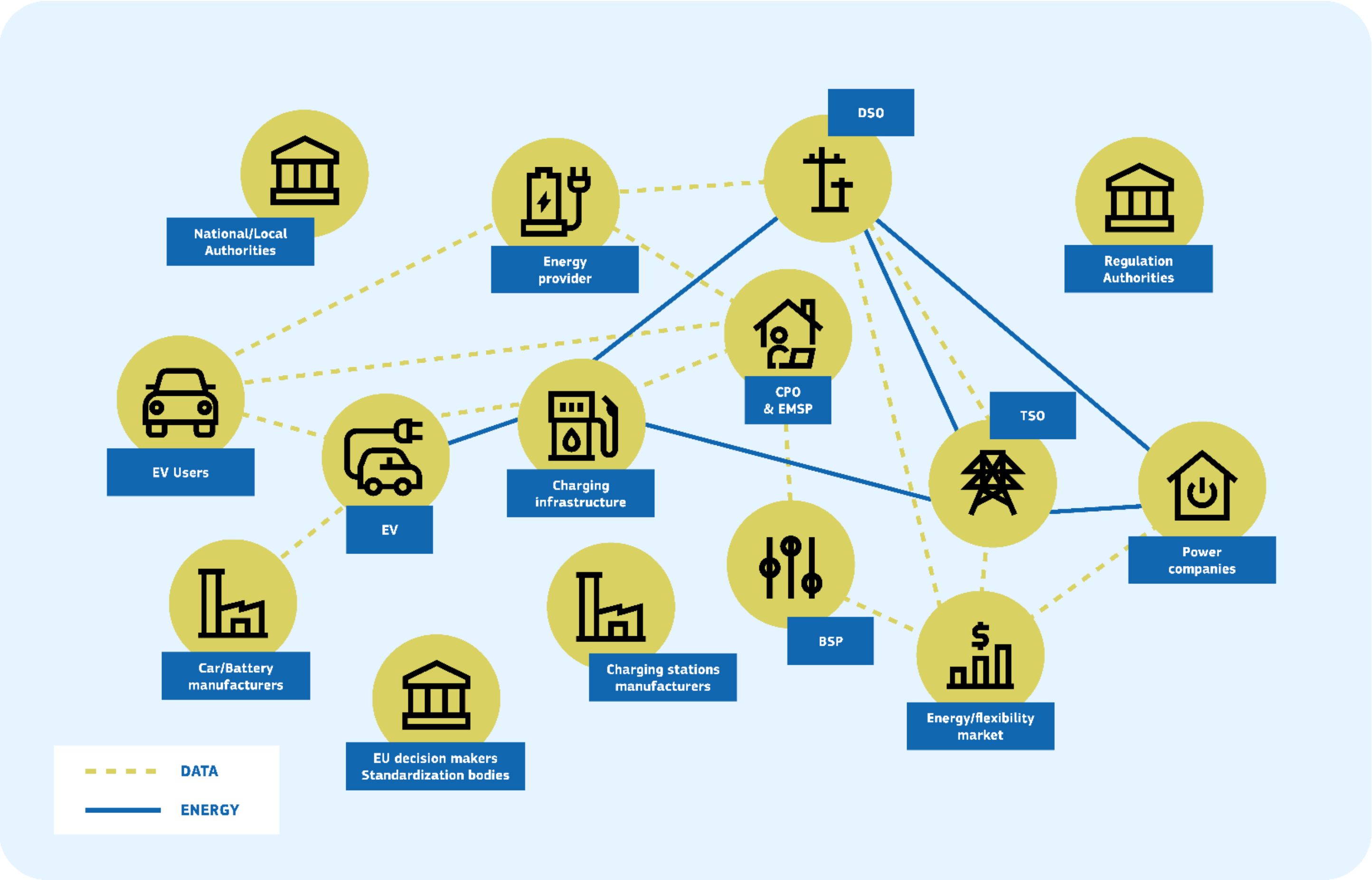

Figure 1 - Interactions among electromobility ecosystem actors. Source "E-mobility deployment and impact on grids", ETIP SNET.

The Alternative Fuel Infrastructure Regulation (AFIR), an EU-wide regulation with mandatory national targets for deploying alternative fuel infrastructure for road vehicles (passenger and freight vehicles), can be considered the most relevant regulation in this context. The AFIR combines mandatory distance-based with fleet-based targets to deploy charging infrastructure on the TEN-T core and comprehensive networks. However, the resources allocated under the AFIR should be distributed at the national level, and the traffic flows should be considered to estimate the real charging demand needs.

The global transition from old transportation to new electric mobility raises a critical challenge: developing extensive charging infrastructure alongside reinforced electricity grids. These two ecosystems must be coordinated-planned to meet the rising demand, ensure cost efficiency, grid capacity, and reliability, and achieve sustainable energy goals. Electricity DSOs (distribution system operators) are expected to play an essential role in enabling transport electrification by ensuring the electricity grid has adequate capacity to serve the upcoming EV charging demand[49]. Grid upgrades might require significant time, which might not align with the time plan for the EV charging network expansion. In light of this, the charging network planning of charge point operators (CPOs) and public authorities needs to consider the network capacity limitations, and they should share their plans with system operators to prepare the necessary grid reconfigurations or upgrades.

5.2 Planning challenges of electricity demand from EVs

The electric mobility charging network is not as mature as the electricity grid. The charging network is still evolving in all EU countries, with different growth rates, and it continuously grows to serve the rapid EV demand increase. Charging stations, which are publicly accessible, must be strategically located for convenience and to serve user needs better, and are mainly based on market needs and business opportunities (e.g. in commercial areas, fuel stations, resting areas, etc..). The cornerstone of strategic planning is an accurate forecast of EV adoption and associated charging demand, considering both short-term needs and long-term trends.

Currently, the charging network expansion has the risk of being decoupled from the electricity network expansion, raising significant concerns about the impact of the future charging network on the grid power capacity adequacy. Each distribution network can host up to a maximum number of EVs without violating any network operational constraint. The maximum number of EVs that can be safely integrated into a distribution network depends on its technical and operational characteristics as well as on the charging

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[49] Grid-Optimised Deployment of Charging Infrastructure for Light and Heavy-Duty Vehicles, EDSO, September 2024.

scheme adopted by EV users (i.e. uncontrolled charging – “dumb”, time of use tariffs, smart charging – “valley-filling”).

As the electricity demand changes over time, continuous adjustment of the network's performance and capacity is necessary. EV adoption is expected to place additional stress on the network, above conventional rates, raising new challenges for grid operating and planning future infrastructure requirements. Grid updates should always be as cost-efficient as possible to ensure affordable connections, and the demand increase from mass deployment of EVs may require significant additional grid upgrades. A significant discrepancy between the timelines for EV adoption and grid upgrades could impede the transition to electric vehicles.

Managing EV charging demand presents different characteristics than conventional (non-EV) demand. These additional challenges mean significant additional grid infrastructure will likely be needed to manage supply and demand. Additionally, EV demand presents several additional challenges due to its spatio-temporal characteristics. The impacts of EV charging on the grid are highly dependent on the existing local consumption profile and the local network specifications. In the case of urban areas, the additional EV demand will be superimposed on the already increased grid consumption, and potential overloading issues might occur, especially when the grid demand peak coincides with the EV charging demand peak. In this respect, additional grid capacity is required to release the congested grid infrastructure (i.e. substations or network lines)[50].

Various analysis and system modelling levels are required, including real-time state estimation based on real-time data and sophisticated demand forecasting tools using metering data and bottom-up aggregation of various load categories. At the same time, looking at synergies between SOs and other agents' forecasting tools can help them improve forecasts, for example, through common design, data exchange and cooperation of the different system operators. This strategy also includes a holistic approach to urban planning that could successfully integrate charging load distribution of electric transport (cars, buses) and benefit both grids and municipalities. Conversely, in rural areas, the loading levels of the local grid infrastructure are often less significant since consumption is relatively low there, and the penetration of renewable energy sources might be pretty high. Still, the electrical distances between the network buses and the substation are significantly longer. Consequently, in rural networks, the additional demand of the transport sector is expected to cause voltage quality issues (i.e. high voltage drops significantly at the farthest connections from the substation or deviation violation) rather than overloading issues, which could be mitigated via voltage regulators.

5.3 Development of the electrical network, flexibility and storage technologies to meet power needs

5.3.1 The role of DSOs

DSOs are making substantial investments to expand, maintain, and strengthen their networks to integrate new capacity into the grid[51]. Anticipatory investments are vital for DSOs as they navigate the challenges of managing the modern grid. On the one hand, the specific case of the load of EVs, highly dependent on the users' behaviour and their daily requirements, is challenging the forecast with certitude where the charging points – and their related network infrastructure – will be placed in the most cost-efficient way. On the other hand, grid reinforcement entails significant costs and long waiting periods while flexibility solutions require careful coordination and comprise some level of uncertainty. Therefore, integrating sustainable transport in the electricity grids makes a very suitable case for anticipatory investments[52]. These proactive investments enable DSOs to strengthen their infrastructure in advance, preparing for future demands as outlined in strategic and master plans. However, since investments made by DSOs are ultimately transferred and socialised in the network charges, some thorough considerations must be considered before the distribution development plans are definitive. In this decision making process, it is important to consider that uture electric mobility scenarios require high grid infrastructure investments[53].

Regarding information requirements, local decision-making cannot overlook the status of the grid because its capacity and stability dictate the feasibility of these decisions. To address these challenges, proactive and integrated planning is essential. By ensuring that the status and needs of the grid are considered in CPOs’ planning, both DSOs and CPOs can align their priorities, leading to a more resilient grid and a well-coordinated charging network growth. Effective communication is the cornerstone of successful collaboration and should be implemented through clear and structured processes. Early engagement with SOs can also speed up the installation of fast chargers on motorways, which places higher power demands on MV grids. These forecasts are highly relevant

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[50] Gallego Amores, Santiago, Losa, Ilaria, E-mobility deployment and impact on European electricity networks. Innovation actions needed in the context of the European Green Deal, CIRED Porto Workshop, 2022.

[51] Grid-Optimised Deployment of Charging Infrastructure for Light and Heavy-Duty Vehicles Overcoming Capacity Constraints, EDSO for SmartGrids, September 2024

[52] How can DSOs rise to the investments challenge? Implementing Anticipatory Investments for an efficient distribution grid, Eurelectric, March 2024.

[53] Another Source of Inequity? How Grid Reinforcement Costs Differ by the Income of EV User Groups, Sarah A. Steinbach and Maximilian J. Blaschke, MIT Center for Energy and Environmental Policy Research.

to network planning and operation.

The experience of the DSO-City collaboration framework promoted by E.DSO under the context of "Local Energy Action Plans (LEAP)"[54] should provide useful guidelines for the DSO-CPO cooperation.

5.3.2 Demand response and storage technologies

Demand response and procurement of flexibility are alternatives that DSOs can exploit for specific cases (i.e., construction of the network postponed until all permits are obtained). From the system operators' point of view, EVs can be viewed as a potential source of flexibility, providing essential solutions to use flexibility in how demand (charging processes) and feed-in to the grid (discharging processes) interact with the network[55]. A clear and very concrete definition of these two possibilities from a technical perspective is the foremost step in preparing the corresponding regulation (e.g., network codes, implementing acts and their subsequent national implementations) and, at the same time, in providing an unambiguous understanding of how they can be used to improve the management of the grid.

The deployment of smart charging schemes can provide demand flexibility, considering EVs as manageable loads or distributed storage. Complementing network reinforcement with the exploitation of flexibility capacities from EVs can result in higher welfare for electric mobility-related actors, EV users and DSOs. Thus, one parameter for the location of the enabled charging stations should be the grid capacity constraints to facilitate and accelerate the charging network growth.

One concrete situation where users and electricity system operators can ensure the power needs is mentioned in the European Commission Communication on how to Decarbonise Corporate Fleets[56]. The use case explores the multiple possibilities that car rental companies could have when operating large fleets at airports. The deployment of recharging infrastructure at airport facilities, where rental cars operate, can be communicated in advance to systems operators. This makes an excellent case for anticipatory investments and integration of charging profiles in network management.

As explained in Chapters 3 and 4, smart charging and discharging of EVs is aligned with the needs of the grid. This could be an essential tool for managing grid stability and efficiently integrating higher volumes of renewable energy sources. It can be done through flexibility services, specific tariffs, or other ways of EV users' participation.

A complementary solution is using storage technologies to support the charging processes. Several research studies have modelled different scenarios analysing the coupling of energy storage (usually batteries) with charging station infrastructure. A relevant study[57] compares the two strategies for mitigating the impact of highway fast-charging stations on the power grid: battery energy storage and demand flexibility. The authors use an operations model based on the 2033 Texas power grid. The study shows that four-hour BESS installed at the station are more effective than demand flexibility in managing the grid impact of highway fast-charging stations. Unlike demand flexibility, which offers only short-term solutions, batteries provide sustained support for these stations with high and inflexible energy demands. It can also generate additional revenue through energy arbitrage, enhancing its economic viability.

Moving from the highway scenario to the daily charging demand scenario, an interesting study[58] evaluates the grid impact under rapid electric vehicle adoption and high electrification scenarios in 2035 for the US portion of the Western Interconnection (WECC) grid, covering 11 states with over 75 million people. The authors focus on different strategies, including battery energy storage, renewable energy generation, EV charging demand management and distribution system infrastructure upgrade. The study results lead to the conclusion that adding 10 GW of energy storage (4 h grid storage capacity per day) at the distribution level would be sufficient to cover the expected demand. However, storage is expensive, as can be, in certain cases, upgrading the distribution system infrastructure. With higher renewable generation, timing is more important and shifting drivers from home afternoon to daytime charging improves all metrics of grid impact, including ramping, use of non-fossil fuel generation, storage requirements and emissions. These findings are robust across different levels of EV adoption. In Europe, the study by (Steinbach & Blaschke, 2024)[59] models potential overloads within the European distribution grid in the Munich region in southern Germany due to household electricity loads and EV charging loads due to the combined effects of decentralised PV generation and home battery operations. The authors analyse representative distribution grids in rural, suburban, and urban settings at different levels of EV adoption to account for differences in the grid structure, household characteristics, and mobility behaviour. Their work

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[54] https://www.edsoforsmartgrids.eu/content/uploads/2024/08/240805-copper-innovation-brief.pdf

[55] E.DSO technical paper on V2G charging mechanisms, Brussels, December 2024

[56] Decarbonise Corporate Fleets, EU Communication COM(2025) 96, March 2025.

[57] Mowry, A. M., & Mallapragada, D. S. (2021). Grid impacts of highway electric vehicle charging and role for mitigation via energy storage. Energy Policy, 157, 112508. https://doi.org/10.1016/j.enpol.2021.112508s

[58] Powell et al. (2022). Charging infrastructure access and operation to reduce the grid impacts of deep electric vehicle adoption

[59] Steinbach, S. A., & Blaschke, M. J. (2024). Enabling electric mobility: Can photovoltaic and home battery systems significantly reduce grid reinforcement costs? *Applied Energy*, *375*, 124101. https://doi.org/10.1016/j.apenergy.2024.124101

demonstrates that decentralised electricity generation with PV and batteries can effectively reduce grid reinforcement costs caused by EV charging. Furthermore, combining this approach with optimised PV and battery sizing, together with dynamic tariffs and demand response strategies, can further improve the effectiveness of peak shaving and grid stability.

The direct benefits for grid stability and increasing capacity of these two solutions, combined or not, are flattening demand peaks caused by EV charging, managing excess generation in the form of storage (EV batteries) and increasing grid capacity using the energy already stored With controlled charging EV owners align their charging with the network needs (over-supply or under-supply). While peak load reduction is an important short-term objective, the longer-term goal is to align EV charging/discharging with renewable energy generation. The combination of smart charging and V2G enables EVs to charge when renewable supply is high and discharge during demand peaks, helping to flatten the load curve while supporting grid flexibility. For instance, on sunny or windy days, allowing high peak loads through coordinated smart charging can absorb excess renewable energy. When V2G is widely implemented, it can also provide valuable services such as backup power during outages and frequency regulation, demonstrating that system-wide flexibility rather than simply reducing peaks is essential for a resilient and renewable-powered future.

Some studies show that the combined effect of smart charging and V2G could reduce peak loads by 10-15% in 2030 and by 15-20% in 2035[60]. Nevertheless, the same studies consider that the possibilities of smart charging and V2G are not fully unlocked. Some barriers remain: lack of incentive from network tariffs, presence of financial disincentives within the current energy tariff structure while performing V2G/G2V (Grid to Vehicle), absence of an LV congestion market mechanism, lack of clarity over the possibility of DSOs to curtail charge points as a last resort, absence of a comprehensive communication standard between the DSO and the CPO/aggregator to enable smart charging, interoperability issues due to differences in standards (plugs, sockets, settlements, etc.). adopted by CPOs and original equipment manufacturers (OEM), lack of incentives (or potential penalisation) for digitalisation and grid modernisation within the DSO tariff regulation.

5.4 Optimisation of the charging process

Integrating V2G technology and advanced storage solutions represents a transformative approach to optimising EV charging processes[61], particularly within smart grid environments. According to the proposal to the amended Requirements for Generators Network Code (RfG NC), ‘V2G electric vehicle’ means a vehicle that is powered, entirely or in part, with electricity and is equipped with technology enabling the vehicle to inject electricity to the network over a V2G electric vehicle supply equipment. This definition considers all solutions, regardless of whether the V2G electric vehicle contains the inverter or not, providing a starting point to establish the most valuable flexibility measures.

Enabled by OCPP (Open Charge Point Protocol) 2.0, smart charging solutions can dynamically support demand-response initiatives, enhancing grid resilience and stability. Through precise management of EV charging, the grid can benefit from real-time adjustments, reducing strain on substations during peak periods while balancing energy needs across the network.

A key aspect of this optimisation involves the management of EV charging reservations. Its application can accurately forecast grid load requirements by implementing a reservation system. This approach allows for better allocation of charging resources, which provides flexibility where needed most, particularly at substations. Smart charging profiles, which dynamically adjust the maximum power output based on building and local energy demands, can also contribute significantly to this flexibility. This setup enables location-based reservations that encourage flexible EV owners to adjust their charging location based on the current grid load, further supporting grid stability.

On a complementary note, another study analysesdifferent scenarios of network expansion versus cross-system solutions to address electricity network challenges, such as EV penetration and its charging infrastructure. The study tries to compare various solutions with the traditional grid investment and network expansion. Implementation timeline, CAPEX, OPEX, and the lifetime of the required assets are the main constraints and will determine the costs of the solution. Demand-side flexibility and storage assets are one of the proposed cross-system solutions, especially in circumstances where the network reinforcement is in the process of completion. In this context, different stakeholders may be involved, and besides the traditional system operators, figures such as aggregators, charging station owners, and energy storage owners prove to be essential in all the interactions within this particular ecosystem. Successful business cases require that all stakeholders create, capture, deliver and share value, which will determine how these costs impact consumers and society. When EV users adapt their behaviour and decide to charge or discharge EVs using smart charging, they can generate extra revenue by charging when electricity prices are low and discharging when prices are high. According to some studies, those revenues can represent 7-13% of their charging costs[62]. In parallel, adequate regulations, remuneration schemes and availability of business collaborative platforms are essential to build a robust business case (Venizelou

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[60] Unlocking EV smart charging to reduce grid congestion - lessons from the Netherlands, Strategy&/ElaadNL, March 2024.

[61] Husam I. Shaheen, Ghamgeen I. Rashed, Bo Yang, Jun Yang, ”Optimal electric vehicle charging and discharging scheduling using metaheuristic algorithms: V2G approach for cost reduction and grid support, Journal of Energy Storage,

[62] Unlocking EV smart charging to reduce grid congestion - lessons from the Netherlands, Strategy&/ElaadNL, March 2024.

et al., 2023)[63].

V2G and smart charging will reduce risks and incentivise flexible EV owners to use recommended charging stations, promoting a symbiotic relationship between grid demand and EV availability. This system enhances grid resilience and encourages user participation in sustainable energy management. This approach demonstrates the potential for integrating V2G and storage solutions across the energy system. Utilising second-life batteries and V2G as complementary resources creates a robust and sustainable framework for peak shaving and load balancing, reducing operational costs while enhancing grid stability. The innovations highlight a sustainable model for EV fleet and storage management, emphasising minimal grid impact and maximising resource efficiency for long-term energy resilience.

The exploitation of storage capacity with local renewable energy sources is critical for the sustainable deployment of ultra-high power charging hubs. The increased power needs will consequently require high grid investment costs at distribution level. The key solution for such charging hubs, which serve the charging needs of several EV types, from light electric vehicles (LEV) up to heavy-duty electric vehicles(HDV), is the deployment of storage and local RES capacities to mitigate the high peak demands. Considering a fixed power capacity contract at the connection point, the served charging demand can reach higher levels, even up to 200% (see details for eC4D project in Chapter 6) given that the behind-the-meter resources serve the demand surplus.

6 APPLICATIONS AND BEST PRACTICES

This chapter summarises the details of some relevant European projects that are making significant progress in electric vehicle charging and discharging capabilities through integrating of electric mobility into electricity grids, in some cases combined with the use of storage for this process. Some of the examples have been mentioned and used as references in the previous chapters.

EV4EU project

EV4EU[64] is an ongoing project aiming to propose and implement bottom-up, user-centric V2X management strategies, creating the conditions for the mass deployment of electric vehicles. The strategies adopt a multi-criteria approach where different dimensions are considered, such as the impact on batteries, user needs, electricity system, integration with energy markets and transformation of cities.

As a relevant note, the penetration level of renewable energy sources is quite high in the Greek pilot project, which is a peri-urban area with industrial and residential consumers. The low voltage monitoring system developed by the Greek DSO helps to boost the exploitation of EV flexibility capabilities for efficiently integrating renewable energy sources and EVs into power grids. PPC, which is the largest CPO/EMSP in Greece, has developed and offered an EV and VEHICLE management platform called OPEN V2X for the public charging network. It promotes synergies between EVs and RES and enables the integration and deployment of new advanced EV charging mechanisms.

Furthermore, pricing and incentive-based schemes for demand response are considered in order to to motivate and help users to participate ininnovative V2X management schemes for different commercial applications (green charging, load sharing, dynamic pricing). Furthermore, flexible capacity contracts are promoted and demonstrated at a pilot level to mitigate network congestion issues.

As an example of how to demonstrate scalability and interoperability challenges, the Portuguese demo recently held a two-day event[65] to host user engagement sessions in which participants had the chance to test the project’s objectives and functionalities. The demonstration at Laboratório Regional de Engenharia Civil (LREC) included a controllable load, vehicle-to-building (V2B) integration, and service network functionality – all being tested under real conditions at the facilities. The testing phase is crucial to validate the system’s performance across various scenarios, including seasonal changes, user behaviour, and technical or economic variables. This use case will help provide insights into how the system performs when users rely solely on the project’s charging ecosystem.

Funded by European Union´s Horizon Europe research and innovation programme, EV4EU project materialises relevant parts of ETIP SNET’s R&I Implementation Plan 2025+[66]. Specifically, EV4EU aligns very well with Priority Project Concept (PPC) 8.2 “Enhancing

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[63] Venizelou, V., Tsolakis, A. C., Evagorou, D., Patsonakis, C., Koskinas, I., Therapontos, P., Zyglakis, L., Ioannidis, D., Makrides, G., & Tzovaras, D. (2023). DSO-Aggregator Demand Response Cooperation Framework towards Reliable, Fair and Secure Flexibility Dispatch. Energies, 16(6), 2815. https://www.mdpi.com/1996-1073/16/6/2815

[64] https://ev4eu.eu/

[65] https://ev4eu.eu/2025/04/09/ev4eu-promotes-user-engagement-sessions-in-the-azores/

[66] ETIP SNET R&I implementation plan 2025+, European Commission and ETIP SNET, 2023.

effectiveness of energy system operation and resilience with electromobility", which seeks to assess the benefits of smart control of different charging infrastructure in providing various system services through connecting EVs to IoT concept. It also seeks to incorporate uncertainties related to the provision of services by the transport sector, specifically considering V2G from private, fleet and public vehicles.

EV4EU project also presented some of their results of the Danish demo[67] at the 2025 ETIP SNET Regional Workshop on Northern Europe, including the development of the research charging cluster of Risø and Bornholm.

eC4D project

The EC4D project aims to design, develop and demonstrate user-centric charging technologies and services to promote and facilitate the market adoption of electric vehicles. The project focused on three domains: i) innovative charging technologies able to offer enhanced information during, before and after the charging session and support Plug-N-Charge service through ISO15118, ii) services to facilitate user accessibility to the charging network (booking and routing services) and to improve the charging experience (smart charging, microgrid concept with local storage and RES to mitigate the grid impact of ultra-high power charging centres and iii) decision support tools to efficiently (technically and financially) distribute the charging network and technologies (fast, medium, V2G, etc.) with a city or region taking into account user charging needs.

The demonstration results of V2G services at eC4D validate the potential of exploiting V2G capabilities for markets and grids. The smart management scheme provided promising results for parking areas at workplaces where parking time is sufficient, and PV production is high. For the microgrid approach for ultra-high power charging centres, the combined nominal power of the installed charging stations can exceed the maximum allowed grid power by at least 180%.

FlexCHESS[68]

As an application, smart charging, enabled by OCPP 1.6, can intelligently deliver dynamic demand response. Reservation is an efficient practice for managing and getting a more accurate forecast of grid needs and loads. Additionally, reservation management will allow flexibility to be provided where the grid needs it (substations).

First, smart charging will change the charging profile of connectors/chargers and the maximum power of the EV parking lot based on the consumption needed by the buildings. Next, location-based reservations will be updated for flexible EV owners to provide flexibility based on substation loads. In this pilot, EV owners will be rewarded if they accept recommended EV stations while allowing for greater grid flexibility and resilience.

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[67] https://evchargersrisoe.windenergy.dtu.dk/

[68] https://cordis.europa.eu/project/id/101096946

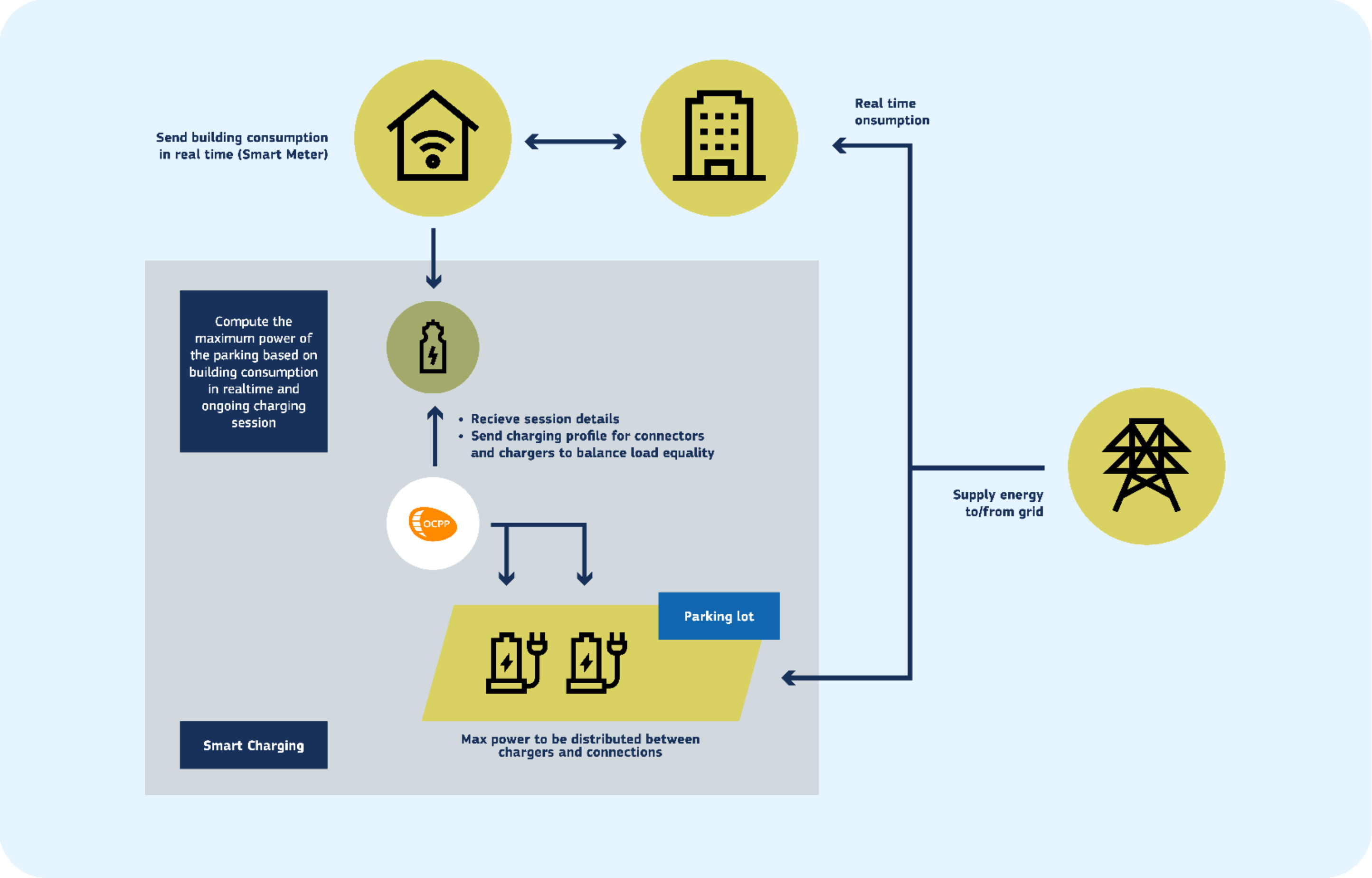

Figure 2 - FlexCHESS. EV community through smart charging for grid stability

Under the FlexCHESS initiative, smart charging technology is being employed to manage EV communities, mainly led by Elektro Ljubljana, contributing to grid stability by carefully balancing charging loads. By adjusting charging schedules and prioritising flexibility, fluctuating demands placed on the grid can be effectively managed. This approach highlights the potential of EV fleets to serve as a decentralised energy resource, dynamically responding to grid needs while maximising charging efficiency.

The FlexCHESS project has equally received funding from the European Union’s Horizon Europe research and innovation programme, and it is focused on advancing flexibility services through connected and interoperable hybrid energy storage systems, revolutionising how energy systems respond to the challenges of modern grids. This represents a good connection with ETIP SNET's focus on real-world innovation, specifically with parts of High-Level Use Case (HLUC) 8 "Transportation Integration and Storage", such as PPC 8.1 "Technical and economic implication of decarbonisation of transport sector" and PPC 8.2 "Enhancing effectiveness of energy system operation and resilience with electromobility".

Helios[69]

The HELIOS project also explores the potential of combining V2G (IREC-RDIUP) with second-life batteries to enhance flexibility services. IREC, in collaboration with RDIUP, aims to develop a proof-of-concept (POC) leveraging second-life batteries with different states of health (SoH) and chemistries. While the HELIOS battery pack may not reach the end of its second life during the project, a dual-chemistry configuration could offer significant advantages in second-life applications such as improved flexibility, extended service life, and tailored performance thereby strengthening the long-term value proposition of this concept (Helios, iBattMan[70] and NEVERFLAT[71]). When used as stationary storage, EVs can be charged via V2G technology, with model predictive control (MPC) algorithms managing the charge and discharge cycles. This coordination enables EVs to act as complementary power sources during peak consumption periods, alleviating pressure on the grid.

This approach can deliver frequency regulation and other flexibility services by interconnecting second-life batteries with multi-port converters, all with minimal grid reinforcement requirements. Furthermore, this setup provides a valuable buffer for ultra-fast

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[69] https://cordis.europa.eu/project/id/963646
[70] https://cordis.europa.eu/project/id/10113885
[71] https://cordis.europa.eu/project/id/101192973

charging stations (UFCS), as second-life batteries can store excess energy without negatively impacting EV charging performance. The combined use of V2G and second-life batteries reduces peak demand, overall energy storage, and lifecycle costs and it encourages sustainable energy practices.

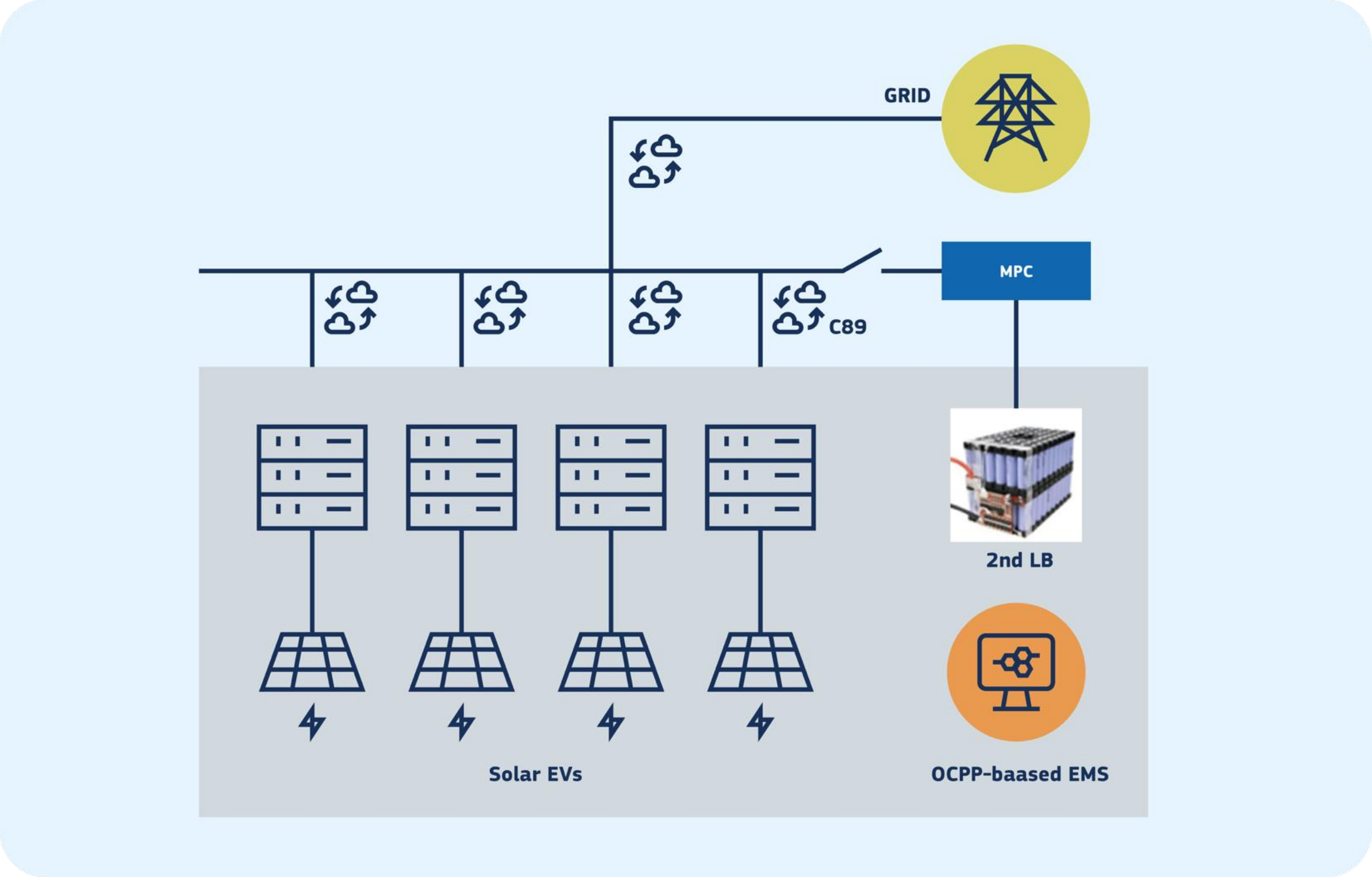

Figure 3 - HELIOS (Source IREC-RDIUP): Flexibility services via V2G and Second-life battery (2ndLB)

7 FINDINGS AND MESSAGES

7.1 R&D and Innovation needs

One of the primary purposes of this paper is to show the work carried out in European projects on integrating electric mobility into networks with the support of storage and V2G. Although the projects described in this document, and several others, demonstrate that solutions being developed to meet the goals in sustainable transport and EV integration, R&D efforts must continue to ensure such solutions are actually viable in economic and technological terms.

We consider it especially relevant to dedicate future resources to the following fields of research:

- Greater attention needs to be paid to developing to advanced AI-driven optimisation algorithms for real-time energy management, grid-aware charging, and predictive analytics to balance demand and supply dynamically;

- Promote research into hybrid storage systems, including second-life batteries and novel materials for high-efficiency energy storage, to improve grid stability and reduce infrastructure costs.

- ETIP SNET should prioritise standardising V2G communication protocols to enable cross-border interoperability between EVs, charging stations, and grid operators in order to ensure seamless integration. Scientific advancements in power electronics, bidirectional inverters, and smart grid architectures will enable more efficient energy flows and enhance the reliability of V2G systems.

- Additionally, studies on economic models and regulatory frameworks are needed to guide policymakers in implementing effective incentives and market structures that support flexibility, aggregation, and decentralised energy trading. A strong multidisciplinary approach combining electrical engineering, data science, economics, and policy research will be critical to driving innovation and overcoming existing barriers to large-scale deployment.

7.2 Policy and regulatory needs

The European Union continues to support sustainable transport and has recently set out its position, promoting new initiatives to maintain the path established in the EU Green Deal. Along this path, specific measures are necessary to avoid losing momentum:

- Establish recommendations and guidance for Member States to reduce connection times for electric vehicle charging points via developing a framework for combined development plans (transmission, distribution and charging infrastructure).

- Determine the conditions necessary to effectively implement anticipated investments, complying with the Action Plan for Grids and again in the recent Industrial Action Plan for the European automotive sector, and thus ensuring that future charging infrastructure needs are considered. A supportive regulatory framework for anticipatory investments should be established to provide appropriate incentives, which will ensure investment certainty and enable the adequate maintenance and development of the necessary network for the charging infrastructure.

- Promote the adoption of electricity retail contracts and tariffs offering dynamic pricing which financially incentivise smart charging.

- Encourage Member States to promote processes to consider distribution infrastructure that facilitates the connection of charging points as being of overriding public interest.

- Highlight user-centric solutions: emphasise user education strategies and incentives (e.g., battery health certifications for V2G participation) to address adoption barriers. As presented at the ETIP SNET Regional Workshop on Northern Europe, scaling up flexibility solutions depends on eliminating regulatory unclarity and fully implementing the necessary roles.

Table 1: Barriers and solutions

Barrier 1: Long connection times
Developing a framework for electricity infrastructure permitting
Considering electricity infrastructure as being of overriding public interest
Transmission and distribution development plans must consider charging infrastructure
Barrier 2: Insufficient grid capacity
Establishing a supportive regulatory framework for anticipatory investments
System operators are given appropriate incentives to develop and maintain the necessary network for charging infrastructure
Barrier 3: Smart charging adoption
Eliminating regulatory unclarity and implementing incentives for users, CPOs and SOs
Promoting user education strategies

From a more technical perspective on integrating electric vehicles into the electricity grid, a significant regulatory advance has been initiating modifications to the rules on requirements for connection to the generator grid (RfG) and demand connection (DC). The updated version includes definitions of V2G and V1G, proposing new requirements for electric vehicles and their supply equipment, and it emphasises the importance of adequately integrating electromobility to support grid stability.

While it represents a valuable step in the flexible use of charging and discharging processes, further detail and regulatory development will be necessary to achieve effective implementation, especially in the following areas:

- A harmonised framework for equipment certificates that SOs can use to validate the suitability and adequacy of the newly connected equipment (e.g., EN50549);

- Communication and interoperability standards widely recognised by all involved agents (e.g., OCPP 2.1 and ISO 15118);

- Mandatory certification schemes for V2G EVs and associated EV supply equipment (EVSE) to ensure rapid and consistent national integration of EVs in the electrical system.

7.3 Conclusions

- V2G can help to boost road transport electrification in cases where the business case is favourable, mainly for company cars in the current situation. Although there is moderate optimism for the near future, we must remain vigilant about the evolution of the V2G and its impact on the electricity grid in the medium and long term, as several uncertainties remain. These include the evolution of the use of second-life batteries, the feasibility of capturing electricity prices in the event of widespread implementation of V1G and V2G, the emergence of new local issues regarding grid stability, and the impact of new opportunities arising from autonomous vehicles.

- The transition to widespread EV adoption and sustainable mobility requires significant improvements to the electrical grid and storage infrastructure. Anticipatory investments by SOs are essential to accommodate unpredictable EV charging demand. Therefore, these investments must be correctly proposed in close coordination between the mobility sector and system operators. In this regard, national development plans based on the National Energy and Climate Plans are the right tool to achieve this integration.

- Studies highlight that battery storage, particularly four-hour systems, effectively mitigates grid strain from fast-charging stations. Additionally, integrating decentralised PV and batteries can reduce grid reinforcement costs and improve stability. Combining storage technologies enhances economic performance and energy efficiency in charging infrastructure.

- Smart charging and V2G technology offer the grids crucial flexibility, helping to flatten peak loads and manage excess renewable energy. However, their full potential remains hindered by regulatory, economic, and technical barriers, such as the lack of incentives for specific network tariffs, standardisation issues, and the absence of dedicated market mechanisms for DSOs. All possibilities must be considered, especially considering that V2G equipment is usually more expensive than the most common smart chargers, which poses an affordability problem for many users.

- Optimising EV charging through smart charging, V2G and storage integration can enhance grid resilience, reduce operational costs, and maximise energy efficiency. Advanced solutions like OCPP 2.0 enable real-time demand-response strategies, valley-filling techniques, dynamic load balancing, and better utilisation of second-life batteries. The deployment of ultra-high-power charging hubs could incorporate local renewable energy sources and storage in certain cases to mitigate grid investment costs while ensuring reliable charging services.

- Best practices from ongoing research projects such as Helios, FlexCHESS, and EV4EU projects demonstrate the feasibility of integrating EVs into smart grids, leveraging flexibility mechanisms (such as demand response) to enhance grid stability and promote sustainable urban transformation. These examples emphasise the need for coordinated policies, technological innovation, and market incentives to unlock the benefits of EV-grid integration.

- Battery performance and degradation: studies, tests and experiences clearly indicate that proper charging patterns can increase longevity and performance of the battery, definitely off-setting the higher wear and tear of its elements due to higher number of cycles typical in V1G and V2G; therefore there is no technical reason to withdraw product warranties by OEM in case of smart charging.

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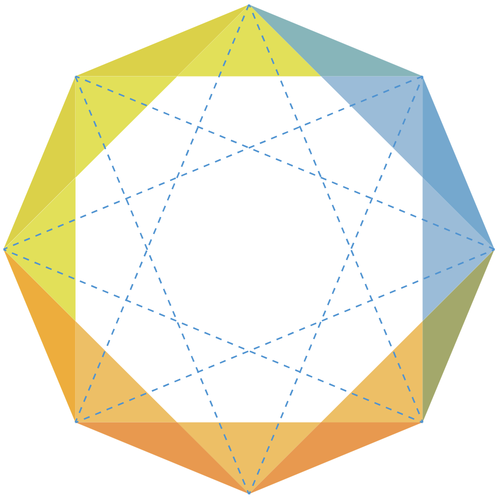

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