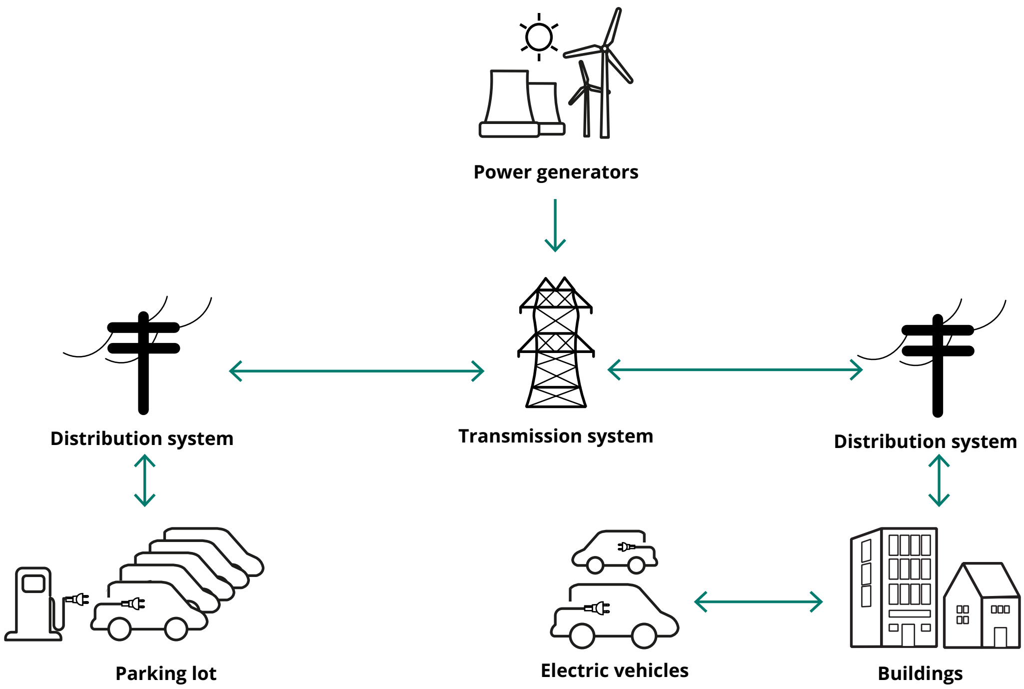
Annex 6
Vehicle-grid integration

Figure A6.1 **A simplified scheme showing the vehicle-grid integration concept**



Source: Ala et al. (2020).

A-S-I: improve (lower carbon content electricity generation and lower costs of and emissions from electric vehicles)

Context: integration between electric vehicles for road transport and the power grid

Time frame: medium to long term. Up until now, vehicle-grid integration has mainly been studied in field tests and research projects. The system still requires a greater uptake of vehicle-to-grid-enabled electric vehicles, the roll-out of the necessary infrastructure and further research, including on battery degradation.

A6.1 Definition

The term vehicle-grid integration (VGI) covers the systems in which electric vehicles (EVs) can communicate with the power grid and, in this way, render unidirectional or bidirectional services to it. The technology is also often called vehicle-to-grid or V2G (Elia 2022).

In the case of unidirectional vehicle-to-grid services or V1G, also known as 'managed (or smart) charging', the charging of EVs is controlled. This can involve, for example, delaying EV charging to avoid times of high power demand on the grid or throttling the charging rate to better accommodate grid needs (e.g. in the event of excess power generation by intermittent renewable energy sources).

In bidirectional vehicle-to-grid, or simply V2G, the EVs can return electricity to the grid in a controlled manner by means of specifically enabled bidirectional chargers. In this way, EVs can render additional services to the grid, such as frequency regulation, which is further described below. VGI could also be applied at a local scale, in vehicle-to-home (V2H), vehicle-to-building (V2B) or vehicle-to-everything (V2X) applications. In this case, the EV battery is used to store electricity produced on site or as a back-up power supply in the event of possible power failures.

VGI can be realised not only with battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs, albeit to a limited extent given the comparatively small capacity of their battery) but also by fuel cell electric vehicles (Oldenbroek et al., 2017). In the last case, the energy transfer is unidirectional, from the vehicle to the grid, with the former operating as a controllable power generator. To provide services to the electricity system, a minimum capacity is generally required. To achieve this, different assets can be pooled in a so-called single virtual power plant. This is enabled by digitalisation in the form of aggregators. These combine power electronics and control algorithms to collect data on connected EVs and the status of the grid and take or schedule charging and discharging decisions in real time for each connected vehicle based on grid needs and the boundary conditions in place (e.g. residual charge) (Krueger, and Cruden, 2018; Rancilio et al., 2022).

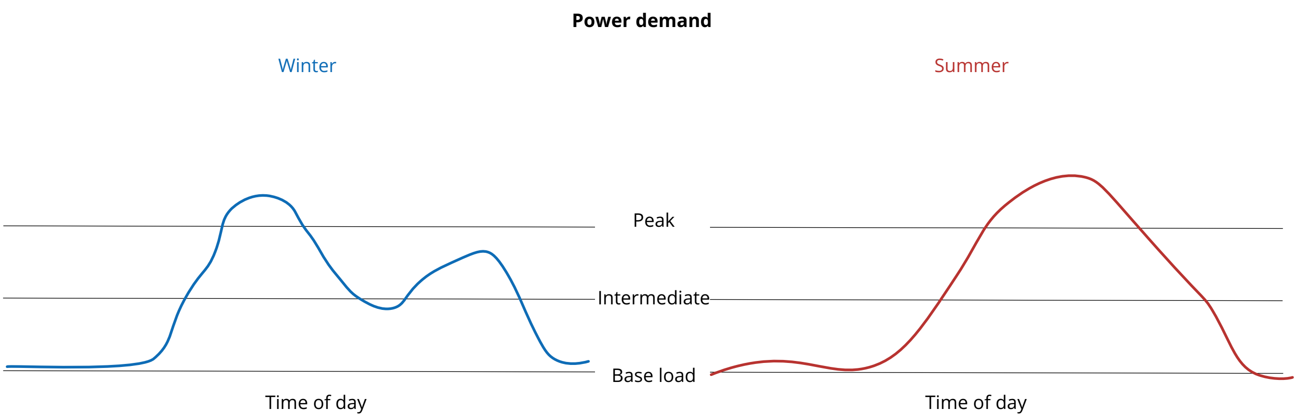
A6.2 Context

To better understand how VGI could impact the environment, it is necessary to have some understanding of the energy generation and distribution system and of the interactions between this and the ongoing electrification of the transport sector.

A6.2.1 The electricity system

Electricity is an energy carrier and is normally obtained from the conversion of other primary sources (e.g. solar and wind energy or nuclear and chemical energy in fuels) realised in centralised, large-scale power plants or in distributed smaller scale installations. This electricity can be immediately consumed, in the case of distributed installations (e.g. a photovoltaic (PV) panel mounted on the rooftop of a residential unit), or sold in an electricity market and distributed through an interconnected network often called a grid or power grid. In general, on a given grid over a span of time, it is possible to distinguish three different levels of demand: baseload, intermediate and peak load, as shown in Figure A6.2. The baseload is the minimum level of demand on an electrical grid over a span of time. This demand can be met by so-called baseload power plants, which run at almost constant output round the clock, or a combination of dispatchable power plants (which control their output within a specific range and that can be either renewable or non-renewable) and variable renewable electricity (VRE) sources (Ueckerdt, and Kempener, 2015). The above-base power demand (intermediate and peak demand) can be met by VRE sources and dispatchable generators, including energy storage. Peak power plants are often constituted by gas turbines operating on natural gas at lower efficiencies (approximately 30-40%) than those achievable in combined cycle gas turbine plants (approximately 64%). Electricity supplied during peak periods is sold at a much higher price per kilowatt-hour than that supplied to cover base load demand.

Figure A6.2 Example of the daily variation in power demand

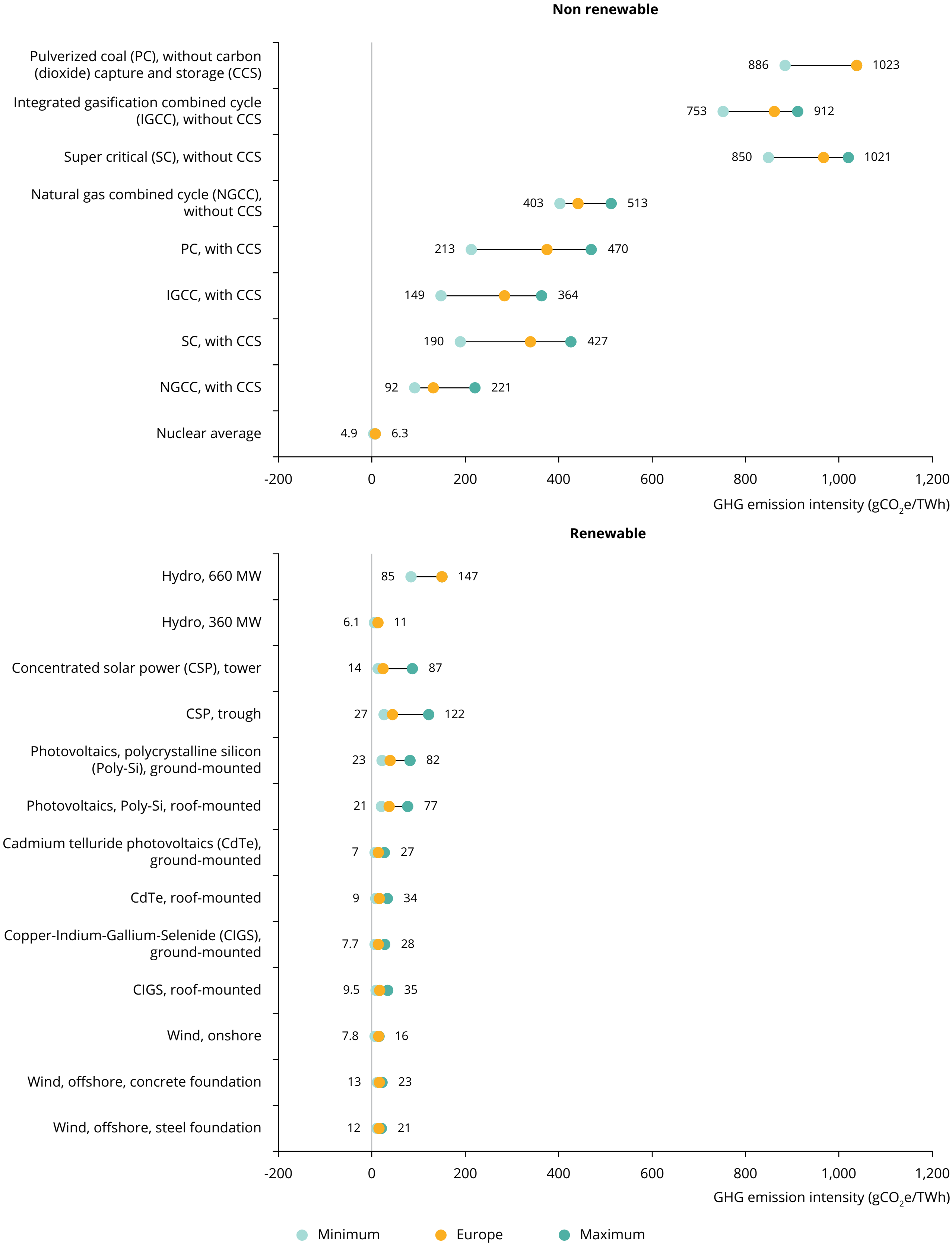


Source: Fedkin (2020).

Apart from providing electricity, actors operating within the grid can provide additional services. These are normally called ancillary services and are 'provisions necessary for the proper operation of a transmission or distribution system' (Electricity Directive, Directive (EU) 2019/944; (EU, 2019g)). These maintain grid reliability, balance supply and demand, and support the transmission and distribution of electricity from the seller (producer) to the buyer (consumer). With the growing share of VRE sources such as wind and solar PV the challenge of ensuring the stability of the power system increases. Given their variability, VRE need to be combined with dispatchable back-up capacity. The need for this could be reduced when a mix of solar and wind power is used, as their production time patterns can be different, or when energy storage is available. With VRE sources, deviations also occur between forecast and actual generation, which requires balancing the available power at short notice (Ueckerdt et al., 2015). The ancillary services thus become even more critical with a high share of VRE in the power generation mix.

In 2020, 37.5% of total gross electricity consumption in the EU-27 was from renewable energy sources (EC, 2022r). Wind accounted for 36% and solar for 14% of the renewable electricity production. Among other renewable sources, hydropower accounted for 33%, solid biofuels for 8% and the remaining 9% was from a range of other sources (Eurostat, 2022i). The average greenhouse gas (GHG) emission intensity of this power generation mix in the EU-27 was 230.7g CO_2e/kWh in 2020, which was 54% lower than in 1990 (EEA, 2022f). With the policies that were in place at the end of 2019, the share of renewables in electricity generation is projected to increase to about 60% in 2030 and 75% in 2050. In 2030, about half of renewable electricity should come from wind and one fifth from solar energy (EU Reference Scenario 2020, reported in EC (2021a)). With the RePowerEU plan, the European Commission puts forward a higher 2030 target at EU level for renewable energy (45% compared to 40%, as proposed in the revision of the Renewable Energy Directive) and the further strengthening of wind and solar energy (EC, 2022b). On 30 March 2023 the European Parliament, the European Commission and the EU member reached the provisional agreement on a legally binding target to raise the share of renewable energy in the EU's overall energy consumption to 42.5% by 2030. EU countries that choose to do so can complement this target with an additional 2.5% indicative top-up that would allow reaching 45% The potential of renewables to reduce GHG emissions by electricity generation is evident as shown in Figure A6.3. The United Nations Economic Commission for Europe has derived CO_2 emissions/TWh based on a life cycle analysis of different power generation technologies (UNECE, 2021). It is expected that, if the above-mentioned target is achieved, the overall average GHG emission intensity of power generation in the EU-27 will further decrease in the coming years. With the RePowerEU plan, the renewable energy share in the electricity sector would reach 69% in 2030 (EC, 2022s).

Figure A6.3 **Life cycle greenhouse gas emissions of power generation technologies in different regions of the world (gCO_2e/TWh), 2020**



Source: UNECE (2021).

A6.2.2 Electric vehicles in the EU-27

In 2022, about 12% of the newly registered cars and vans in the EU were BEVs, and 9.5% were PHEVs. The current share of EVs in the EU is still small (1.2% for BEVs and 1.1% for PHEVs in 2022) and distributed unevenly across Member States (EAFO 2023) , with only high-income countries in the top five in terms of EV share in the fleet (Sweden, Denmark, Netherlands, Luxembourg, Germany), while the share of EVs is very small in the countries with the lowest income per capita. In 2022, the highest share of EVs in the car fleet was recorded in Sweden: 9.7%. Outside the EU, Norway recorded a share of 25.7%. With the EU policy framework that was in place at the end of 2019 for the decarbonisation of road transport, the EU Reference Scenario 2020 projected a share of electricity in road transport of 2.7% by 2030 and about 12% in 2050 (EC, 2021a).

In the meantime the EU has further strengthened the CO_2 emission standards of cars and vans. By 2035 all new passenger cars and vans should have zero CO_2 emissions per kilometre at the tailpipe. It is expected that the regulation will further strengthen the uptake of EVs (Erbach, 2022; Goulding Caroll, 2022). However, the EC have also committed to prepare proposals to enable the registration of cars and vans exclusively running on carbon-neutral fuels after 2035. The impact assessment of the revised regulation indicated that the share of light-duty vehicles in electricity consumption could increase from 2.8% in 2030 to 11% by 2040. Over the period 2030-2050 the cumulative savings in petrol and diesel would amount to 1,100Mtoe (megatonnes of oil equivalent) compared to the baseline (EC, 2021w).

A6.2.3 Interactions between electric vehicles and the grid

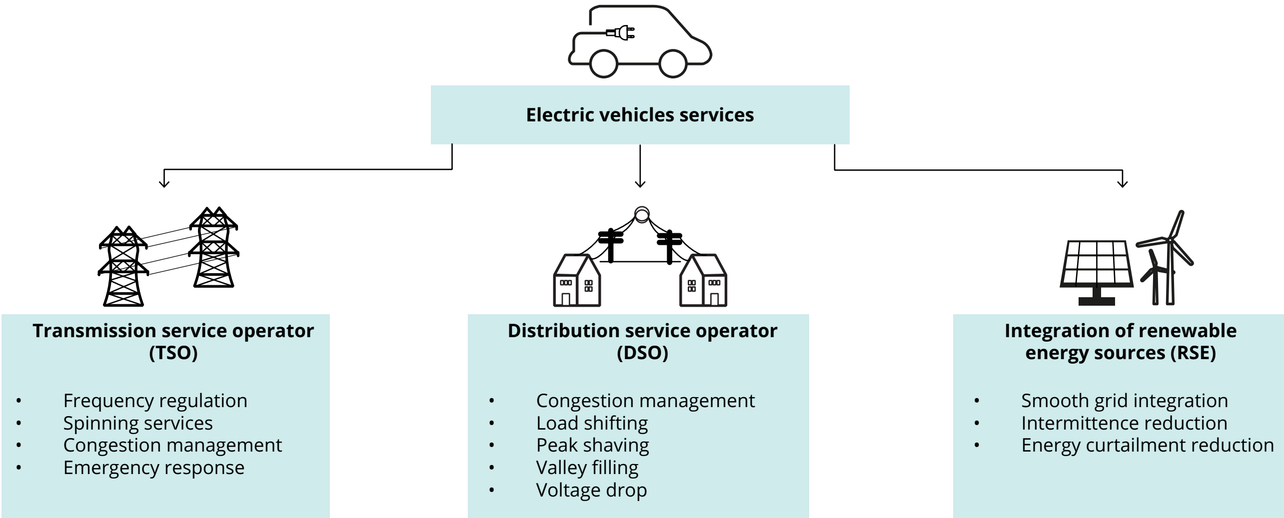
While contributing to the decarbonisation of road transport, the electrification of the road vehicle fleet will significantly increase the demand for electricity. The impact assessment of the CO_2 emission performance standards of cars and vans indicates that, with a high penetration of EVs, their electricity consumption could reach around 11% of total electricity consumption in 2040, compared to a share much below 1% in 2020 (EC, 2021w). If EV charging is unmanaged or managed incorrectly when the fleet becomes large, this can create additional challenges for the electricity system, including distribution grids (RTE, 2019). Most risks could be caused by two factors: the simultaneous charging of a large number of vehicles in the same area and/or coinciding with a peak in the electricity demand. Indeed, in a situation in which charging is unmanaged, it could be expected that many EV drivers will plug in their vehicles when arriving home in the late afternoon/early evening, when electricity demand is already high, thereby causing a substantial increase in peak load and saturation of the infrastructure. This could require the development of additional peak power capacity, nowadays less efficient and more GHG intensive, and the realisation of supplementary investment in the grid to accommodate the increasing peaks in the energy flows. Other impacts could be, for example, reduced voltage, overloaded electrical equipment and possibly power outages. Such impacts become larger when fast chargers are used rather than regular chargers (Cleary, and Palmer, 2019).

It is important to state, however, that EVs are used for only part of the day. Based on a big data analysis for a selection of European cities, Paffumi et al. (2018) conclude that the share of private vehicles that are being driven at the same time is never larger than 12%. During the day, the use of private vehicles peaks at three times: in the morning, at noon and in the evening, although the pattern is more prominent in some cities than others. A large majority of the private vehicles studied were driven less than 100km per day. This creates the possibility of using the batteries of EVs parked and connected to the grid as distributed storage and generator units. In this way, it is possible to support the power system and mitigate some of the challenges associated with considerable penetration of both VRE sources and EVs.

Figure A6.4 gives a general overview of the different services that EVs can provide through VGI. A distinction is made between services to transmission system operators (TSOs) and distribution system operators (DSOs) and services contributing to the integration of renewable energy sources. The TSOs manage electricity transmission, dealing with high-voltage grids, while DSOs manage electricity distribution (mostly dealing with medium- and low-voltage supplies to consumers' meters) (Prettico et al., 2021). Although it goes beyond the scope of this factsheet to dive into the details of each of these services, it is worth mentioning that Thompson (2018) indicates frequency regulation, i.e. the process of ensuring the balance of electricity supply and demand at all times, as one of the most attractive services that can be provided by VGI. This is because it requires an almost instantaneous response and little energy, while the market prices can be relatively high. EV batteries are well suited for this, as they can respond within seconds and have only limited capacity to provide energy to the grid (since their primary use is for driving). VGI services can also be provided by fleets of vehicles with known and regular schedules (Tomić, and Kempton, 2007), such as school buses (Horrox et al., 2022).

Figure A6.5 gives another overview of the services that can be rendered by VGI and also provides information on the timescale of these services (Muratori et al., 2021).

Figure A6.4 Electric vehicle services that can be provided to partners in power systems



Source: Reproduced with permission from Bañol Arias et al. (2019). © IEEE, 2019.

Figure A6.5 Summary of opportunities for EVs to provide demand-side flexibility to support power system planning and operations across multiple timescales

Smart electric vehicle-grid integration can provide flexibility — the ability of a power system to respond to change in demand and supply — by charging and discharging vehicle batteries to support grid planning and operations over multiple time-scales

Power system application	Generation capacity and transmission/ distribution planning	Resilience to extreme events	Seasonal planning (Hydro/long-term storage dispatch)	Commitment and dispatch decisions	Balancing and power quality	Support end customers
Time scale	Multi-year	Years (planning), hours (real-time response)	Months	Days and hours and sub-hours	Seconds to sub-seconds	Years (planning), hours (real-time response)
Vehicle-grid integration value	Ability to reduce peak load and capacity requirements and defer distribution systems upgrades if reliable EV charging flexibility is available	Load responses to natural events (heat waves, tornados) or human-driven disasters, load postponement over days, and support microgrid management and grid restoration (V2G)	No role for EVs	Leverage EV charging flexibility to support supply dispatch and load-supply assignement (tariff management), variable renewables, inegration, operating reserves, energy arbitrage (V2G)	Provide voltage/ frequency regulation and support distribution system operations	Tariff management (e.g. mitigate retail demand charges), complement other distributed energy resources (smart load, generation and storage), and minimise equipment ageing/upgrades

Source: Reproduced with permission from Muratori et al. (2021). © IOP Publishing Ltd 2021.

A6.3 Time frame

VGI is expected to contribute to decarbonisation in the medium to long term, although the possibilities offered by the technology have been already extensively demonstrated at the pilot scale. This is mostly because currently the number of EVs is still limited and the VGI-enabled infrastructure is lacking, but the potential of VGI increases as the number of EVs increases. In addition, to facilitate acceptance among final users, the range of EVs needs to be sufficiently large or not significantly affected by the provision of VGI services.

In Denmark, in the framework of the Parker project (Andersen et al., 2019) which ran from August 2016 to July 2018, the following main results were demonstrated: (1) the EVs studied in the project (PSA, Mitsubishi and Nissan) and the infrastructure and digital technology used were able to support V2G and to provide advanced services to the grid; (2) the technology can be brought to the market to provide frequency regulation; (3) the battery degradation experienced by the EVs used and under the project conditions was limited; and (4) providing VGI services can be economically attractive for the end user. Further steps need to be taken to put in place a system that can cover all EV brands, standards and markets. The system cost also needs to be brought down.

In 2021, the *Vehicle to grid Britain* report, aiming to assess the long-term viability of VGI in the United Kingdom, was published (ElementEnergy, 2021). One of the findings of this Energy Systems Catapult project is that residential V2G charging can be economically viable in the short term if a number of conditions are met: high plug-in rates, lower installation costs of the metering equipment, the combination of revenues from different services, and the potential to switch easily between these revenue streams.

In 2021, a stated preference survey about the willingness of vehicle owners to participate in V2G in Belgium (Vanpée, and Mayeres, 2022) showed that unfamiliarity with the concept still represents a barrier. Moreover, the respondents were found to be unresponsive to the financial compensation that was presented to them in the choice experiment: annual savings in their electricity bill ranging between EUR 25 and EUR 120 in combination with a one-time compensation that ranged from zero to EUR 1,000. The only contract specification that was found to be statistically significant was the minimum driving range guaranteed by the V2G contract, which positively influences the likelihood of supplying V2G services. VGI is currently being actively researched outside the EU, with examples such as the Los Angeles Air Force Base vehicle-to-grid pilot project (Black et al., 2018) and the METI project in Japan (Nuvve, 2019).

A6.4 Expected environmental effects

Using the taxonomy set out in Chapter 3 the following higher order environmental effects of VGI can be identified.

A6.4.1 Indirect impacts — efficiency effects

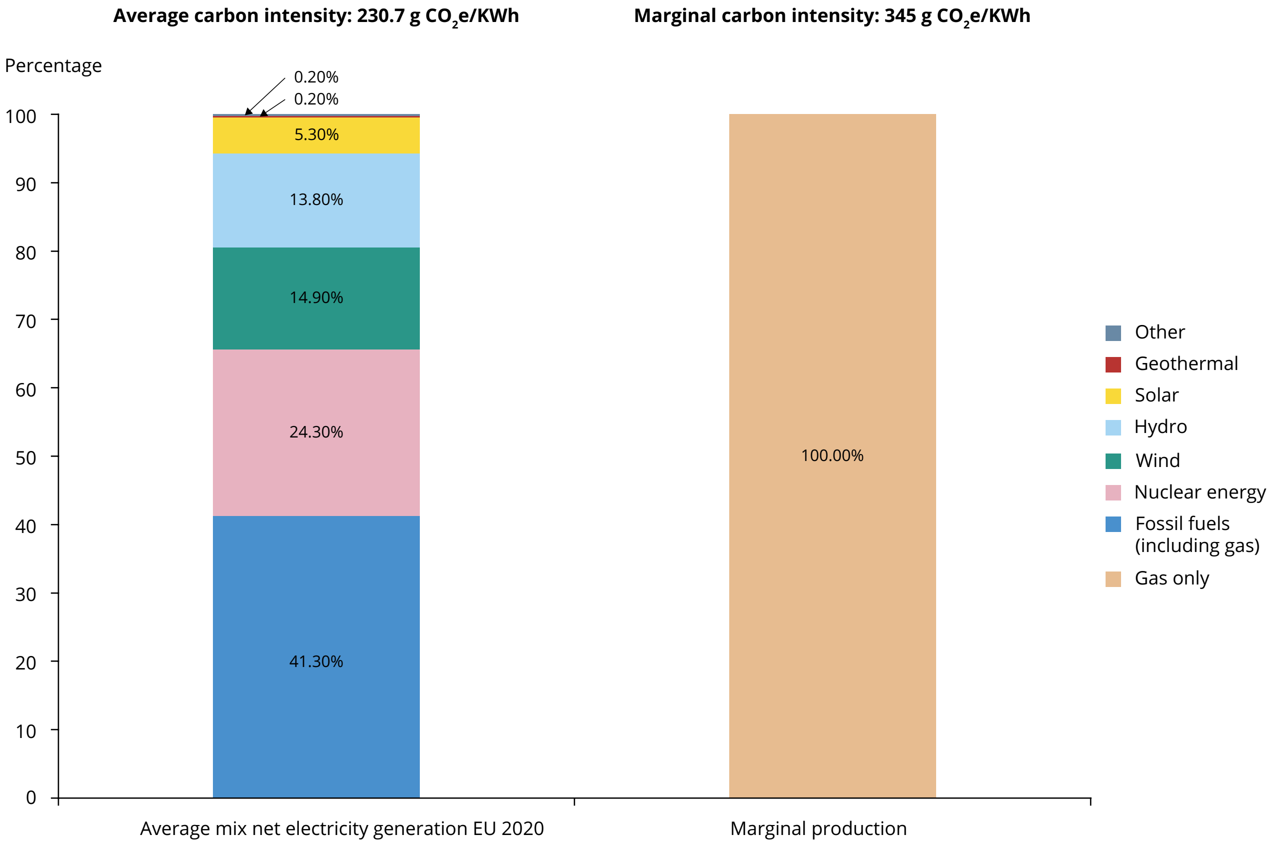
VGI can help to reduce the environmental impacts of the transport sector in various ways. It can promote the uptake of EVs by reducing their total ownership costs and their well-to-tank emissions. In addition, it can increase the use of VRE sources and better exploit existing infrastructure in the electricity system.

Various pilot projects have shown that VGI could decrease the cost of ownership of an EV by providing an economic benefit to the end user willing to provide ancillary services to the network. Total estimates vary considerably, depending on the number and magnitude of services provided to the network and on the local policies in place and the market structure. In Denmark (Andersen, et al., 2019), for example, estimated yearly revenues for providing bidirectional frequency regulation for 14 hours a day through a 10kW charger may vary between EUR 1,700 and EUR 2,500 per car. In the case of unidirectional regulation, such revenues decrease to EUR 680-700 yearly per car. In the United States, the pilot project led by the University of Delaware indicated that the yearly gross revenues generated from selling frequency regulation services for 19 hours a day to the network at 10kW could be up to USD 2,000 per car (Kempton, et al., 2008). In the US context, where diesel prices are relatively low, the results from a Blue Bird Corporation project indicate that VGI can reduce the total ownership costs of electric school buses to levels comparable to the diesel buses (Moore, 2021). VGI thus has the potential to significantly reduce the overall expenses associated with owning an EV. In parallel, a successful implementation VGI will require a diffused bidirectional recharging infrastructure to achieve effective EV participation. Both these aspects are regarded as essential to increase the uptake of EVs. It should also be noted that, with an increase in the uptake of VRE sources, the availability of frequency regulation services, as well as other ancillary services normally provided by conventional installations, will be reduced. The first case study below indicates that in order to successfully provide this service the EV fleet needs to be sufficiently large and that the benefits increase as the share of VRE sources increases and fall if the initial level of flexibility in the system is already high.

VGI can be used to optimise the charging time of EVs to minimise their well-to-tank emissions of both air pollutants and greenhouse gases. In the short term, an uptake in electrification of vehicles could, if not well managed, potentially lead to an increase in the peak power demand, which is normally covered by fast reacting gas power plants operating at suboptimal efficiency. In this framework, consuming an additional unit of energy will have a different impact depending on the moment at which that unit is produced, as shown in Figure A6.6.

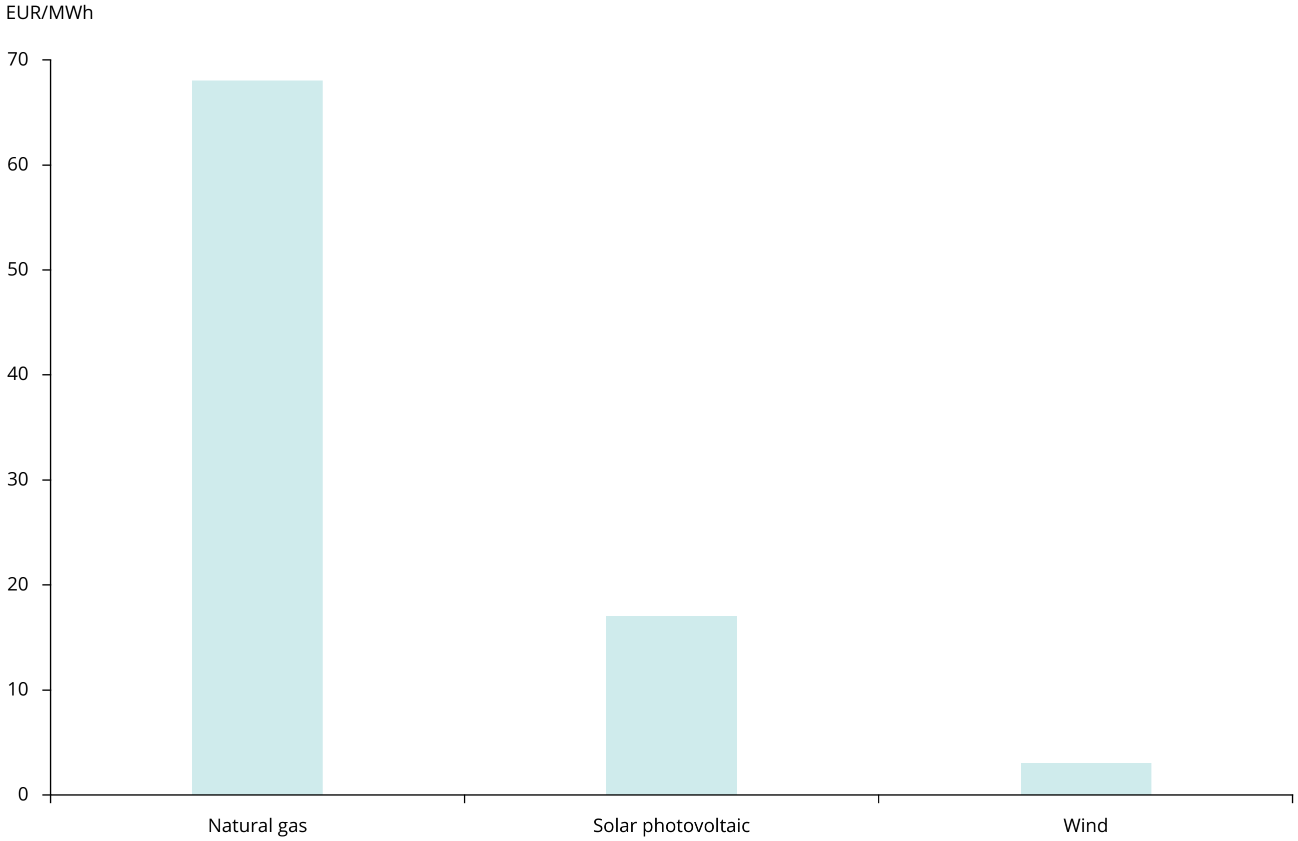
In the ideal case, in which it is possible to shift 1MWh of energy produced during peak hours from natural gas to the same amount but produced from renewables, by managing EV charging well, significant environmental benefits could be achieved, as shown in Figure A6.7.

Figure A6.6 Average versus marginal greenhouse gas emission factors for electricity generation



Source: EEA compilation based on EEA (2022f), Eurostat (2022j) and Scarlat et al. (2022).

Figure A6.7 Environmental costs of electricity production (EUR/MWh)

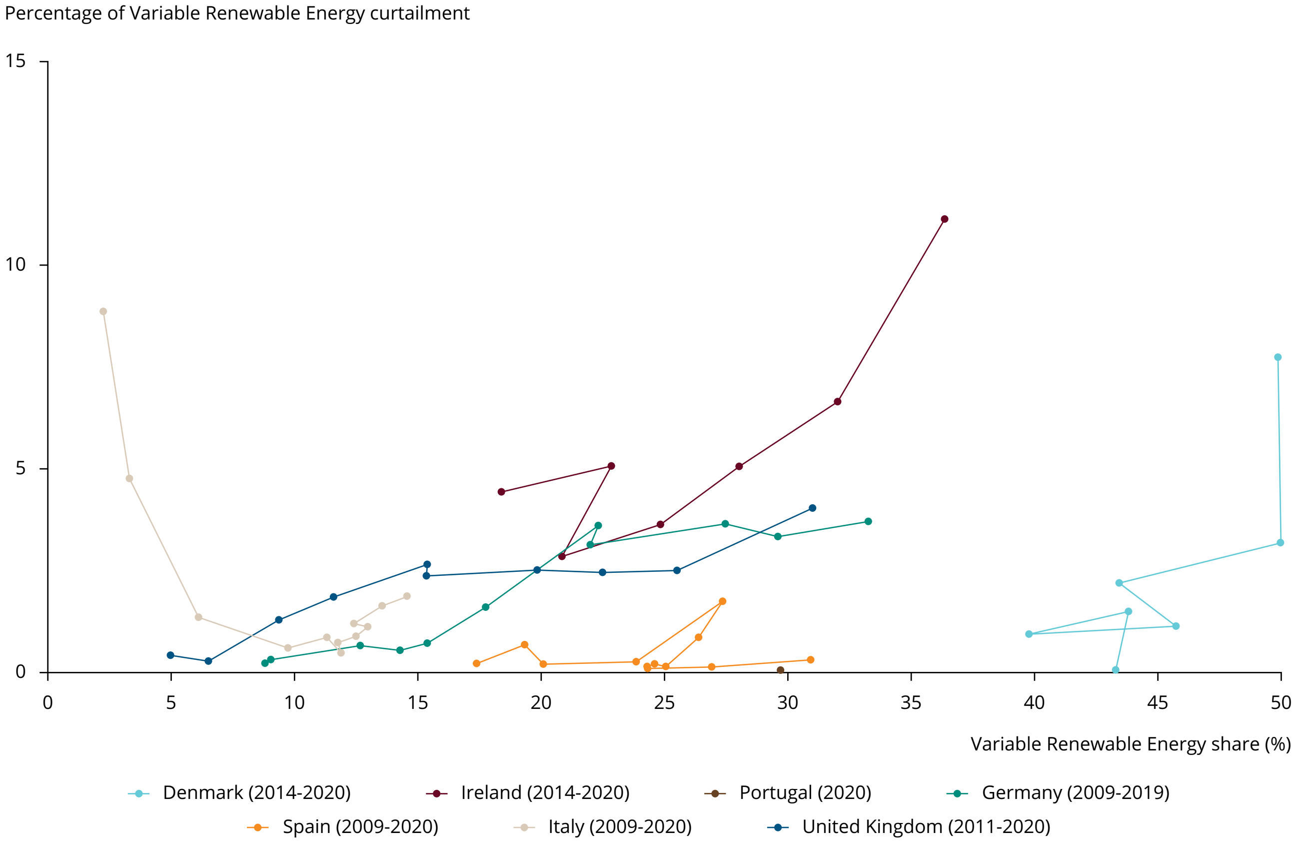


Note: Natural gas is a combination of combined cycles and open gas turbines. Wind is both on shore and off shore.

Source: EC (2020f).

Figure A6.8 gives an overview of the curtailment rate (i.e. the deliberate reduction in the power output of a power generator in order to balance supply and demand or due to transmission constraints) in a selection of European countries and its evolution over time, together with the trend in the share of VRE. The curtailment rate is presented for a combination of wind and solar sources. In general, the solar curtailment rate is smaller than that of wind, as wind power plants are larger and easier to control. The curtailment rate varies between the countries considered, depending upon their energy mix, grid conditions, policies and regulations, operational practices, and the evolution of these factors over time. In some countries, the curtailment rate is non-negligible, indicating that there is potential for VGI to reduce the GHG emissions from electricity by improving the use of the intermittent renewable electricity sources. Generally speaking, by adjusting the charging of EVs it is possible to better exploit the availability of such sources by closely matching production and consumption profiles. In this framework, EV batteries could be used as controllable loads and could be charged at moments where an excess of energy is available. This could in principle reduce the curtailment rates of renewable forms of energy, increasing their use and possibly reducing transmission bottlenecks (CAISO, 2022). This could also be used to increase the self-consumption of energy generated by rooftop PV or other distributed VRE installations, reducing congestion and grid-related costs. Ultimately this would lead to a reduction in the GHG emissions from electricity generation. Indeed, the renewable energy stored in the EV battery could be either used for driving (thus with very low emissions, as also shown in Figure A6.3) or returned to the grid during periods of peak demand or to deal with the intermittent nature of solar and wind power generation, thereby reducing the need for electricity sources with a higher environmental impact.

Figure A6.8 **Curtailment rate: energy share map of variable renewable electricity sources in selected European countries**



Source: Yasuda et al. (2022).

Lastly, it is important to state that with the EU Emissions Trading System (EU ETS), any changes in the GHG emissions of power generation will be compensated for by the other entities under the EU ETS, while the cap — which decreases over time — must be respected. When the GHG emissions from power generation drop, thanks to V2G deployment, this means that emission rights become available to other entities covered by the EU ETS.

A6.4.2 Indirect impacts — efficiency effects related to battery degradation

The environmental benefits of VGI may be counteracted by the environmental costs related to battery degradation. EV batteries slowly degrade over their lifetime as a result of two phenomena: calendar ageing and cycling ageing. The first mechanism takes place when the battery is at rest. It mainly depends on temperature and state of charge (SOC). The higher the ambient temperature and the SOC, the more relevant it becomes (Wang et al., 2016). The second mechanism takes place when the battery is being used. Here temperature, charge/discharge rate and energy throughput are the relevant parameters (Wang, et al., 2016; Thompson, 2018).

It is conventionally assumed that EV batteries will reach their the end of their life and be no longer suitable for driving applications once they have lost 20-30% of their original storage capacity (Wang, et al., 2016). However, other research has challenged this assumption, showing that driving performance will not be significantly impacted even at 30% residual capacity (Saxena, et al., 2015). It should also be considered that, once batteries are no longer suitable to meet driving needs, they can still be used in stationary applications before being recycled or decommissioned (Zhao, and Baker, 2022).

In general, unidirectional VGI, in which charging periods are adjusted according to the needs of the grid, is expected to have a very limited additional effect on battery degradation (Wang et al., 2016). Several studies have provided quantitative estimates of the additional degradation induced by providing bidirectional VGI services and, in particular, frequency regulation and peak shaving.

Wang et al. (2016) showed that the extreme case of providing systematic peak shaving services to the grid, every day between 19.00 and 21.00 for 10 years, could result in significant additional degradation of the battery, up to 5-14% more than the baseline case and depending on the charger used (1.44kW vs 7.2kW). In the worst-case scenario, total battery degradation could be above 45% after 10 years. 30% battery degradation could be reached after 6-7 years in this case, depending on the conditions. However, in a more realistic situation in which V2G services are supplied only on a limited number of days when the grid needs them most, the additional battery degradation is minimal. In the case of frequency regulation, assuming that the service is provided daily between 19.00 and 21.00 for 10 years, the simulated additional loss of capacity will be approximately 3.6% compared to the baseline under the hypotheses used (Wang et al., 2016).

A modelling study based on the environmental conditions, driving patterns and network performances recorded during a whole year in Bornholm, Denmark, indicates that the additional battery degradation due to the provision of 14 hours of frequency regulation with a ±9kW bidirectional charger every day for 5 years is 2% (Thingvad, and Marinelli, 2019).

In the Danish Parker project, Thingvad et al. (2021) studied the evolution of the battery capacity of 10 Nissan e-NV200 electric vans that have provided frequency regulation with 10kW chargers for 5 years. After 2 years the usable battery capacity was reduced by 10% and after 5 years by about 18% due to the combined effect of driving and providing the service. A battery degradation model assigns one third of this capacity loss to the additional cycling due to VGI and the rest to normal ageing.

The literature also suggests that the degradation of batteries supporting VGI can be limited if certain conditions are satisfied (Wang et al., 2016; Uddin et al., 2018; Zhao et al., 2022). According to Uddin et al. (2018), a smart control algorithm could be developed that controls access to the energy stored in the EV battery such that the longevity of the battery is not reduced. Good battery prognostic models are essential for this, and further research is needed on the factors playing a role in battery degradation.

If VGI leads to faster degradation of batteries, then the environmental impacts of earlier replacement of batteries needs to be taken into account. These environmental costs include GHG emissions, but also other costs such as human toxicity, ecotoxicity and material depletion (Díaz-Ramírez et al., 2020). Case study 6.2 on the environmental impacts of EV batteries illustrates the potential magnitude of such effects. Other uses of EV batteries could also help lower the environmental impacts, such as battery swapping and reusing end-of-life EV batteries (Mobilize, 2021; Zhao et al., 2022), as discussed in the same case study.

A6.6 Policy corner

In the Parker project, Andersen et al. (2019) provide a general assessment of the barriers to V2G in Europe and national barriers in four European countries, using the Pestel framework as shown in Figure A6.9, which considers the political, economic, social, technical, environmental and legislative dimensions.

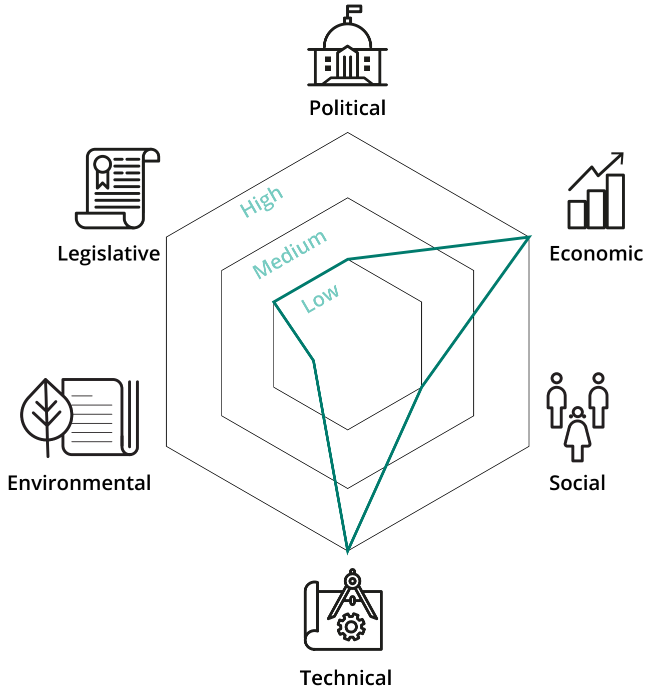
For Europe as a whole, the most important barriers identified in 2019 were economic and technical, while others were assessed to be of lower importance. The main general barriers are the lack of V2G infrastructure and its cost (Andersen, et al., 2019; ElementEnergy, 2021), the uncertainties about the extent of battery degradation, and the still limited number of V2G-capable EVs.

At the national level, the type of barriers and their magnitude varies widely across European countries. Additional obstacles to the large-scale adoption of VGI could be:

- the uptake of other systems that provide similar services (e.g. stationary battery storage);
- regulatory barriers, the lack of a market framework and international standards, and also aggregator services (Bañol Arias et al., 2019);
- possible conflicts of interest between TSOs and DSOs (Bañol Arias et al., 2019);
- the general public's lack of familiarity with V2G (Vanpée, and Mayeres, 2022).

The existing and proposed policies for decarbonising road transport and power generation in Europe have consequences for the potential of and the need for VGI: the number of EVs is expected to increase substantially and further growth in VRE sources will increase the need for grid-supporting services. By targeting regulatory barriers and possible conflicts between different actors in the electricity system, policymakers can create a policy framework for overcoming them. There is also a need for an appropriate policy framework for creating a market for V2G services. To bring down the system costs and understand and resolve issues regarding battery degradation due to VGI will also need further R&D financing.

Figure A6.9 Barriers to the provision of V2G services in Europe — Parker project, 2019



Source: EEA compilation based on Andersen et al. (2019).

A6.6 Bottom line

VGI can support both considerable EV penetration and a large deployment of VRE sources, contributing to the decarbonisation of both the transport (by reducing the well-to-tank emissions of EVs) and the electricity system. VGI has the potential to strengthen the link between the energy and transport sectors, creating opportunities for synergies and underlining the need for the sustainable transition of both sectors to progress in parallel. This potential increases with the increasing share of VRE sources but becomes smaller when other providers of such services are present. In addition, the compensation that EV owners can earn by providing VGI services reduces the total cost of ownership of EVs, which can contribute to the uptake of these vehicles. VGI systems should, however, be operated in such a way that battery degradation is minimised, when compared to the situation in which no VGI services are provided, and the environmental costs associated with earlier battery replacement are avoided as much as possible.

A6.7 Case study 6.1: E4Future project

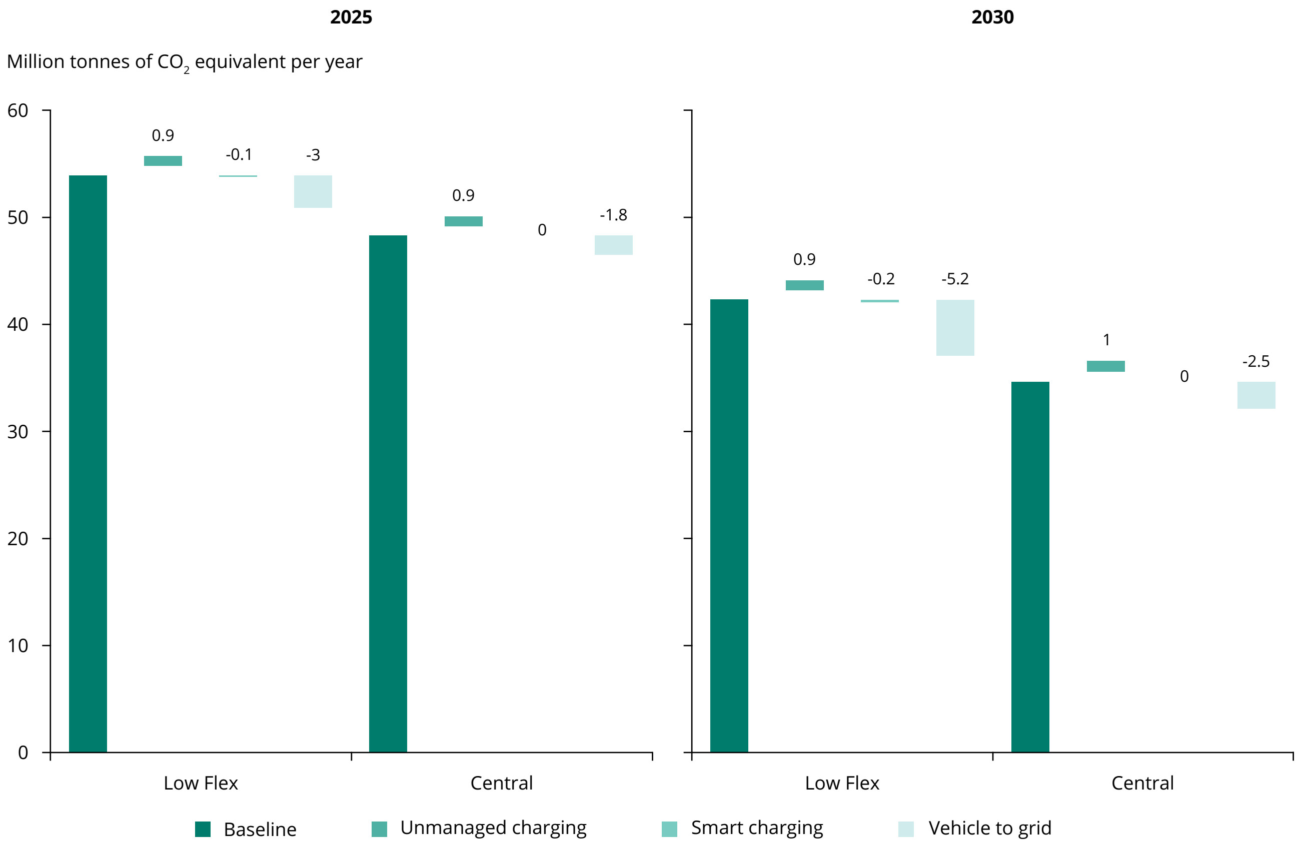
Aunedi and Strbac (2020) simulate the carbon emissions of the UK power system in 2025 and 2030 using the WeSIM model. They consider two different cases for system flexibility, in terms of the importance of energy storage and demand-side response (DSR). The former is expressed as the share of electricity generated that can be stored, while the latter refers to changes in electricity consumption patterns by users following a signal or incentive. In particular, the authors assume:

- low flex case: storage limited to 3-4% of power generation and no use of DSR;
- central case: storage equals 10% (2025) to 13% (2030) of power generation and the penetration of DSR is 25%.

For these two cases, the study compares the baseline, in which there are only private EVs and no fleet EVs, with three scenarios with a large number of fleet EVs in addition to the same number of private EVs as in the baseline. Fleet EVs are studied because their schedules are more regular than those of individual private EVs. All three scenarios assume 1 million fleet EVs, but consider different charging regimes: unmanaged charging, smart charging and V2G operation. With smart charging (also known as unidirectional vehicle-to-grid, V1G) the electricity demand from EVs is shifted from the peak period to the night-time, taking account of constraints on the state of charge. In the V2G regime vehicles also provide frequency regulation services to the grid.

Figure A6.10 shows the simulated impact of the different charging regimes on annual CO_2 emissions from the power system. In the baseline scenario the emissions fall between 2025 and 2030 due to the higher penetration of renewable electricity sources, with an almost constant level of electricity demand. The baseline emissions are lower in the central case than in the low flex case because of the higher flexibility of the latter to make better use of the renewable electricity sources.

Figure A6.10 **Carbon emissions in the UK power system in 2025 and 2030 under different flexibility and EV charging scenarios**



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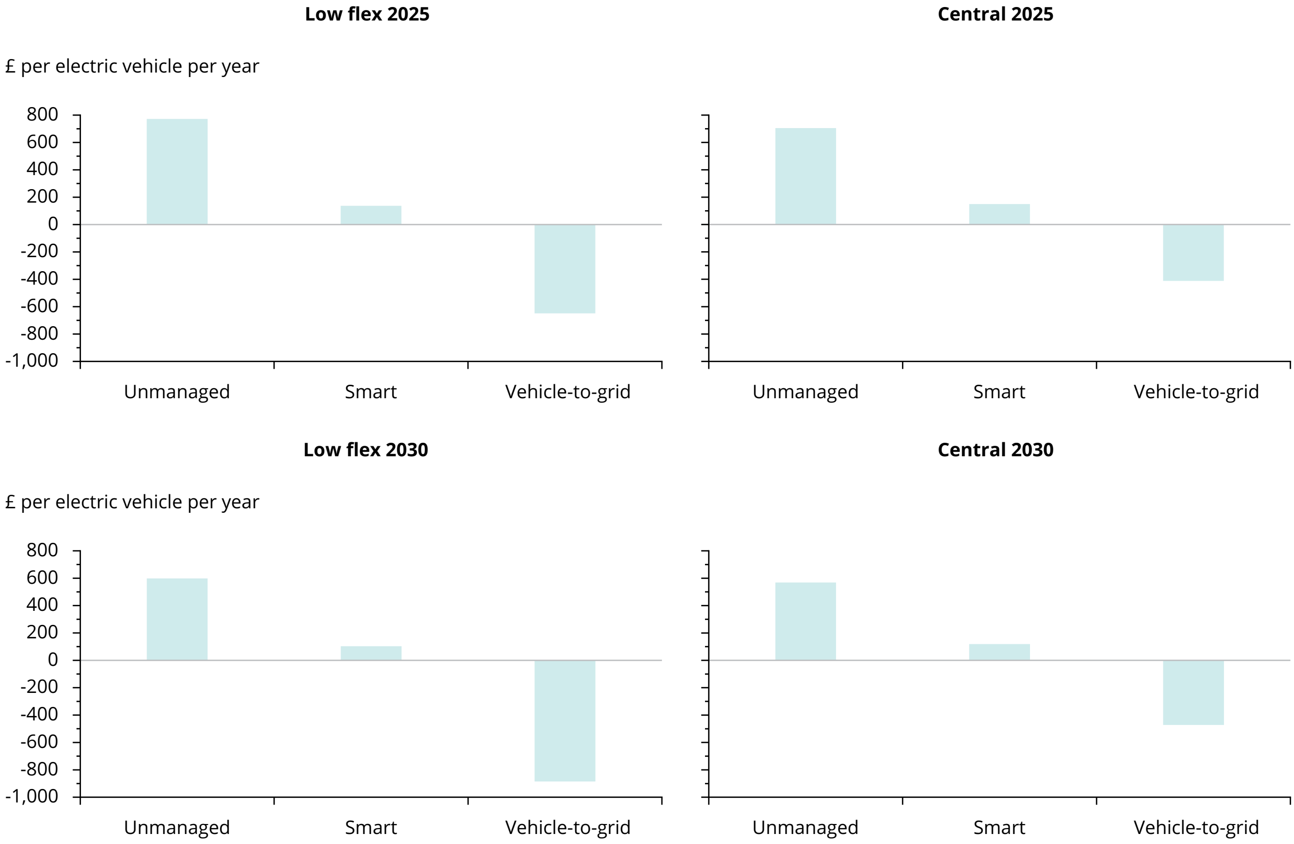
Unmanaged charging of the fleet EVs leads to an increase in carbon emissions. Charging EVs leads to higher peak demand, which is met by additional peak gas power plants. With smart charging this increase can be essentially avoided. With V2G carbon emissions can be further reduced below the level of emissions without fleet EVs. This is because V2G allows the carbon emissions from frequency regulation to be reduced by reducing the need for more CO_2-intensive generators and allows better integration of renewable electricity sources (less curtailment of these sources). In 2030 the potential reduction in carbon emissions is higher, as the share of renewable electricity sources is higher.

In a power system with central flexibility (central case) the reduction in carbon emissions thanks to V2G is about half that with lower flexibility (low flex case). This is because in the former case there is less opportunity to support the power system, as other sources of flexibility are also available.

The carbon emission reductions realised by V2G also mean that fewer renewable electricity installations need to be built to meet the decarbonisation targets of the power system.

Considering the costs, accommodating 1 million fleet EVs with unmanaged charging leads to significant additional system costs as shown in Figure A6.11, with the main share being due to the additional generation capacity that is required. Moreover, more distribution capacity is needed, and the operational costs also increase. With smart charging these costs are reduced substantially: only a small increase in generation capacity is needed and no extra distribution capacity. With V2G the system cost is lower than in the baseline. This is because even less generation and distribution capacity is required. Moreover, the operational costs are reduced, as 50% of frequency regulation is no longer provided by fossil fuel plants and there is also less curtailment of renewable electricity sources.

Figure A6.11 Additional system cost of supplying electricity to fleet EVs in the United Kingdom in 2025 and 2030



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The life cycle environmental benefits of the above-mentioned changes in investment and operational costs are not considered in the study, nor does it consider the additional costs and environmental impacts of the V2G system itself or those related to battery degradation.

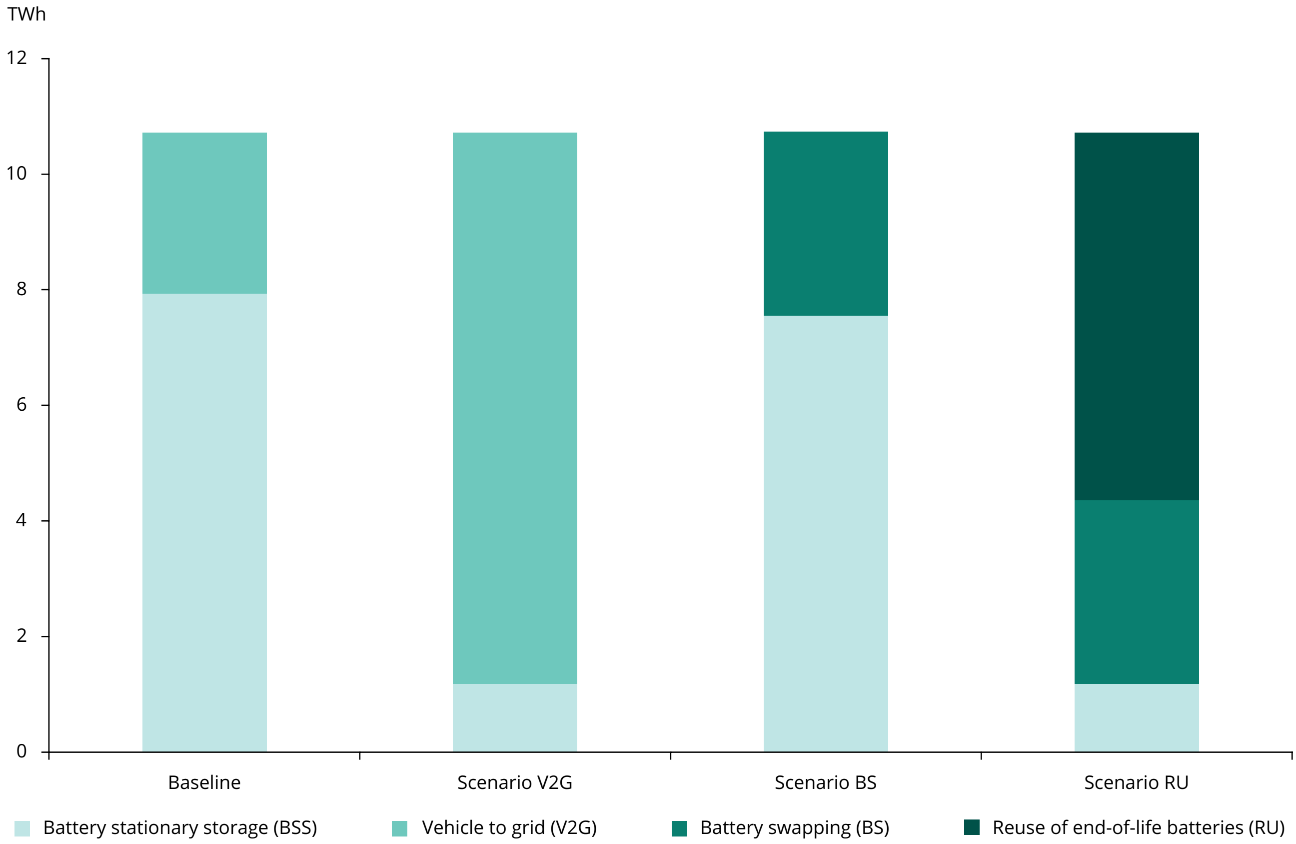
A6.8 Case study 6.2: Environmental impacts of using EV batteries as storage — a case study for the United Kingdom

Zhao and Baker (2022) shed light on the life cycle impacts of GHG emissions of VGI provision and the role of battery degradation. They study EV battery degradation using the model of Wang et al. (2014) and a model using stationary batteries for storage by Schimpe et al. (2018). Zhao and Baker's study is a life cycle analysis of different energy scenarios for the United Kingdom in 2050.

The baseline scenario is a low-carbon scenario for 2050 in which solar and wind energy are combined with storage to balance supply and demand. In this scenario the share of fossil fuels is only 2%. Smart charging applies for 78% of EVs (for a total of 31.7 million EVs) and 14% of EVs render V2G services. Battery storage accounts for 2.4% of electricity demand, delivering 10.7TWh, with the main share provided by stationary batteries, as shown in Figure A6.12. Zhao and Baker consider three other scenarios for 2050, as shown in Figure A6.12: in the V2G scenario most of the battery storage is provided by V2G, without reusing end-of-life batteries for storage. In the battery swap scenario stationary batteries are combined with battery swapping. In the battery reuse scenario end-of-life EV batteries are reused to provide the main share of storage services. No V2G is assumed in this scenario.

The upper panel of Figure A6.13 shows that in the baseline, GHG emissions per kilowatt-hour are projected to be substantially lower than in 2018. Part of the remaining GHG emissions is linked to V2G. Increasing the role of V2G in 2050 as in scenario SV2G, increases the GHG emissions from a life cycle perspective by 16% compared to the baseline. With battery swapping and reuse of end-of-life batteries, the GHG emissions per kilowatt-hour are 2% lower than in the baseline.

Figure A6.12 Battery storage in the different scenarios for the United Kingdom in 2050



Source: EEA compilation based on Zhao and Baker (2022).

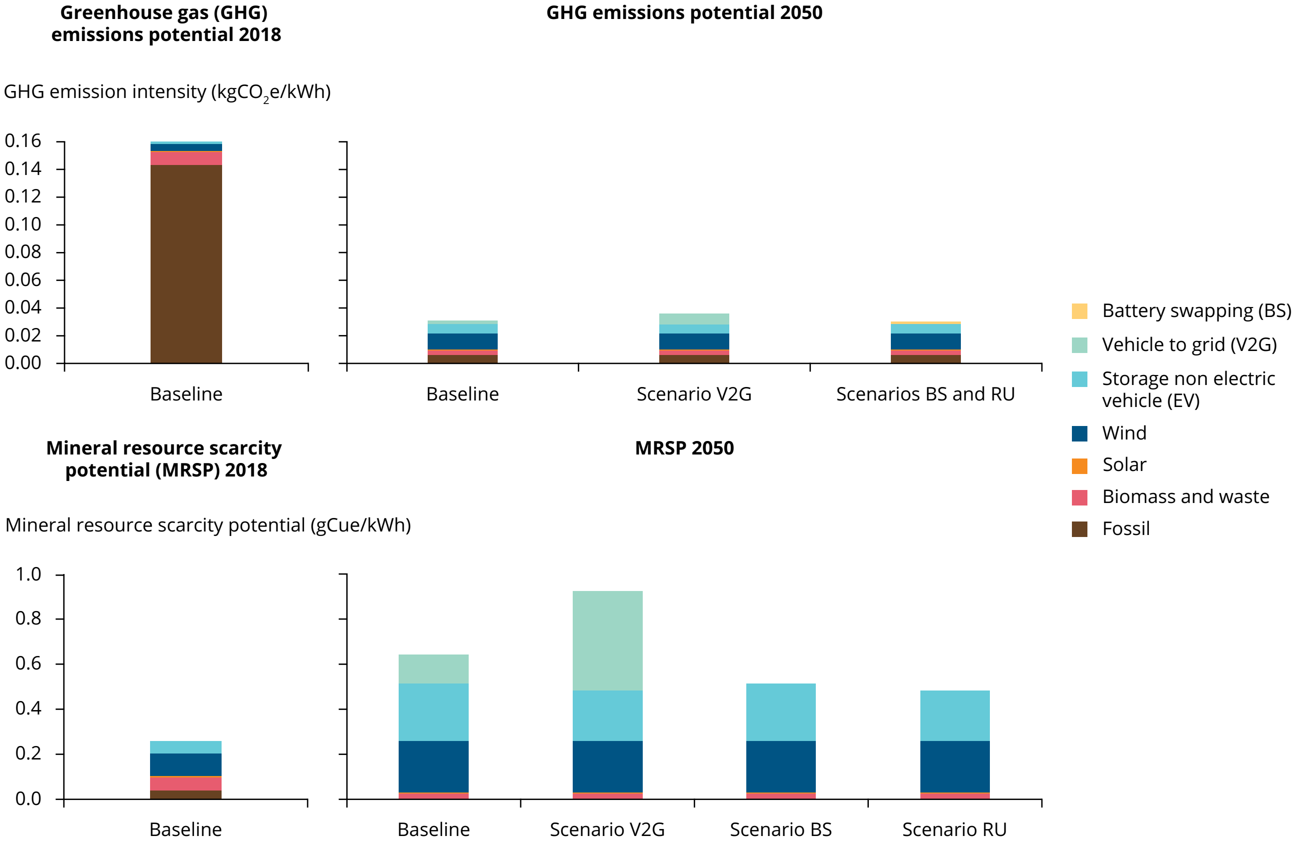
In 2050, some environmental costs counteract the reduction in GHG emissions, due to the materials that are required for the renewable energy installations and the storage facilities. This is the case, for example, for the indicator for mineral resource scarcity potential ([14]), one of the 11 indicators considered in the study, as illustrated in bottom panel of Figure A6.13. Providing V2G services is contributing to this impact, as it leads to faster battery degradation. As the share of V2G increases, this degradation impact increases further. With battery swapping this effect is much smaller, because in that case EV batteries are stored under better conditions while not in use for driving. A small additional reduction can be realised in the case of reusing end-of-life EV batteries.

However, based on a sensitivity analysis the authors indicate that the additional battery degradation due to V2G can be reduced if EV owners do not supply a lot of energy to the grid and do not keep the battery in a state of high charge. With high ambient temperatures these recommendations become even more important. The authors also point out that, for EV owners with low mileage, V2G could even reduce battery degradation.

A second lesson that can be drawn from the study is that reusing end-of-life EV batteries can also be environmentally beneficial.

([14]) The mineral resource scarcity potential gives an indication of the amount of mineral resources consumed both directly and indirectly.

Figure A6.13 GHG emissions (top) and mineral resource scarcity potential (bottom) per kilowatt-hour in the different scenarios



Source: EEA compilation based on Zhao and Baker (2022).

A6.9 Case study 6.3: Energy storage from electric vehicles and pumped hydro in La Palma, Canary Islands

Ramirez-Diaz et al. (2016) study the potential of two possible energy storage systems on the island of La Palma: pumped hydro energy storage (PHES) and bidirectional VGI. Table A6.1 presents the projected results for 2024, when there are assumed to be 3,400 EVs on La Palma with a total battery capacity of about 101MWh.

In scenario 1A no storage is available and the charging of the EVs is unmanaged. In that scenario the share of renewable sources is about 28%, and almost half of the renewable energy is curtailed, i.e. not available on the grid. Scenario 1B introduces smart charging of the EVs, which allows an increase in renewable energy sources and a substantial reduction in the share of curtailment. The CO_2 emissions from the power system are reduced by 5.7% compared to scenario 1A. The introduction of PHES enables a larger reduction in emissions and in the curtailment, when compared to scenarios 2A and 2B. In scenarios 3 and 4, very similar results can be achieved with the highest benefits in terms of reduction in CO_2 emissions. In scenario 4, the installed capacity of renewables is more than doubled (an increase by 25MW), with the support of 20MW from PHES and VGI services provided by about 3,400 EVs. A minimum state of charge of the EV batteries of 40% is assumed. The renewable share then increases to about 49%. The estimated reduction in CO_2 emissions compared to scenario 1A is almost 23%. In all scenarios with storage, the share of renewable energy that is lost is reduced substantially compared to scenario 1A, with the largest reduction in scenario 4, while the levelised cost of energy ([15]) is lowest in scenario 3.

([15]) The levelised cost of energy is 'an indicator for the price of electricity or heat required for a project where the revenues would equal costs, including making a return on the capital invested equal to the discount rate' (Badouard, et al., 2020).

Table A6.1 Impacts of electricity storage and vehicle-grid scenarios in La Palma in 2024

Scenario	Storage	EV charging	Renewable share (%)	Curtailment (%)	Electricity mix LCOE (EUR/MWh)	Electric power system emissions ($ktCO_2$)
1A	No	Unmanaged	28.2	47.3	125.7	141.3
1B	No	Smart	33.3	22.6	118.8	133.2
2A	PHES	Unmanaged	42.8	3.6	113.3	121.4
2B	PHES	Smart	43.9	1.8	111.9	117.4
3	VGI	VGI	47.1	3.2	109.4	109.0
4	PHES+VGI	VGI	48.8	0.7	111.7	108.9

Notes: In scenario 3 all EVs are used for storage; in scenario 4 priority is given to pumped hydro energy storage (PHES), with the help of VGI. LCOE, levelised cost of energy.

Source: Ramirez-Diaz et al. (2016).