Flexible energy systems Leveraging the Optimal integration of EVs deployment Wave

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Deliverable 5.2

New business models and economic opportunities for e-mobility stakeholders

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List of Acronyms

Acronym	Meaning
EV	Electric Vehicle
DC	Direct Current
AC	Alternate Current
M	Month
WP	Work Package
V1G	Flexible Charging
V2G	Vehicle To Grid
V2H	Vehicle To Home
V2X	Vehicle To X
TSO	Transmission System Operator
DSO	Distribution System Operator
PV	PhotoVoltaic
HEMS	Home Energy Management System
SOC	State-Of-Charge
DOD	Depth Of Discharge
CSO	Central Statistics Office
HP	Heat Pump
TOU	Time-Of-Use
LCOS	Levelized Cost Of Storage
BSS	Battery Storage System
SPU	Service Providing Unit
SPG	Service Providing Group
LMO	Local Market Operator
BSP	Balancing Service Provider
POD	Point of Delivery
UVAM	Unità Virtuali Abilitate Miste
BTM	Behind the Meter
FCA	Flexible Contract Agreement
PGUI	Power Grid User Interface
CPO	Charging Point Operator
eMSP	Electric Mobility Service Provider
FSP	Flexibility service provider
LMO	Local Market Operator
TU	Time Unit
UC	Use Case
UJ	User Journey
TSO	Transmission System Operator
DSO	Distribution System Operator
API	Application Programming Interface
DR	Demand Response

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Executive Summary

This report describes the work done in Task 5.2 of the FLOW project concerning the evaluation of economic opportunities and potential business models for exploiting flexible unidirectional and bidirectional charging of Electric Vehicles. The structure of the report moves from a general discussion of economic opportunities to the evaluation of specific use cases.

A review of the previous literature on the economics associated with smart, flexible EV charging reveals a very wide range of revenue estimations for different use cases. The estimates range from negative revenue (no economic benefits) to values in the range of several thousand euro per EV per year. However, several conclusions can be drawn from the review. For EV owners, there are almost always significant economic benefits associated with flexible charging, i.e. shifting charging to low cost times (assuming a variable electricity pricing tariff) and these economic benefits are generally enhanced by changing from unidirectional to bidirectional charging. Therefore, use cases such as Vehicle to Home (V2H) would seem to offer significant economic opportunities for EV and home owners. As regards Vehicle to Grid (V2G) the situation is less clear with some studies suggesting negative revenues depending on the grid service being provided and the assumptions regarding payments etc. In general studies seem to indicate that the provision of services such as secondary frequency control and load levelling offers the best potential for positive economic benefits.

Practical implementation of any specific use case typically requires the involvement of a range of different stakeholders and for any use case to be economically viable there should be an incentive for all of the stakeholders. Studies in the literature necessarily tend to simplify the stakeholders involved. To illustrate the range of stakeholders involved in practical implementation we review the specific use cases being pursued in the FLOW large scale demonstration projects. Although the full business case or business models for the these uses cases are still under development in WP7, it is useful to review the stakeholders, their potential economic motivations and the barriers to obtain a more realistic picture of what is needed for practical implementation. These demonstrations cover a spectrum of use cases and business models. V2G applications are covered by the Rome and Menorca cases which focus on the provision of frequency regulation services to the TSO and grid congestion management services to the DSO in the Rome and Menorca cases respectively. The main business model here is for the aggregator in the provision of flexibility services. The second Rome case and first Copenhagen case is concerned with imposing time dependant variable power limits on EV chargers as a means to provide non-firm grid connections for charging infrastructure. The business model here is more focussed on the DSO and enhancing its ability to connect charging infrastructure in a more timely manner without having to wait for the complete network upgrade. Two of the Copenhagen cases cover charge cost reduction scenarios, one based on charge cost reduction for semi-public chargers in a parking lot and the other based on charge cost reduction for residential EV owners. The business model in this case is centred around the Charge Point Operator (CPO) in the case of the parking lot and the residential user in the second case.

The final sections of the report take a deeper dive into quantifying the economics of two use cases based on V2H and V2G. The Vehicle to Home Case Study is set up to quantify the economic benefits to EV owners from the use of bi-directional charging to minimise their overall home energy costs. The study is based on data for home energy usage, PV generation and EV usage from Ireland and Italy. An

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optimisation model has been developed to optimise EV charging schedules in order to minimise annual energy bills for a household. The results would suggest that there are significant cost savings on home energy bills to be obtained from the implementation of V2H charging strategies. Although these cost savings are sensitive to the specific household conditions, assuming an average case they are in the range of 20% to 30% for the case of a commuting EV driver in Ireland and more likely to be closer to 30% in the case of a non-commuting EV driver who can make better use of PV generation. The difference in savings between unidirectional and bidirectional are also substantial. For example, for unidirectional charging compared to uncontrolled the savings are in the range of 20%, whereas they are more in the range of 27% for V2H. These savings assume a 3 tier Day/Nigh/Peak tariff structure. The savings also hold under a dynamic hourly pricing tariff structure and also potentially increase in the Italian case. Making use of V2H assumes the installation of bidirectional chargers (unless the bidirectional charger is onboard) and the installation of a home energy management system which can calculate optimal charging schedules based on electricity tariffs, PV generation and household demand. Such systems require an investment cost and the analysis for the Irish case study suggests that if initial investment costs are in the range of €9000 then the discounted payback period would be less than 10 years. Obviously lower initial investment costs would result in lower payback periods.

To perform a more detailed study of the economics of V2G we present an analysis of the potential revenues from participation of an EV delivery van fleet in a demand response (peak shaving) pilot programme in Ireland. This is a relatively simple scheme in its implementation in that participants (commercial entities or aggregators) get paid for demand reduction relative to an historical baseline demand. Overall, the study finds that there is significant advantage to participation in this peak shaving scheme, with the payments from the scheme contributing to an 8% reduction in overall fleet charging costs in the case of unidirectional charging. Assuming that exports from V2G were also allowed under the scheme (which is not the case at the moment), then charging cost reductions would be significantly higher at 20%. Although the implementation of bidirectional charging does significantly increase the revenue per vehicle earned from the scheme, it would be likely also to incur significant extra costs in terms of upgrading charging systems. For example, in this specific case study the savings from charging cost reductions amounted to approximately €5000 per year for the fleet of 28 delivery vans using 24 charge points. The economic feasibility of implementing V2G is therefore highly dependent on the additional extra costs associated with upgrading the charging system.

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1. Introduction

This report describes the work done in Task 5.2 of the FLOW project concerning the evaluation of economic opportunities and potential business models for exploiting flexible unidirectional and bidirectional charging of Electric Vehicles. The structure of the report moves from a general discussion of economic opportunities to the evaluation of specific use cases.

Section 2 presents a review of the literature with a focus on the economics of flexible unidirectional and bidirectional charging for the different use cases of vehicle to home and vehicle to grid.

Section 3 discusses business models in the context of the use cases being pursued in the large scale demonstrations in the FLOW project with an overview of the potential economic opportunities from the perspective of the different stakeholders involved.

Since the economic benefits are very dependent on the specifics of the use case it is difficult to generalise about the economic case for bi-directional charging. Specifics include vehicle uses such as private vehicles, fleets, locations of charging such as home, work, public, market structures for services provision, electricity tariff structures, equipment and systems costs, etc. Therefore, in Section 4 a detailed study of the economics of V2H compared to V1G is presented for a case study using data from Ireland and Italy.

In Section 5 to further explore the economic opportunity for V2G we also provide an economic analysis of a specific V2G case study based on the participation of a fleet of battery electric delivery vans participating in provision of a peak shaving service using as an example a pilot peak demand reduction programme currently in operation in Ireland.

The modelling for the case studies is implemented using the Spine modelling platform. The platform and the models are available in the open access repository (Zhang 2025)

2. Overview of Economic Opportunities

2.1. Economics of Bi-directional EV Charging

There have been many studies reported in the scientific literature which have investigated the economic benefits of bi-directional charging. One study of particular note is the review by Ghatikar and Alam, 2023, which conducted a review of eleven demonstrator case studies from the US and Europe which implemented bi-directional charging. A summary of the range of potential economic benefits in terms of $/EV/year is shown in Figure 2.

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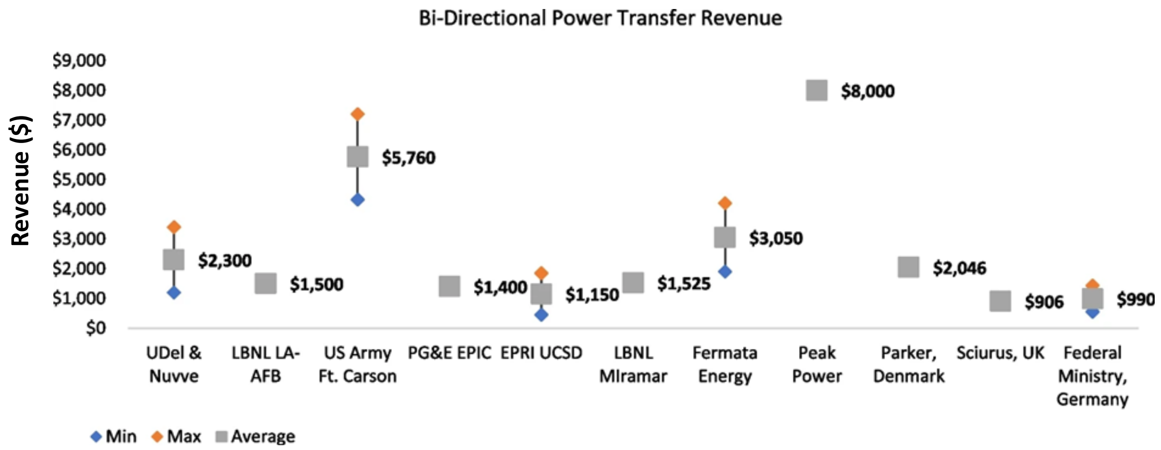

Figure 1. Revenue from bi-directional power transfer obtained from a review of 11 case studies. Taken from Ghatikar and Alam, 2023

As can be seen the potential economic benefits vary considerably depending on the study and are quite dependent on the assumptions behind the services being provided and the vehicles providing the service, with many of the estimates based on stacking of services. For example the highest revenue case of $8,000/EV/year was associated with a vehicle to building case where the EV batteries were used to reduce peak demand in office buildings in Toronto and was very much tied to electricity pricing structures unique to the Toronto region. The second highest revenue was projected from a study where US army vehicles were used to provide services to a microgrid proving reactive power export (from DC chargers), peak shaving and frequency regulation. The paper notes that the projected revenue from the European studies were among the lowest compared to the US studies. The paper did not review the costs associated with the equipment and systems required to deliver the services, although it does note that for provision of the services to be considered profitable it might be expected that the costs should not exceed 60% of the revenues based on industry norms for the sector.

The study by Heilmann and Friedl (2021) is motivated by the fact that various studies in the literature have contradictory results with a very wide variation in economic benefits being reported. For example, mean net revenue results reported from different studies varied from almost -$2,000 to over +$5,000 per EV per year. The study therefore performed a comprehensive review of V2G studies in order to try to explain this variation and identify the factors which most strongly impacted V2G revenue. The study collated independent variables used in 340 V2G simulations by 35 authors between 2010 and 2018. Fig. 3 shows a summary of some of the findings in terms of a plot of revenue per EV per year reported by the various studies, where revenue includes charging costs (negative revenue) plus any payments for supply of services The review is plotted against the simulation study year used in the article and is categorised according to application. Frequency control refers to participation in frequency regulation markets, load control refers to peak shaving and load levelling and trading refers to charging cost reductions and energy arbitrage. The “Revenue” is revenue not accounting for costs associated with battery degradation while “Revenue net” refers to revenue accounting for cost reductions. The majority of studies indicate revenues in the range of several hundred euros per EV per year with some notable exceptions. Participation in frequency control applications seem to have significant economic potential, with the exception of participation in tertiary frequency control which

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generally shows negative net revenue when battery degradation is accounted for. The mean Revenue declines from €549.95 for secondary frequency control to €361.79 for primary control and finally to €−337.30 for tertiary control. Generally, more recent studies tend to be somewhat more pessimistic regarding revenues.

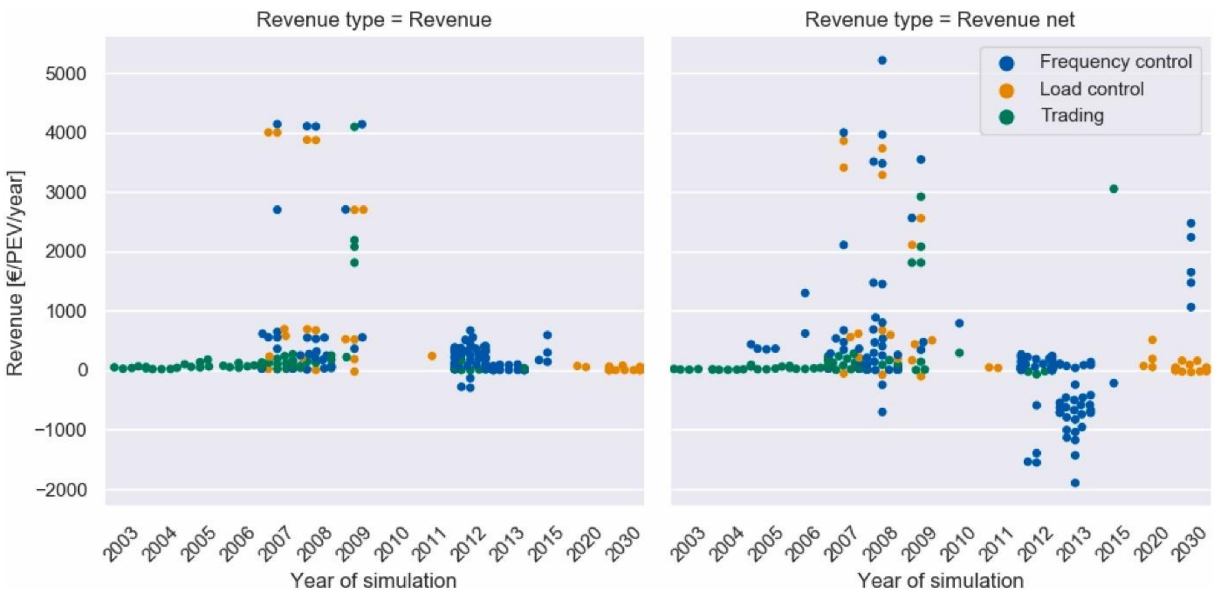

Figure 2. Revenue types for 340 V2G simulation cases, pooled by year of simulation. Taken from Heilmann and Friedl (2021)

The study highlights several important findings which can be observed from the detailed review of the literature:

- Charging cost reductions by moving charging to low-cost times is almost always economical for vehicle owners and these cost reductions can be enhanced by implementing V2G, although the level of enhancement will be dependent on local conditions.
- The economic benefits from price arbitrage are typically low and, in some cases, can be entirely eliminated by costs associated with battery degradation.
- Load control applications (e.g. Peak shaving, or load levelling) can provide economic benefits under certain circumstances, such as when charging power is high enough and battery degradation costs are not too high.
- Frequency regulation applications, especially participation in secondary frequency regulation generally shows positive economic benefits. Participation in tertiary frequency control is generally less economically viable because of the impact the longer duration support has on battery degradation.
- Although benefits to the system increase with increased participation from EVs the benefit to an individual EV decreases as overall participation rates increase (Secchi et al., 2025). Additionally, higher levels of EV penetration will mean more people charging their vehicles at night, and thus potentially higher real-time electricity prices for charging. Higher prices during

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charging and lower prices during vehicle-to-grid discharging translates into decreased profits from the energy market.

- Secondary frequency control and load levelling are the most promising applications for V2G.
- Benefits tend to be higher for vehicle owners rather than for aggregators or grid operators. For example, when the publications are categorised according to "Viewpoint" the mean revenue net for aggregators was €-297, for grid operators was €327 and for vehicle owners was €728.
- The technical parameters such as switching from unidirectional to bidirectional charging, higher charging power and higher efficiency all tend to increase the economic benefits.

2.2. Vehicle to Home

The literature suggests that the largest potential for economic benefits is associated with the EV owner and can be realised through the use of flexible, unidirectional or bidirectional charging perhaps also in combination with renewable generation such as rooftop PV. A charging strategy adjusts the charging time and rate with respect to the grid demand, electricity tariffs and the availability of renewable energy generation (Barman et al., 2023). Smart homes combined with small-scale distributed photovoltaic (PV) and EV have been shown to decrease daily electricity costs (Erdinc et al., 2014). Bi-directional charging, V2H, can also work as an alternative controllable load/generator not only to offer home energy savings for EV users but also to provide a backup power supply in the case of grid outage.

The following are some examples of findings from the literature.

- Flexible and bidirectional charging of EVs can significantly save 8~33% of annual costs compared to uncontrolled charging in a Swedish household with PV (Salpakari et al., 2017).
- The uni-directional flexible charging of EVs can reduce charging costs by 30% and grid operational costs by 10% (Sadeghian et al., 2022).
- The total electricity cost of bidirectional charging was 2.6% less than unidirectional smart charging in a smart home nanogrid with EV, PV arrays and stationary battery (Wu et al., 2017).
- Abdalla et al. (2020) found that V2H implementation with PV could reduce daily electricity costs by 20%.

To effectively implement the V2H strategy, a home energy management system (HEMS) is required to monitor and control energy generation, storage, and consumption within a household, thus optimizing the PV self-sufficiency and cost reduction. V2H applications in Netherlands (Scharrenberg et al., 2014), UK (Aguilar-Dominguez et al., 2020), Japan (Kobashi et al., 2020), Germany (Kern et al. (2022)), and Ireland (Zhang et al. (2025)) have been investigated. Compared to the HEMS with PV and a stationary battery, the integration of an EV and PV is better from an economic perspective, because the EV battery has dual functionality for both transportation and energy storage (Kobashi et al., 2020). Additionally, the EV battery usually has greater capacity than a stationary battery, which better maximizes the self-consumption of PV and offsets more household demand into off-peak times. A case study from Kern et al. (2022) based on a smart German household investigated the effects on V2H cost savings by varying EV battery capacity, household electricity demand, PV generation, EV charging rate, PV export tariff, and driver profiles under the flat tariff and found that the V2H cost savings

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increase with increased PV capacity. The combination of PV generation with a stationary battery or V2H save up to 30% on electricity bills regardless of the electricity tariff and a 3-tier tariff can further bring about a reduction of up to 85% in the electricity bills with the Nissan Leaf 2018 EV (Aguilar-Dominguez et al., 2020).

2.3. Vehicle to Grid

By utilizing EVs as energy storage devices, vehicle-to-grid (V2G) technology, proposed by Kempton and Letendre (1997), can effectively address the overloading issue resulted from the widespread integration of EVs into the power grid. The provision of system services such as synthetic system inertia, frequency control, replacement reserves, congestion management, and voltage regulation have all been theoretically proven as possible V2G provisions (Sevdari, 2023). V2G users can take advantage of varying time-of-use (TOU) tariffs, thus enabling EVs to charge during low-tariff hours, and sell back to the grid during high-tariff hours (Wan et al., 2024). However, the barrier to the widespread V2G usage is that the requirements, costs, and benefits of V2G must be balanced among the three primary stakeholders: EV manufacturers, EV owners, and grid operators (Steward 2017). Thus, the adoption of V2G technology includes the technical, economical, political-related and user-related challenges.

Patil and Kalkhambkar (2021) emphasized that the commercialization of V2G requires the participation of the EV manufacturers, utility and end users, thus achieving economic benefits under the grid integration with EVs. V2G suppliers typically have rapid response times and reliable communication technologies, as well as more flexible operational modes than other suppliers. These additional suppliers can allow the system operators to defer investments, incorporate additional renewable generation, and reduce the risk and severity of system events. People expected an average reduction in electricity bills of 144 $ (72% of the average monthly bill) as compensation for utilizing V2G while V2G is utilized under the minimum SOC of 71% (Mehdizadeh et al., 2023). Geng et al. (2024) examined V2G profits from the vehicle's perspective and indicated that the net present value of V2G is projected to reach around 7000 $ over the vehicles lifetime with the progression in battery technologies. Rahman et al. (2023) examined the levelized cost of storage (LCOS) of V2G, by developing a model to estimate the associated costs for V2G applications across a range of temperatures. The base case values for the LCOS are 230,88 $/MWh for energy arbitrage and 329,93 $/MWh for frequency regulation. By considering the uncertainty in key parameters, such as ambient temperature, daily travel distance, electricity price, etc, the likely distributions for the LCOS are 158 ~ 290 $/MWh for energy arbitrage and 244 ~ 485 $/MWh for frequency regulation. By investigating the V2G frequency regulation without the consideration of battery degradation, the revenue is between 100 and 500 £/year for a 40 kWh EV with 8kW charging capacity in UK market (Thingvad et al., 2019), whilst the annual revenues range between €100 and €1100 per vehicle with regard to battery charging capacity in Danish market (Banol Arias et al. 2020).

Pelzer et al. (2016) presents the optimal energy arbitrage of battery storage system (BSS) with the uncertainty of price in real-time and look-ahead markets from four different markets by considering non-linear relation between BSS aging and operational parameters. In comparison to unidirectional

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smart charging, energy arbitrage boasts a better peak shaving performance for V2G by around 15% and the resultant demand profile is about 17% smoother, under the average price of 0.13 $/kWh (Visakh and Selvan, 2022). As studied by Nunez et al. (2022), Ireland has one of the best electricity arbitrage due to its great volatility in the electricity market. However, as Haji Bashi et al. (2022) notes, the barriers preventing aggregated storage from participating in day-ahead and intra-day markets in Ireland heavily restrict the potential for any distributed arbitrage such as V2G. By applying optimisation with battery degradation, the annual cost savings range between 956€ and 2224€ by comparison to uncontrolled charging (Englberger et al., 2021). Synthetic user behavioural data was combined with actual regional EV characteristics to examine the impacts of local grid conditions on resulting V2G revenues in China (Zhou et al., 2020). It was found that the participation in frequency regulation and peak shaving provision reduced net costs by 66% and 48% in Chengdu and Shanghai respectively.

Freeman et al. (2017) examined the sensitivity analysis based on a five-year, hourly economic model of V2G based in the New York City area. it was revealed that key factors like round-trip efficiency and battery lifespan significantly impact the economics of selling electricity back to the grid. Overall , economic benefits were relatively small ($100-$200 per year) due to the cost of additional wear on the vehicle's battery. Gomes and Neto (2024) conducted the sensitivity analysis based on different selling prices (0,50 €/kWh, 0,30 €/kWh, and 0,20 €/kWh) and found that high selling prices are profitable for EV users with minimal vehicle usages, but any selling price would significantly offset operational and maintenance costs for heavy users. Zhang et al. (2025) performed factor analysis on the parameters influencing V2H revenue and found that electricity tariff, household demand, EV availability and EV usage have significant impact on V2H cost savings.

Heilmann and Friedl (2021) revealed that frequency regulation and peak shaving can be both feasible and profitable, The key factors to have major influence on V2G techno-economic analysis are to be investigated for an Irish case study.

In summary some main take away points from previous studies is that there are clear potential economic benefits to EV owners to participate in flexible charging and in V2H. On the other hand the potential for economic benefits from V2G are less clear, especially considering that there are a range of stakeholders involved and for V2G to be feasible there should be economic benefits to all stakeholders. With that in mind, it is worth reviewing the range of stakeholders and the potential economic opportunities for each.

2.4. Stakeholders

Studies in the literature tend to oversimplify the number of actors necessary to implement smart charging use cases. In practice, as illustrated by the demonstrator projects in FLOW, implementation of any particular use case typically involves a wider range of different stakeholders with responsibility for different aspects of the implementation. For there to be a viable economic opportunity there should be sufficient incentive (economic or otherwise) for all of the stakeholders involved in the specific use case. The motivation, demand and drivers for the various stakeholders were described in an earlier Deliverable 1.1. The full range of potential stakeholders involved in the delivery of flexible

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EV charging and the map of potential interactions between stakeholders and stakeholder platforms is shown in Fig. 1.

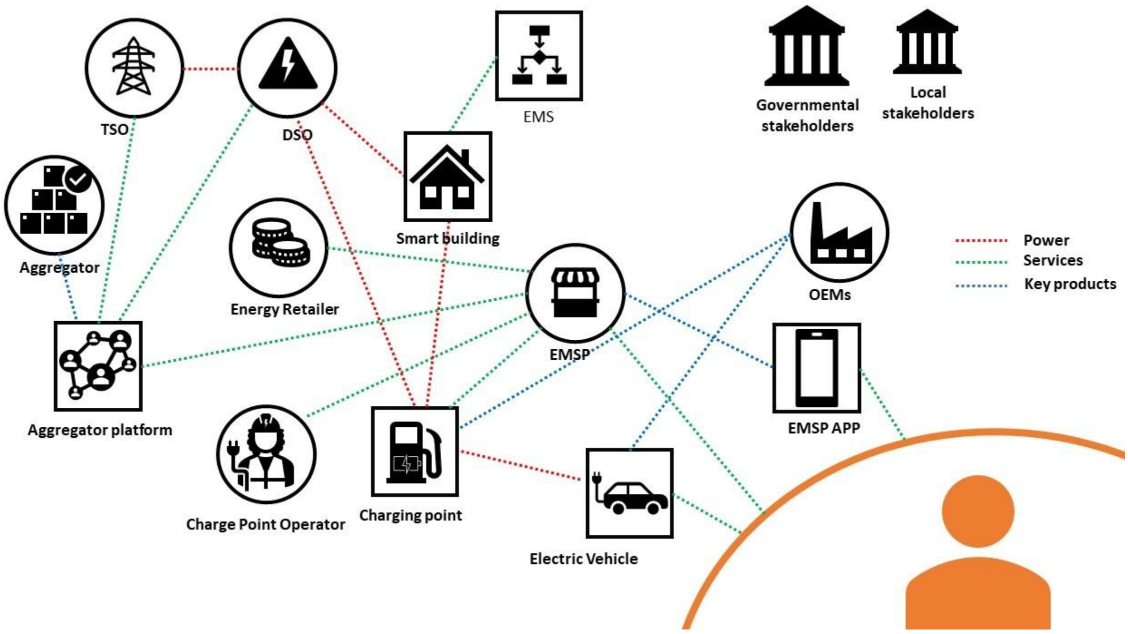

Figure 3. Most relevant interactions between stakeholders (in circles) and key products (in squares). If a stakeholder is responsible for a key product, this is marked by a blue line. Taken from FLOW Deliverable 1.1 External Drivers.

The opportunities and threats associated with the leveraging value from flexible EV charging approaches have been explored in a series of workshops in the FLOW project. The potential economic benefits for the main stakeholders are summarised in Table 1. Nevertheless, it is also important to keep in mind that there are significant barriers which act as disincentives and these are also summarised in the table below.

Table 1 Error! Reference source not found.

Stakeholder	Potential Economic Benefits	Barriers/Threats
End User	• Reduction of charging costs by optimal scheduling of charging according to variable electricity tariffs. • Lowering of home energy bills by utilising home energy management optimisation in combination with ToU tariffs. • Reduced charging costs in return for offering flexibility from EV • Specific payments for the provision of grid support services such as peak shaving, etc.	• Initial investment cost of equipment and systems. • Lack of Interoperability and standards case an increase in adoption costs. • Fear of smart charging and giving up control. • Data privacy concerns.

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Aggregators	• Market payments for the provision of specific grid support services from aggregated assets, e.g. capacity payments, energy payments, etc. • Creating value for TSO/DSO and asset owners.	• Lack of coordination between TSO and DSOs • Technical characteristics of the assets, e.g. response speed, etc. • Lack of acceptance by users in terms of giving up control. • Poor data management and sharing across the system.
TSO	• Procuring of grid support services to enable more effective, secure and reliable grid management. • Reduction of system operational costs through avoidance or reduction of use of expensive peaking plants. • Avoidance or deferral of infrastructure upgrades	• Lack of standards and interoperability. • Limited volumes of services. • Uncertainty about technical capability of assets.
DSO	• Procurer of local grid support services to enable grid management. • Avoidance or deferral of infrastructure upgrades • Improved network management	• Lack of markets • Lack of DSO/TSO coordination to prevent grid congestion and voltage violations.
Energy Retailers	• Customer expansion through the provision of new customer services to customers • Possibility to deploy new services (leveraging data gathered by the customers or by the vehicles)	• Regulatory, standardisation and interoperability barriers when wanting to launch new services. • Lack of trust from TSO and DSO on flexibility provided by smaller assets ? • Insufficient grid capacity
Equipment Suppliers	• Sale of energy management products and equipment.	• Lack of standardisation adds costs and implementation delays.
Charge Point Operators	• Sharing of revenue from service provision • Revenue for role in enabling flexibility service from EVSE with monitoring and control systems.	• Competition from home and workplace charging. • Interoperability between diverse charging systems. • Effective management of data flows with increased volume of transactions.
EV Manufacturers	• Potential for new revenue streams by partnering with energy companies. • Increased sales of EVs by adding features, such as bidirectional charging which make EVs more attractive to users.	• Battery degradation concerns • Data privacy concerns regarding sharing of data from EVs.

Perhaps the main take away point from this analysis is that although the potential for economic benefits certainly exists, there are sufficient barriers to make the business case unclear at this stage. To explore the potential further, the specific uses cases being pursued in the FLOW project are described in the next section.

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3. Business Models

Several demonstrations of use case for flexible EV charging are being conducted in the FLOW project. Analysis of the business case for these are ongoing and are expected to be detailed later in the project on completion of the trials. Although it is not possible at this stage to conduct a detailed business case analysis for these use cases it is nevertheless of interest to summarise the main point of the use cases and the stakeholders involved to illustrate the potential for different business models. The main stakeholders and their role in the use case is summarised in the tables below.

Of these use cases, the Rome use case 1 and the Menorca use case could be described as system services provision use cases. The Rome use case focusses on the provision of frequency regulation services. Here it is notable that the UVAM programme allows participation of an aggregated mix of demand reduction and supply units which is an important consideration for V2G participation. The Menorca use case is focussed on the provision of congestion management services to the grid, in the case where the grid demand is highly seasonal. In terms of the business model in both these cases, the customer for the services is the grid operator (TSO in case of Rome, and DSO in case of Menorca) and the value proposition is the supply of grid support services under a services market arrangement.

The Rome use case 2 and the Copenhagen use case 2 both fall into the category of maximising access to EV charging in the context of limited network capacity. In the case of Rome flexibility from EV charging is used to provide non-firm grid connections to chargers. In these use cases the customer could be considered to be the charge point operators (and ultimately the EV owners who use the charge points, either residential or public). The value proposition here is associated with the increased public charging infrastructure which can be installed/accessed without the need to wait for an upgrade of the power network infrastructure. EV owners benefit from better access to EV charging infrastructure (albeit it at reduced capacity), CPOs benefit from being able to provide the charging infrastructure and potentially share in the revenue from service provision, and the system operator benefit from deferring network infrastructure upgrades.

The Copenhagen Use case 1 and use case 4 both fall under the category of charging cost reduction through the use of flexible charging. In the case of Copenhagen use case 1 the target is a public parking lot (i.e. a hospital) and the value proposition is the reduction of EV charging costs for both the CPO and EV owners in the parking lot. By shifting EV charging according to electricity costs or local PV generation overall charging costs can be reduced. It is also possible to use the same approach to reduce emissions associated with the EV charging as an alternative. In the case of use case 4 the target customers are residential EV owners, with the value proposition being the reduction of charging costs through the shifting of charging times according to electricity price tariffs.

Table 2: Summary of Use Case – Rome Use Case 1.

Rome Use Case 1: Provision of Flexibility Services to TSO	
Description	Provision of frequency regulation services to the TSO (Terna) from aggregated EVs in the Italian UVAM (Virtually Aggregated Mixed Units) market which aims to facilitate provision of ancillary services from distributed energy resources.

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Stakeholder	Role
Private EVs	Providing the EV flexibility assets and allowing the BSP and e-MSP to register the end-user in the aggregation group.
Public EV Chargers	Providing the EV flexibility assets.
Charge Point Operator (CPO)	Providing the monitoring and control systems to facilitate flexible charging through EV chargers. Provide to the BSP all necessary data to enable EVSE participation to the program. Receive the set point from the BSP and send the command to the aggregated assets
Balancing Service Provider (BSP)	Providing the balancing services to the TSO, e.g. the frequency regulation service, availability offer and the baseline of the EV aggregate, according to the EVSE data gathered from the CPO.
Distribution System Operator (DSO)	Ensuring that local distribution network management standards are adhered to and validation the points of delivery associated to the EV aggregates.
Transmission System Operator (TSO)	Customer for the provided flexibility services. Implementation of the tests including 1) request for aggregate registration on CBP; 2) activation of resources on the basis of BSP Availability offer; 3) performance validation on the basis of aggregate submeter data and baseline communicated by the BSP; 4) cross-check and comparison between POD data provided by DSO and assets measurements.

Table 3: Summary of Use Case – Rome Use Case 2.

Rome Use Case 2: DSO Flexible Contract Agreement - general description and goal	
Description	Implementation of a flexible connection agreement (FCA) between DSOs and CPOs for selected public charging stations as a means to avoid delays in the provision of public charging infrastructure while deferring network infrastructure upgrades.
Stakeholder	**Role**
Public EV Chargers	Providing the EV chargers with flexible connection. Equipped with interface to allow the communication between DSO and CPO on the setpoint to be sent to the charging units as well as POD measurements.
Charge Point Operator (CPO)	Provide information on the EVSE assets that will be involved in the Demo. Receive the set point and perform the command to the asset. Inform the end-users during the testing phase
Electric Mobility Service Provider (eMSP)	Inform the customers during the testing phase
Distribution System Operator (DSO)	Detect the DSO needs, define the FCA service, provide the IoT device to enable the resource, perform the service.

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Table 4: Summary of Use Case – Menorca Use Case 1.

Menorca Use Case 1 – DSO Flexibility services - General Description and goal	
Description	Deploy and validate smart chargers and V2G on the island that has high seasonality on energy demand, providing congestion management flexibility to the DSO and allowing the development of mechanisms to compensate the energy transaction across Aggregators, CPO, MSP and EV drivers
Stakeholder	Role
Private EVs	Providing the EV flexibility assets. Receive invitations (e.g., via mail, direct approach, flyers) to take part in a series of online-surveys focusing on the users' mobility and charging behavior, as well as their experience of smart charging in Menorca.
Public EV Chargers	Providing the EV flexibility assets. Equipped with V1G technology with V2G to be considered.
Charge Point Operator (CPO)	Providing the monitoring and control systems to facilitate flexible charging through EV chargers. Provide to the BSP all necessary data to enable EVSE participation to the program. Receive the set point from the BSP and send the command to the aggregated assets
Balancing Service Provider (BSP)	Manage the resources registration on the platform. Communicate with the CPO platform to gather telemetry, interval data, and availability data from charging point assets. Communication and transactions with the market platform. Receive from the DSO the activation order and send the set point to the EVSE assets through the CPO platform
Distribution System Operator (DSO)	Definition of the use case of congestion management in agreement with the other Parties
Electric Mobility Service Provider (eMSP)	Engage the end-users in the experimental campaign. Inform the customers during the testing phase Send the EVSE interval data, and availability data to the BSP. Receive the set point from BSP on the aggregate and send the command to the assets

Table 5: Summary of Use Case – Copenhagen Use Case 1.

Copenhagen Use Case 1 – Smart charging in Parking Lots - General Description and goal	
Description	Test the feasibility of centralised V1G smart charging in parking lots, for reduction of charging costs (for CPO and/or EV owners) or CO_2 emissions minimisation including the integration with PV generation.
Stakeholder	Role
Private EVs	Providing the flexibility assets.
Parking lot/EV chargers owners	Provision of access to the EV chargers in the parking lot.

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MSP	Measurement of the power consumption, and periodically sending data to check if the scheduling was followed.
Charge Point Operator (CPO)	Provide the electricity costs and PV production.
DTU server	Read the electricity costs (spot market price) or the CO2 emissions from (TSO) website and estimates the session energy and charging duration. Elaborates an optimal schedule for all the EVs connected to the system
Transmission System Operator (TSO)	Provide the electricity costs (spot market price) or the CO2 emissions to DTU

Table 6: Summary of Use Case – Copenhagen Use Case 2.

Copenhagen Use Case 2: Conditional Connection Agreement - General Description and goal	
Description	Modify the maximum allowed consumption of two kerbside EV charging clusters to better utilise the available network transformer capacity. Test the possibility to perform "load sharing" between sites, i.e. raising the capacity of one and lowering the other.
Stakeholder	Role
Private EVs	Communicate with Zaptec Pro charger using OCPP 1.6 J (Open Charge Point Protocol).
Electro-Mobility Service Provider (eMSP)	1) gathering and provision of EV charging data, 2) enabling control of the EV chargers, 3) technical support to the smart charging demonstration, 4) results analysis support.
Charge Point Operator (CPO)	Read the electricity costs from eMSP
DTU server	1) historical data analysis for the chosen kerbside EVSEs and transformer, 2) development of the control algorithm to raise or lower the max. charging capacity at the locations, 3) setup of control hardware, 4) execution of the tests, 5) analysis of the results.
Distribution System Operator (DSO)	Provide the real time transformer loading levels

Table 7: Summary of Use Case – Copenhagen Use Case 4.

Copenhagen Use Case 4: Smart charging in residential context - General Description and goal	
Description	Test V1G smart charging in the residential context, either for costs reduction or CO2 emissions reduction.
Stakeholder	Role
Private EVs	Providing the EVs and chargers.
Electro-Mobility Service Provider (eMSP)	Gathering and provision of EV charging data and metering of consumption, enabling control of the EV chargers.
DTU server	1) historical data analysis for the chosen kerbside EVSEs and transformer, 2) development of the control algorithm to raise or lower the max. charging capacity at

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	the locations, 3) setup of control hardware, 4) execution of the tests, 5) analysis of the results.
Transmission system operators (TSO)	Provide the real time CO2 emission data

The consensus for the literature to date is that the clearest economic potential for flexible charging is in charging cost reduction for EV owners responding to variable electricity price tariffs. Several studies also conclude that these charging cost savings can be enhanced by using bidirectional charging to the home (Erdinc et al., 2014), (Datta et al., 2018), (Kern et al., 2022). However, the exact value depends on specifics such as electricity price tariffs, EV travel patterns, household energy consumption, etc. In order to quantify the economic benefits, the following sections present a detailed study based on two case studies.

4. Vehicle to Home Case Study

One of the simplest use cases with direct benefit to EV owners is the vehicle to home use case, where the EV battery is used as an energy source to minimise home energy costs. This use case is simple in that the primary stakeholder is the EV owner who obtains direct economic benefit from the reduction in energy costs. This also provides added motivation for the adoption of EVs. Moreover, the use case can be implemented entirely as a behind the meter (BtM) service thus avoiding the regulatory issues associated with grid connection. With an appropriate electricity tariff structure, the overall electricity system can also benefit by reducing peak hour residential energy demand. Motivated by these advantages we do a “deep dive” analysis of the economic benefits of V2H using data relevant to an Irish and Italian case study. An optimisation tool has been developed to optimise EV charging schedules in order to minimise annual energy bills for a household.

4.1. V2H model configuration

The optimisation model aims at minimising home energy costs over one year. The model takes as input hourly profiles for home electrical energy assuming use of a heat pump (HP) for heating, generation from rooftop PV, an EV usage profile, and tariffs for import and export of electricity from/to the grid. The primary objective is to optimise the charging strategy of the EV and use of PV generation to optimise home energy usage so as to minimise energy costs for the home owner. The optimisation model is implemented using the Spine modelling platform and makes use of the SpineOpt tool for the optimisation. Spine is a flexible open-source energy system modelling framework developed in Julia (Ihlemann et al., 2022). The EV driving data, household demand data, PV generation data and water and space heating data (for the heat pump) are critical inputs for the optimisation model to determine the EV battery state-of-charge (SOC), charging and discharging power, electric power imported from grid, etc. The V2H model configuration as set up in the Spine modelling tool can be seen in **Figure 4**. This configuration is set up to represent the possible energy flows between the household, PV generation, space and water heating electrical demand, EV charging, and the grid.

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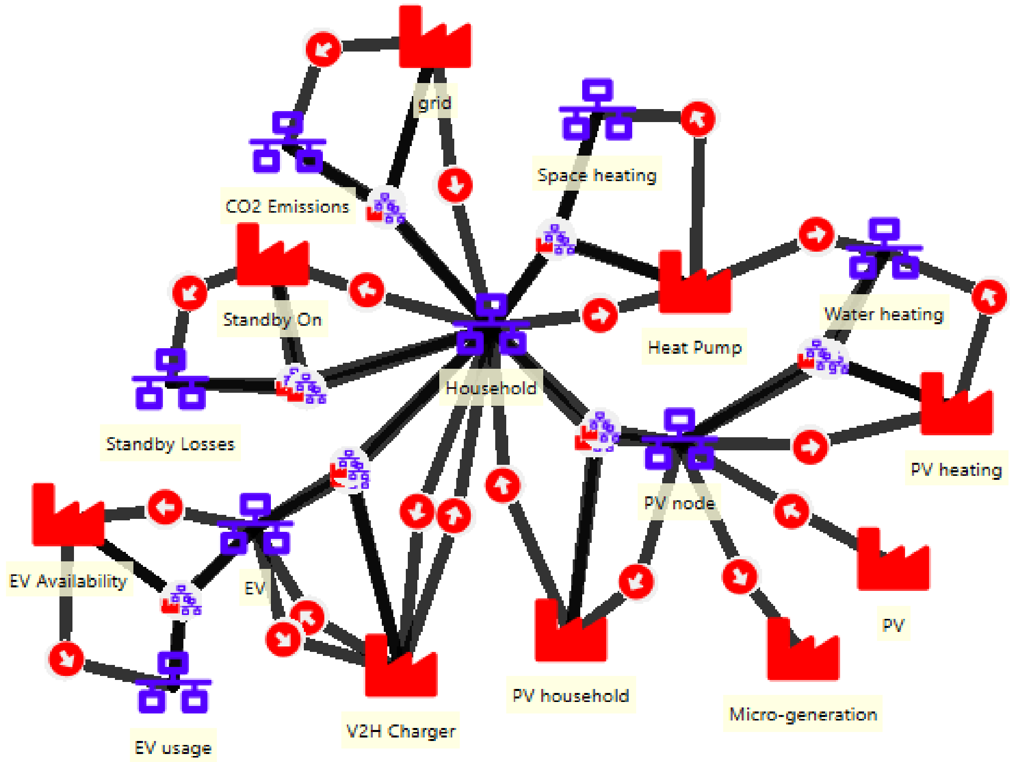

Figure 4. Configuration of V2H model.

The model aims to optimise the energy flows, so as to minimise the annual household electricity costs based on time-varying electricity tariffs with a set of predefined inputs and parameters. For the V2H model, the nodes, units, connections and V2H constraints with the objective functions are presented in detail in Zhang et al. (2025). The case study is based on the adoption of V2H by an Irish household. The model inputs include household electricity demand, HP electricity demand, PV generation profiles, and EV driving profiles. The baseline household electricity demand adopts the electricity demand in an average Irish household, which has an annual electrical consumption of 4200 kWh (CRU 2024). Hourly HP demand data profiles are obtained from a study on 38 German households (Schlemminger et al., 2022) scaled to the average HP electrical demand for Ireland which is 3300 kWh (SEAI, 2023).

Irish PV generation data from 2019 is taken from Renewables Ninja (2025). The baseline model assumes a PV rated capacity of 3 kW with a yearly generation of 3129 kWh. In this case study, the baseline EV battery capacity of 57.5 kWh is adopted, based on a Tesla Model Y (EV database 2023). The EV charging and discharging capacity E_{cap} is set at 7.2 kW with an efficiency of 90%. The EV charger standby losses are given at a constant of 0.05 kW. EV SOC is allowed to range between a minimum of 30% and a maximum of 80% for V2H services, whilst at the departure hour (7am everyday), the minimum SOC must be beyond 70%.

For the sake of illustrating the economics benefits of adopting V2H, An EV non-commuter and a a commuter profile are selected for comparison in the case studies. The non-commuter profile is chosen from realistic driving profiles based on German national driving data (Kern et al., 2022). For the commuter profile, Irish National Transport statistics are utilised with the average daily driving distance

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of 33.6 kilometres (CSO 2022), by consuming an average energy of 0.2 kWh per kilometre (EV database 2023). The electricity tariffs used for the baseline model are reflective of a typical static day/night/peak tariff from an Irish energy supplier. The fixed electricity export tariff of 0.2 €/kWh is also typical of a tariff available in Ireland. To summarise, the input parameters used in this work are given in **Table 8**, which is applied to simulate the non-commuter and the commuter profiles.

Table 8. Input parameters of V2H model (Irish case study)

Household	
Household electricity demand p.a.	4200 kWh (Non-commuter)/ 1520 kWh (Commuter)
Heat pump demand p.a.	3620 kWh (Non-commuter)/ 2485 kWh (Commuter)
Grid electricity prices	
Day rate (08:00 -17:00, 19:00 - 00:00)	0.4451 €/kWh (off peak)
Night rate (00:00 - 08:00)	0.2239 €/kWh
Peak rate (17:00 - 19:00)	0.4746 €/kWh
PV system	
PV capacity	3 kW
Electricity export price	0.2 €/kWh
EV system	
Max EV charging/discharging rate	7.2 kW (90% efficiency)
EV charger standby losses	0.05 kW
EV battery capacity	57.5 kWh
Travelling distance per day	33.6 km (Commuter)
Average EV energy consumption per km	0.2 kWh (Commuter)
Max SOC	46 kWh (80%)
Min SOC (08:00 - 07:00)	17.25 kWh (30%)
Min SOC (07:00 - 08:00)	40.25 kWh (70%)

4.2 Comparison of uncontrolled, flexible and V2H charging strategies

To provide a snapshot comparison of the impact of different charging strategies on a household, **Table 9** shows a breakdown of energy generation and consumption and electricity costs for uncontrolled, optimal flexible unidirectional and bidirectional V2H charging strategies. For uncontrolled charging, the EV is assumed to be charged to 100% as long as it is plugged in. For flexible and V2H charging, their SOC ranges are given in **Table 8**.

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Table 9a. Results under uncontrolled, flexible and V2H charging scenarios (non-commuter)

Output parameter	Uncontrolled	Flexible	V2H	Units
Household demand	4179	4179	4179	kWh
HP demand	3620	3620	3620	kWh
Standby losses	0	381	381	kWh
EV depletion	2529	2529	2529	kWh
EV charging	2529	2529	6240	kWh
EV discharging	0	0	3801	kWh
Annual throughput	5058	5058	12570	kWh
PV self-consumption	1533 (48%)	2427 (76%)	2842 (89%)	kWh
PV export	1646	769	357	kWh
Grid electricity import	8782	8576	8911	kWh
Electricity costs	3174	2818	2235	€
% Saving compared to Uncontrolled	0%	11%	30%	

Table 9b. Results under uncontrolled, flexible and V2H charging scenarios (Commuter)

Output parameter	Uncontrolled	Flexible	V2H	Units
Household demand	4179	4179	4179	kWh
HP demand	3620	3620	3620	kWh
Standby losses	0	253	253	kWh
EV depletion	2529	2529	2529	kWh
EV charging	2542	2519	4095	kWh
EV discharging	0	0	1593	kWh
Annual throughput	5071	5048	8217	kWh
PV self-consumption	1621 (51%)	2212 (70%)	2211 (70%)	kWh
PV export	1560	968	969	kWh
Grid electricity import	8721	8823	9142	kWh
Electricity costs	3458	2684	2457	€
% Saving compared to Uncontrolled	0%	22%	29%	

The results for the uncontrolled scenario can be considered as a reference for comparison of the two optimised charging strategies. In the case of the flexible charging the optimisation primarily shifts EV charging to make better use of the PV generation where possible during the day and the lower night time electricity tariffs. In the case of V2H the main additional impact of the optimisation is to use the EV battery to cover household energy demand during peak time electricity tariffs. Consequently, for the optimised scenarios for a non-commuter EV profile, PV self-consumption is increased significantly

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from 48% in the Uncontrolled scenario to 78% in the Flexible scenario, and 89% in the V2H scenario, while for the commuter profile, PV self-consumption shows less improvement, increasing from 50.99%in the Uncontrolled scenario to 69.58%in the Flexible scenario, and 69.53%in the V2H scenario. Thus the export of PV generation is greatly reduced under the flexible and V2H charging strategies. Compared to flexible charging V2H can make further use of the household PV generation but only if the EV is at home during daylight hours. So for example the savings from implementing V2H are likely to be higher for the non-commuter user as the EV is plugged more during daytime and peak hours and so can avail of charging from PV during the day and can also avail of discharging to cover household usage during peak hours.

The total quantity of EV charging is greatly increased in the case of V2H by about 2.5 times (for non-commuting users) and 1.6times (for commuting users) compared to that of uncontrolled and flexible strategies, resulting in its PV export being much lower than its flexible and uncontrolled counterparts. The annual throughput refers to the amount of energy that passes through the EV battery in a given year, consisting of EV charging, EV discharging and EV depletion from driving. It is notable that annual throughputs under V2H are over two times (for non-commuting users) and over 1.5 times (for commuting users) higher than annual throughput under uncontrolled and flexible scenarios.

The comparison of EV battery SOC across the full year for both non-commuter and commuter profiles are illustrated in **Figure 5**. For uncontrolled and flexible cases, the EV battery energy usage only results from driving, whilst the energy usage of V2H is results from both driving and discharging to supply the household. Flexible and V2H strategies share the same SOC constraints from **Table 8**, however the time variations of the SOC under V2H are more frequent and most dense, due to the discharging to supply household electricity consumption. By comparison to the non-commuter profile, the commuter profile has more frequent variations in EV SOC, due to its higher EV depletion from **Table 9**.

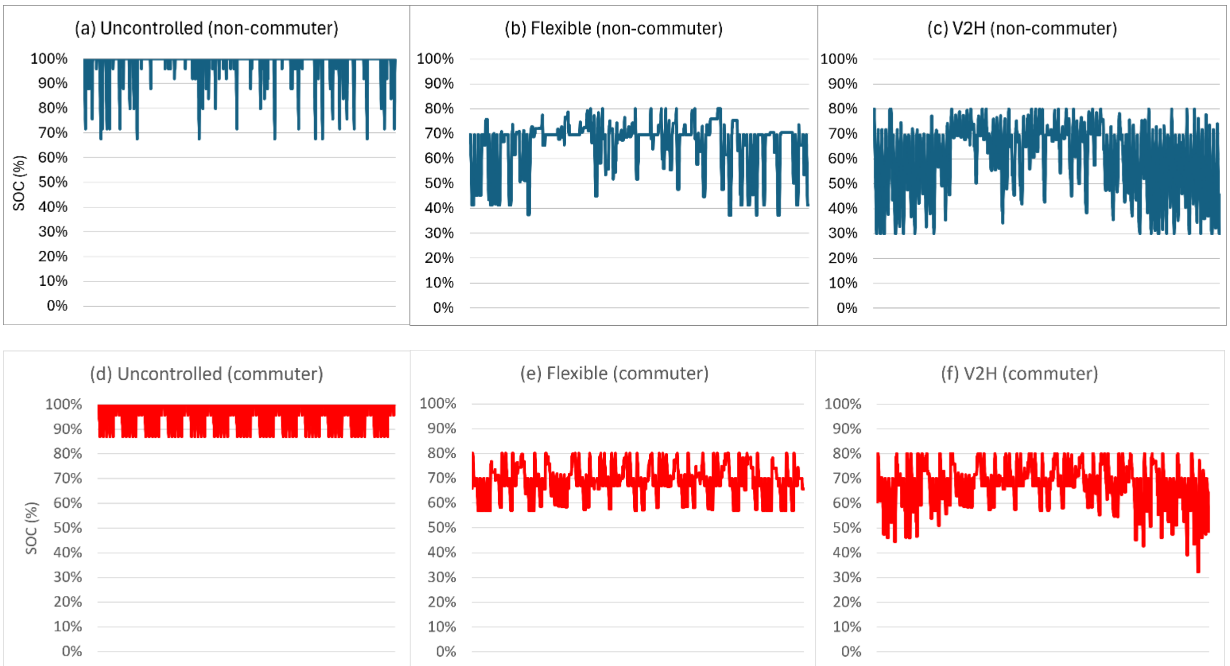

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Figure 5. EV SOC for every hour throughout the year under (a) uncontrolled (non-commuter), (b) flexible (non-commuter), and (c) V2H charging strategy (non-commuter), (d) uncontrolled (commuter), (e) flexible (commuter), and (f) V2H charging strategy (commuter).

Despite the greatly increased charging energy for V2H in **Table 9**, V2H presents only a marginal increase by merely 1.7% (for non-commuting users) and 9.2% (for commuting users) in the total grid electricity demand, compared to the uncontrolled charging. Also, by comparison to uncontrolled charging, flexible and V2H charging strategies lead to substantial reductions in electricity costs with a 11% reduction in energy costs (€356) using flexible charging and a 30% reduction (€939) using V2H in energy costs for non-commuting users. For a commuting user, there are a 22% reduction (€774) using flexible charging and a 29% reduction (€1001) using V2H in energy costs. A non-commuting V2H user has a cost saving of €939/a, whilst a commuting V2H user has a cost savings of €1001/a. The V2H cost savings are comparable to the revenue in the Sciurus V2G case study (Ghatikar and Alam, 2023),

The average grid demand (averaged across all days of the year) at each hour of the day under the three different charging strategies is shown in **Figure 6**. Due to the increased PV self-consumption rates, flexible and V2H charging show significant reductions in grid demands during the afternoon and evenings, enabled by the shifting of EV charging to the nighttime making use of the low electricity tariffs. The V2H charging strategy further reduces peak time electricity demand bringing about significant cost savings and reducing the grid stress during peak hours. For the non-commuting profile in **Figure 6**(a), the negative grid demand from 10:00 to 12:00 results from the PV export for which uncontrolled charging has the highest negative quantity. Furthermore, compared to the non-commuting profile, the commuting profile in **Figure 6**(b) brings about higher peaks during the nighttime under the flexible and V2H scenarios, and leads to deeper negative grid demand from 09:00 to 15:00 under all charging scenarios. The uncontrolled scenario for EV commuter brings about a spike during the peak hour of electricity tariff. These results highlight the potential for V2H to significantly alter the shape of the residential energy demand profile which can clearly be used for the benefit of the homeowner in terms of energy bill savings but also for the power grid in terms of load demand reduction during peak times.

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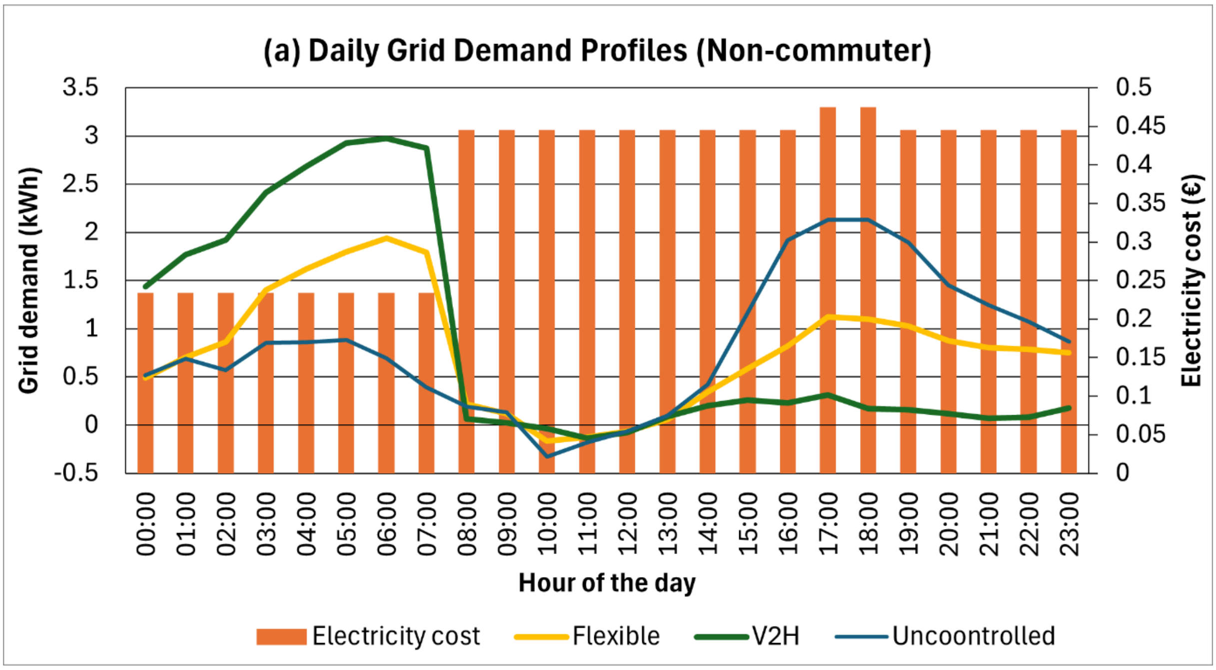
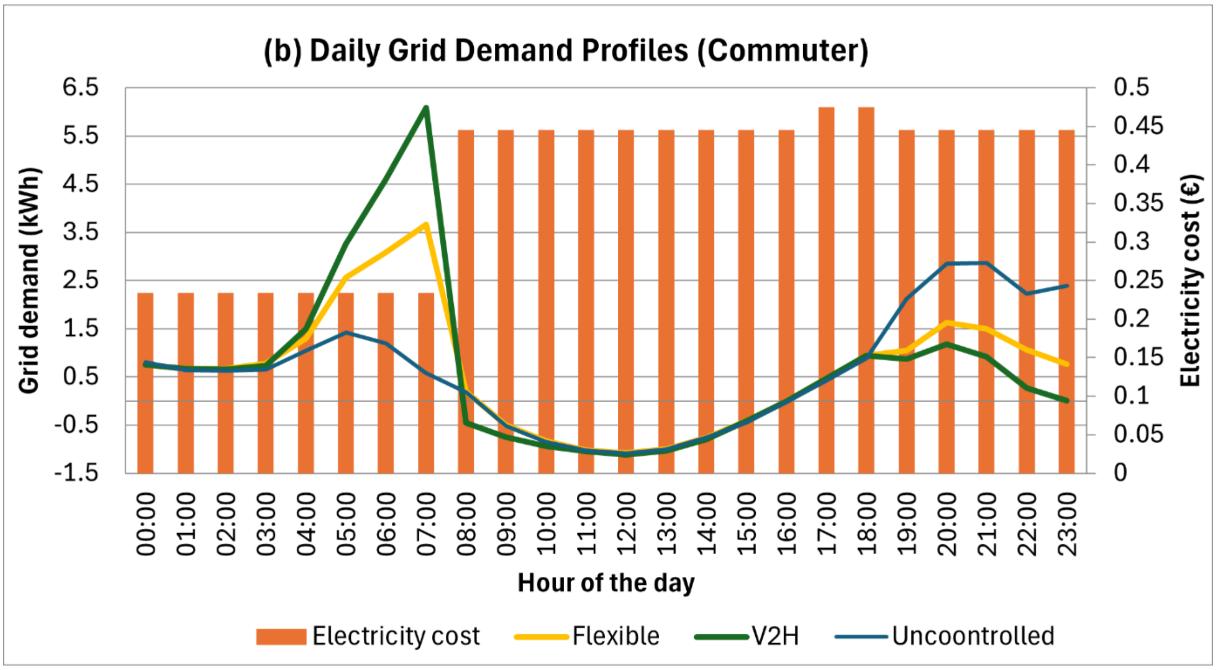


(a)



(b)

Figure 6. Averaged grid demand for each hour of the day averaged over all days of the year (a) Non-commuter, (b) Commuter

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4.3 Sensitivity analysis for V2H cost savings

The results presented in the previous section are based on an "average" commuting and non-commuting user. To better understand how the cost savings are affected by different parameters, it is interesting to perform a sensitivity analysis on these results.

Figure 7 investigates the dependence of the electricity costs using V2H electricity on the installed PV capacity. The dark bars show the cost savings associated with the use of V2H compared to uncontrolled charging for the same installed PV capacity. The orange bars show the total costs. With the increase of PV capacity, total electricity costs show significant declines largely due to the impact of the PV offsetting household electricity consumption and increasing exports. Although the cost savings for V2H compared to uncontrolled charging remain high, there is actually a slight decrease with increased installed PV capacity. When using V2H, a house with no PV has a 25% reduction in total electricity costs of 1050 €/a while a house with a 6-kW PV system has a 37% cost reduction of 913 €/a on the basis of using uncontrolled charging strategy. A large portion of cost saving can be attributed to increased self-consumption of the installed PV system. As cost savings from V2H are due to supplying household energy consumption during higher electricity cost times (peak hours and daytime), with larger installed PV there is less need to do V2H as more of the household demand can be supplied direct from the PV.

In practice for any given household, the V2H cost savings will be influenced by the parameters such as household demand, PV capacity, day and night tariff disparity and PV export prices or EV parameters such as depth of discharge (DOD), battery capacity, charging rate, EV usage and EV availability. A sensitivity analysis is carried out to determine the key factors, which have the more important influence on V2H cost savings. The findings can be seen in **Figure 8**, in which the origin (0%, 0%) represents the base case parameter and savings using the parameters from the non-commuter profile defined in **Table 8**. The individual curves in the graphs therefore represent the change in savings relative to the base case, which results from a percentage change in the given parameter. For example, in **Figure 8**(a) for the curve representing the sensitivity to PV capacity, the base used a PV capacity of 3 kW with savings of approximately €2235, as shown in **Figure 7**. The sensitivity curve then shows the % change in savings if the PV capacity is varied from zero to 6 kW where the values are consistent with those shown in **Figure 7** and show that increased PV capacity has a slight negative impact on V2H savings. The graph also shows that an increase in the PV export tariff negatively impacts V2H savings as this tends to make export of PV to the grid more favourable than using it to charge the EV.

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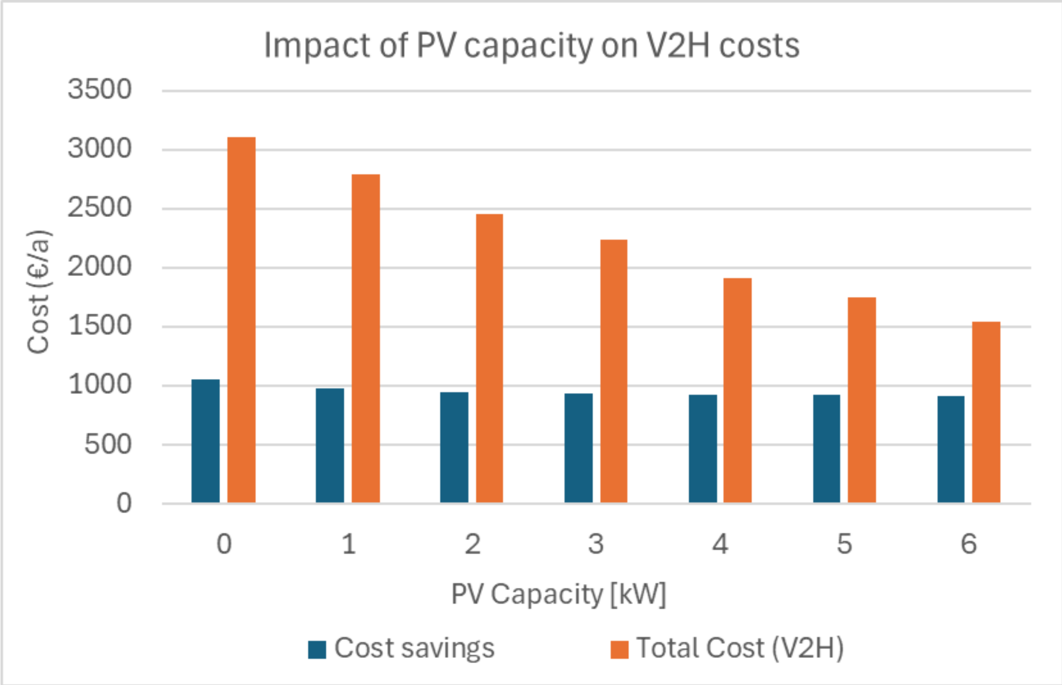
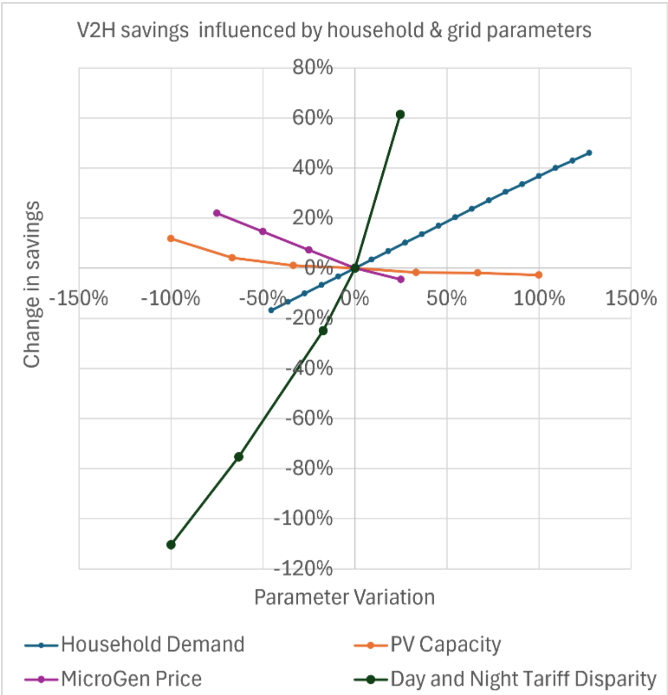


Figure 7. Impact of increasing PV capacity on annual electricity costs and cost savings relative to uncontrolled charging.



(a)

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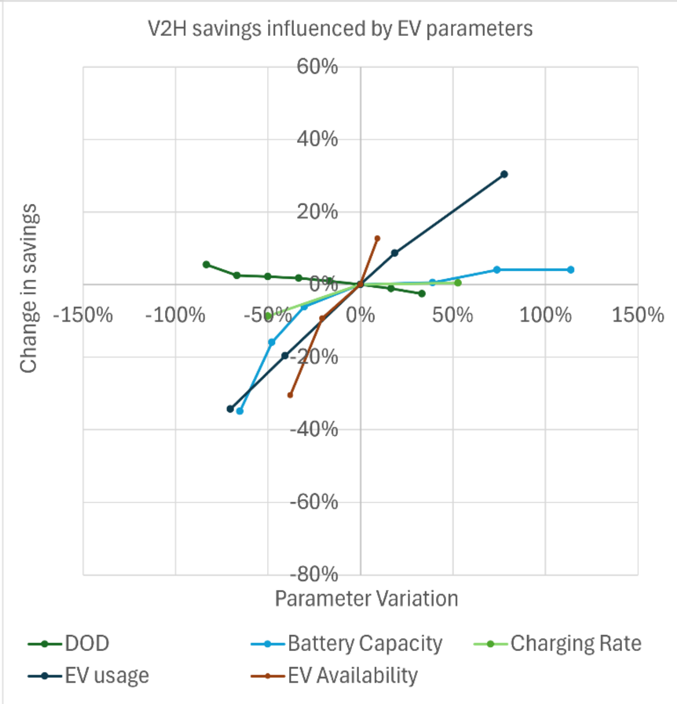

(b)

Figure 8. Impact of various parameters on V2H savings (a) household and grid parameter, (b) EV parameters (DOD refers to EV battery depth of discharge)

Factors which have a very significant positive impact on V2H savings are an increase in household demand and an increase in the difference between day and night tariff rates. $\pm 50\%$ variations in household demand will lead to approximately $\pm 20\%$ changes in V2H savings. Increased household demand gives more opportunity for V2H to shift more of the household grid imports to less expensive times. Similarly, a greater difference between day and night tariffs increases the saving associated with the time shifting of household imports from the grid. $+20\%$ and -50% variations in electricity tariffs will lead to resultantly $\pm 60\%$ changes in V2H savings.

Figure 8(b) shows the sensitivity analysis for parameters associated with the EV. In this graph it can be seen that increasing the allowable minimum DOD has a negative impact on V2H savings, since a higher minimum SOC reduces the capabilities of V2H to supply the house load. Increasing all other parameters show a positive impact on savings. Increases in battery capacity and charging rate (i.e. EV charger maximum power) show a saturating effect, where low values of both definitely constrain savings but increasing beyond a certain value doesn't significantly increase savings. For the investigation of EV parameters, the savings are largely affected by an increase in EV availability and an increase in EV usage. As well as household demand, $\pm 50\%$ variations in EV usage will also bring about approximately $\pm 20\%$ changes in V2H savings. And the slope of EV availability is more than 2 times higher than that of EV usage.

However, the trend from the sensitivity analysis of PV capacity from **Figure 8** is in contrast with the findings in [Kern et al. (2022)](), which found that V2H savings could increase by approximately 58.3%

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with a 100% increase in PV capacity under the flat tariff. However, by adopting the 3-tier tariff, increasing the PV capacity by 100% results in a decrease in savings by merely 3%. Under the 3 tier tariff structure the main cost savings results from the difference between day and night electricity tariffs and the consequent shifting of electricity demand and charging to the nighttime. With the increase of PV capacity, however there will be less grid demand to be shifted to the nighttime. However, under a flat tariff there is no financial advantage to shifting the grid demand to the nighttime and the savings are due to the higher PV capacity offsetting more of the demand.

4.4 Net present value and discounted payback period of V2H investment

To evaluate the business case for V2H application in a household, it is necessary to calculate the net present value (NPV) of a V2H investment across multiple years and determine its discounted payback period (DPP) under a variety of scenarios. NPV is defined as the difference between the present value of cash inflows and the present value of cash outflows over a period of time (NBER 2023).

The NPV over a 10-year timeframe is shown in **Figure 9**. It is difficult to obtain reliable cost estimates at present for bidirectional chargers and their installation costs. Some online resources suggest that the costs of bidirectional chargers may be two to three times higher than unidirectional chargers. Online prices for the Wallbox Quasar 2 bidirectional charger suggest prices of approximately $6,000. Because of the uncertainty associated with the cost parameters the NPV is calculated for three cases. Low-cost, medium-cost and high-cost cases are modelled with capital investment costs of €3000 (3% discount rate), €6000 (6% discount rate) and €10000 (9% discount rate), respectively. As a result, in the low-cost case the expected NPV after 10 years is positive at €4549 with a very low payback period of just over 3 years. In the medium cost case, the NPV is also positive after 10 years with a value of €514 and a payback period of approximately 8 years. The high-cost case shows a deficit of -€4318 after 10 years indicating that if the initial costs are too high then the economic case for V2H is very weak. These NPV values are undoubtedly sensitive to the parameters examined earlier in **Figure 8**.

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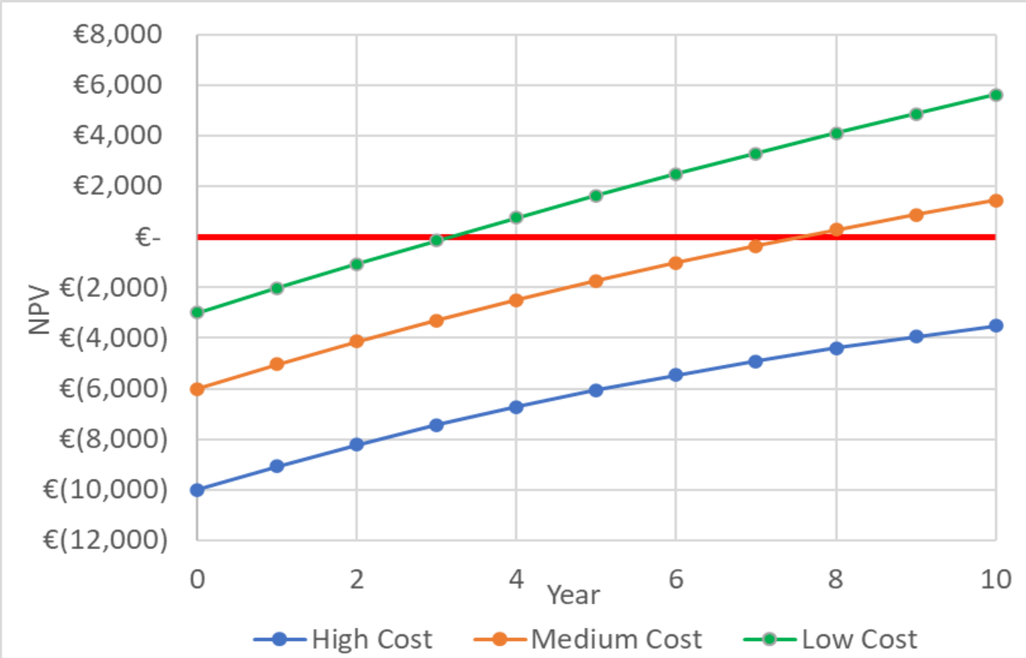

Figure 9. NPV of V2H investment over 10 years under High Cost (investment cost €3000 with 3% discount rate), Medium Cost (investment cost €6000 with 6% discount rate) and Low Cost (investment cost €10000 with 9% discount rate) Scenario cases.

Figure 10 investigates the DPP under the influence of investment costs by assuming a discount rate of 4% with a 3-tier electricity tariff over a 10-year period. The baseline case reflects the conditions represented by the origin (0%, 0%) in **Figure 8**. In addition, to the baseline case, there are three additional scenarios investigated in this sector: 1) Scenario I reflects the least favourable household conditions from **Figure 8**. It assumes a low annual household demand of 2400kWh, 40-kWh EV battery capacity, 54% EV availability and small difference between day and night electricity tariffs; 2) Scenario II reflects the most favourable household conditions for V2H from **Figure 8**. It assumes the house has a high annual household demand of 9600kWh, 100-kWh EV battery capacity, 95% EV availability and a large difference between day and night electricity tariffs; 3) Scenario III reflects the baseline case with its electricity costs inflated by 5% each year.

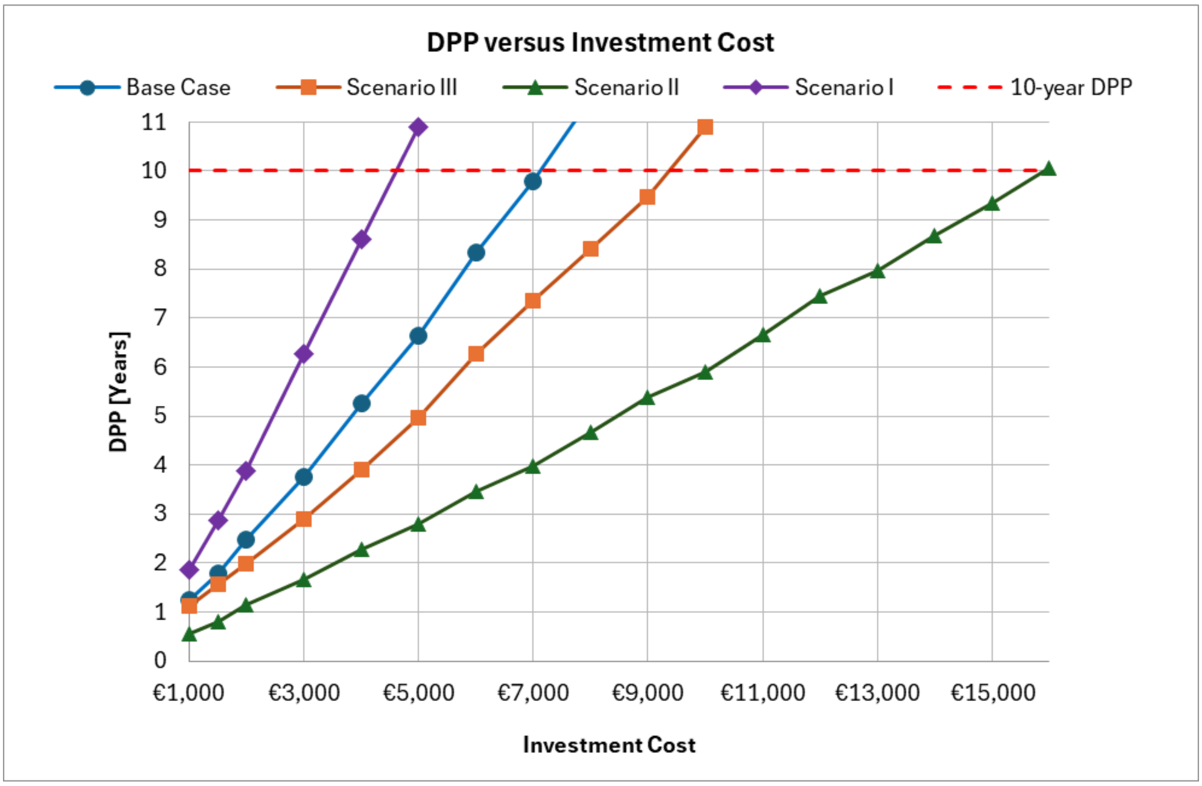

Figure 10. DPP against Investment cost for a variety of household scenarios

The DPP of the baseline case is within 10 years once the investment cost is below €7,000. Scenario I will earn its investment back within a decade if its investment cost is approximately €4,000, whilst for Scenario II, an investment of up to €15,000 would be deemed worthwhile. This is due to the fact that Scenario II has V2H savings of 2038€/yr, and by comparison, Scenario I generates V2H savings of merely 98€/yr. Scenario III assumes that electricity costs increase by 5% each year over the 10 year period and under this scenario the maximum investment cost could be approximately €9,000 in order to get its payback within a decade. The baseline case could be considered a worthwhile investment as its DPP is below 10 years assuming an initial cost of €7,000 and this maximum investment cost will decrease to €6,000 under a discount rate between 5-7% and further decline to €5,000 under a discount rate between 8-9%.

4.5 Comparison of Irish and Italian V2H cases

The economic case for V2H may also be impacted by factors which are country specific, and it is therefore interesting to compare the economics between countries. Here we compare the case of Ireland with that of Italy. It is worth noting that the average annual household electrical consumption is considerably higher in Ireland (approximately 4200 kWh) compared to Italy (approximately 2000 kWh). To make a better comparison in the results below, we assume an Italian household with the same annual energy consumption as the average Irish household. It is also worth noting that the

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portion of the population living in apartments in Ireland (approximately 10%) is also much lower than in Italy (approximately 52%) which may mean that V2H has less potential market in ItalyI . Electricity tariff structures also differ between the two countries. As a comparison we compare an hourly dynamic pricing tariff structure for both cases. Ireland does not yet have hourly dynamic tariffs for residential consumers, although such tariffs will be introduced in 2025. The hourly tariffs for Ireland are therefore estimated based on historical hourly electricity prices ENTSOE (2024). The 3-tier D/N/P tariff structure previously described in **Table 8** is also shown for comparison. The Irish hourly dynamic price $C_{Ireland}$ has a normal distribution of $C_{Ireland} \sim N(0.2480, 0.00081)$, whilst the Italian hourly dynamic price C_{Italy} has a normal distribution of $C_{Italy} \sim N(0.10844, 0.00088)$. The rated PV capacity is chosen to be 3 kW for both Irish and Italian users, and the total mean capacity factors of PV are 16.9% in Italy (assuming a location in Rome) and 12.7% in Ireland, according to Renewables Ninja (2025). Other assumptions for the comparison are given in **Table 10**.

Table 10. V2H parameters of Irish and Italian cases

EV system	
Max EV charging/discharging rate	7.2 kW (90% efficiency)
EV charger standby losses	0.05 kW
EV battery capacity	57.5 kWh
Travelling distance per day	33.6 km (Commuter)
Average EV energy consumption per km	0.2 kWh (Commuter)
Max SOC	57.5 kWh (100%)
Min SOC (08:00 - 07:00)	17.25 kWh (30%)
Min SOC (07:00 - 08:00)	46 kWh (80%)

To provide a snapshot comparison of Irish and Italian households under different pricing strategies, **Table 11** shows a breakdown of energy generation and consumption and electricity costs for uncontrolled and V2H charging strategies.

The results for the uncontrolled scenario can be considered as a reference for comparison of V2H cost savings. The electricity costs in the Italian case are much lower than the Irish cases, due to its much lower hourly electricity price, greater amount of PV self-consumption and greater PV exports. By adopting V2H assuming the same annual household consumption, an Italian household will import less electricity from the grid than an Irish household, due to its greater PV generation.

Consequently, by comparison to uncontrolled charging, V2H lead to substantial reductions in electricity costs with a 22.22% reduction in energy costs (€400) under Ireland 3 Tier tariff, a 34.77% reduction in energy costs (€393) under Ireland Dynamic tariff and a significant 61.61% reduction in energy costs (€451) under Italy Dynamic tariff. PV self-consumption is increased significantly from 54.52% to about 72% for Irish cases and from 36.25% to 67.76% for the Italian case. Thus, the export of PV generation is greatly reduced under the V2H charging strategies.

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Table 11. Uncontrolled charging results of Irish and Italian cases

Output parameter	Ireland 3 Tier Tariff	Ireland Dynamic Hourly Tariff	Italy Dynamic Hourly Tariff	Units
Household demand	4200	4200	4200	kWh
EV depletion	2203	2203	2203	kWh
EV charging	2226	2226	2226	kWh
EV discharging	0	0	0	kWh
Annual throughput	4429	4429	4429	kWh
PV self-consumption	1507 (54.52%)	1507 (54.52%)	1607 (36.25%)	kWh
PV export	1257	1257	2826	kWh
Grid electricity import	4920	4920	5685	kWh
Electricity costs	1800	1462	731	€
% Saving compared to Uncontrolled	0%	18.78%	59.39%	

Table 12. V2H results of Irish and Italian cases

Output parameter	Ireland 3 Tier Tariff	Ireland Dynamic Hourly Tariff	Italy Dynamic Hourly Tariff	Units
Household demand	4200	4200	4200	kWh
EV depletion	2203	2203	2203	kWh
EV charging	3045	2341	2766	kWh
EV discharging	842	138	564	kWh
Annual throughput	5248	4544	4969	kWh
PV self-consumption	1994 (72.14%)	1988 (71.92%)	3004 (67.76%)	kWh
PV export	770	776	1429	kWh
Grid electricity import	5269	5126	4290	kWh
Electricity costs	1400	1069	280	€

Table 13 compares the details of the uncontrolled, flexible and V2H cases for the Italian data in order to give some more insight in to the relative advantage of V2H over flexible unidirectional charging. As can be see a large portion of the savings are achievable with flexible unidirectional charging which makes better use of PV generation for charging and charge shifting to low cost hours. As can be seen from Table 13, PV self-consumption improved significantly from 36% in the Uncontrolled scenario to 67.13% in the Flexible scenario, and 67.76% in the V2H scenario. Consequently, there are a 53.08% reduction (€388) using flexible charging and a 61.70% reduction (€451) using V2H in energy costs showing that there is still an incentive of an extra 9% saving for implementing V2H

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Table 13. Results under uncontrolled, flexible and V2H charging scenarios (Italian case)

Output parameter	Uncontrolled	Flexible	V2H	Units
Household demand	4200	4200	4200	kWh
EV depletion	2203	2203	2203	kWh
EV charging	2226	2210	2766	kWh
EV discharging	0	0	564	kWh
Annual throughput	4429	4413	4969	kWh
PV self-consumption	1607 (36.25%)	2975 (67.13%)	3004 (67.76%)	kWh
PV export	2826	1457	1429	kWh
Grid electricity import	5685	4017	4290	kWh
Electricity costs	731	343	280	€
% Saving compared to Uncontrolled	0%	53.08%	61.70%	

4.6 Summary

In summary there are significant cost savings in terms of home energy bills to be obtained from the implementation of V2H charging strategies. Although these cost savings are sensitive to the specific household conditions, assuming an average case they are in the range of 20% to 30% for the case of a commuting EV driver in Ireland and more likely to be closer to 30% in the case of a non-commuting EV driver who can make better use of PV generation. The difference in savings between unidirectional and bidirectional are also substantial. For example, for unidirectional charging compared to uncontrolled the savings are in the range of 20%, whereas they are more in the range of 27% for V2H. These savings assume a 3 tier Day/Night/Peak tariff structure. The savings also hold under a dynamic hourly pricing tariff structure and potentially increase in the Italian case.

Making use of V2H assumes the installation of bidirectional chargers (unless the bidirectional charger is onboard) and the installation of a home energy management system which can calculate optimal charging schedules based on electricity tariffs, PV generation and household demand. Such systems require an investment cost, and the analysis for the Irish case study suggests that if initial investment costs are in the range of €9000 then the discounted payback period would be less than 10 years. Obviously lower initial investment costs would result in lower payback periods.

5. Vehicle to Grid Case Study

To perform a more detailed study of the economics of V2G we present an analysis of the potential revenues from participation of an EV fleet in a demand response (peak shaving) pilot programme in Ireland. The pilot programme, referred to as "Beat The Peak" (https://www.esbnetworks.ie/services/manage-my-energy-use/beat-the-peak-programme/beat-the-

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peak-business) is a demand response programme run by ESB Networks, the Distribution System Operator in Ireland. The programme has two variants, one for residential users and one commercial or business users. The focus of the scheme is to incentivise energy users to reduce their demand during daily peak periods defined as being between 16:30 and 19:00 on working days (Monday to Friday).

Here we focus on the business user case (Beat The Peak Business). The scheme is relatively simple in in its implementation. Commercial Electricity customers or energy management companies (e.g. aggregators) sign up to the programme to provide demand reduction during the peak times. The means by which the demand reduction is achieved is entirely up to the specific customer. For any signed up customer, a baseline value of demand is established from historic metered data. Demand reduction is then measured relative to this established baseline for each demand reduction event. Demand reduction events consist of Daily Events at peak times and other Peak Events which occur depending on grid conditions.

For daily event peak reduction (between 16:30 and 19:00) a minimum payment of €340 per MWh reduced up to a maximum of €680 per MWh reduced is provided. For other peak events the payment is €820 per MWh reduced. Demand reduction is voluntary with payments being reflective of how much demand reduction has been achieved during the specific event time periods.

For the case study we investigate the potential savings associated with flexible charging of an EV fleet of delivery vans, optimised to as to minimise the charging costs for the fleet. The study is based on the real charging data from one depot which accommodates 28 vans being charged from 24 x 7.4 kW chargers. The site also had an overall electricity import capacity limit of 41 kW for EV charging. The vans have a mix of 50 kWh and 75 kWh battery capacities. The delivery vans in question operate a relatively consistent daily schedule five days a week and consequently have a relatively consistent day to day charging demand. Currently, the vans simply use an uncontrolled charging schedule subject to a maximum charging power capacity. The charging costs associated with this form the base case for the analysis.

Figure 16 shows the distribution of plug-in times and plug-out times for the van fleet, which shows the most common plug-in times are in the afternoon before 19:00 and plug out times are in the morning hours between 06:00 and 09:00. Figure 17 shows the distribution of energy consumed by the van fleet during charging sessions. The most common charging session consumes between 15 and 20 kWh.

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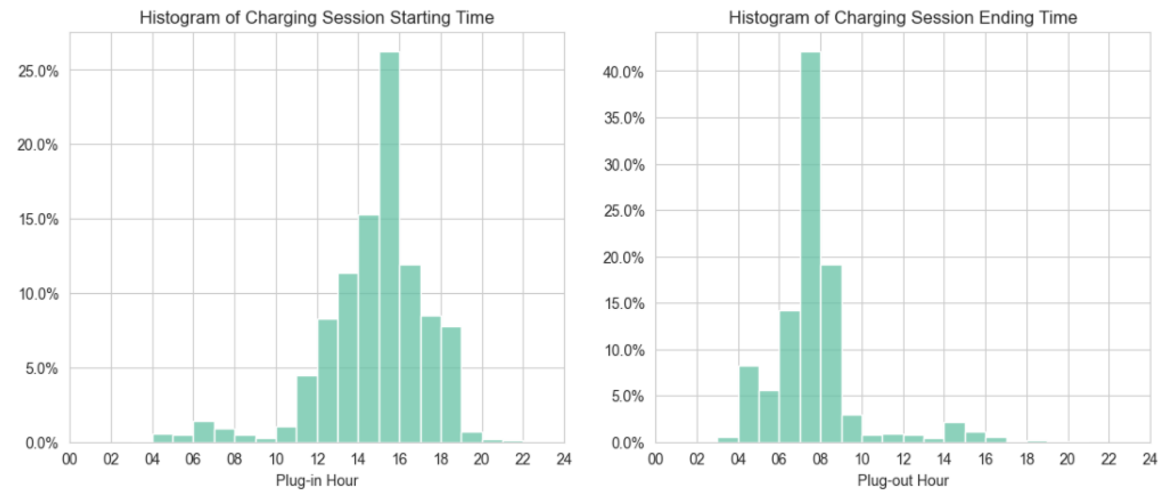

(a) (b)

Figure 16: Distribution of plug-in and plug-out times for the fleet of vans.

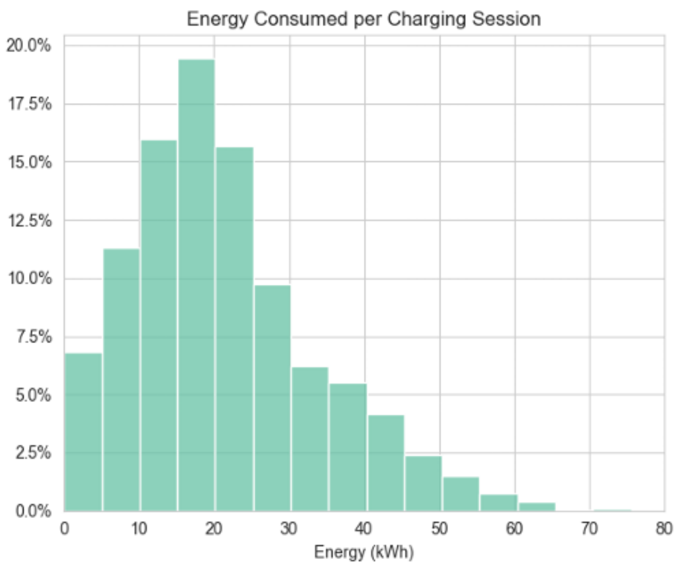

Figure 17: Distribution of energy consumed during a charging session.

A charging schedule optimisation model, similar to that described in the previous section on V2H has been developed, with goal of the optimisation being to reduce total charging costs. Optimisation is performed on an hourly basis for a full year of data. The calculation of costs also includes a cost of battery degradation which has been calculated according to the model in Thingvad at al., 2021 (see appendix A for details)

The charging costs under three cases are investigated.

- **Base Case** assumes a flat electricity tariff structure of 0.287 €/kWh and consequently the charging has no preferred time.

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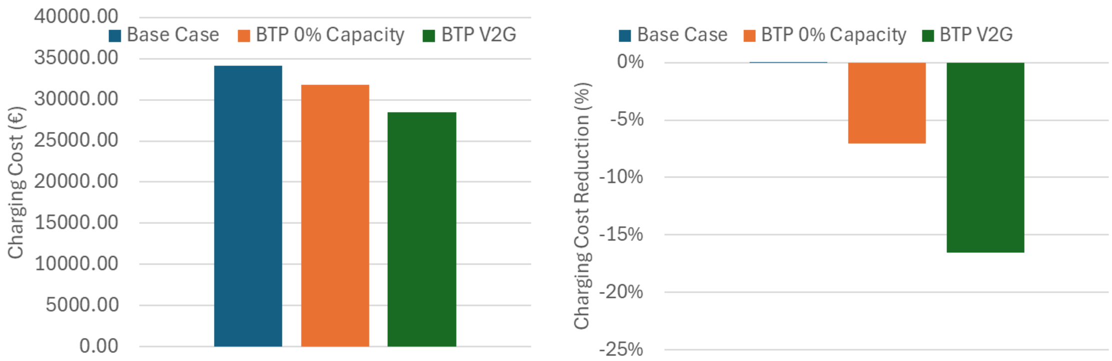
- **Uni-directional Charging** with charging reduced to the greatest extent possible (i.e. 0% or no charging is allowed during peak hours) during peak times while still satisfying the overall charging demand for the vehicles. In this case revenue is also generated from the payments for participation in the BTP programme. The payment is assumed to be a medium payment of €510 per MWh reduced.
- **Bi-directional charging,** with the possibility to export power from the EV batteries during peak times while still satisfying the overall charging demand for the vehicles. In this case it is assumed that revenue is also generated from the exported power at the same rate of €510 per MWh reduced. Note this payment for exported power is not a feature of the BTP programme in its current implementation as it is primarily aimed as demand reduction.

Figures 18 show the results obtained in terms of overall charging costs and percentage reduction in charging costs. The results are based on an optimisation using one year of charging data at an hourly resolution.



(a) (b)

Figure 16 (a) Total Charging costs and (b) percentage cost reduction for the three cases. BTP 0% capacity allows no charging during peak times. BTP V2G allows for export from the EV battery.

The implementation of flexible unidirectional charging, where charging is avoided during peak times, results in an overall reduction in annual charging costs of approximately 7%. The implementation of bi-directional charging more than doubles the reduction in charging costs to 16%. These are relatively significant savings in terms of charging costs reduction, and they mainly accrue from the revenue obtained from participation in the BTP programme. The savings in terms of charging costs per EV per year compared to the base case are shown in Figure 17. These are estimated at €85 and €201 per EV per year for the unidirectional and bi-directional charging respectively. In the case of the bi-directional charging the payments received for export during peak hours more than compensates for the costs associated with the extra charging required. Note that all costs include an estimate of costs due to battery degradation estimated as an average hourly degradation cost over the lifetime of the battery as further detailed in Appendix A . For bidirectional charging the extra degradation cost due to increased cycling is almost 1.4 times the cycling degradation cost associated with unidirectional

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charging. Nevertheless, this extra degradation cost remains a relatively small fraction of the overall charging costs at about 3%.

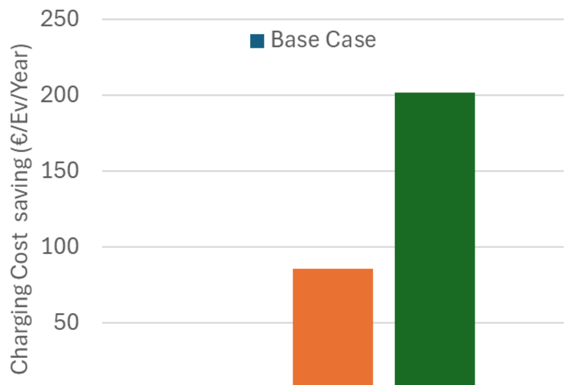

Figure 17 Charging cost savings per EV per year compared to the base case, inclusive of payments under the BTP scheme.

It is worth noting participation in the BTP programme would result in considerable reductions in demand during peak hours. The base case had a demand during peak hours of approximately 3000 kWh. This is reduced to zero under uni-directional charging where no charging is allowed during peak times. Bi-directional charging under V2G could see an additional 17,000 kWh supplied to the grid during peak times

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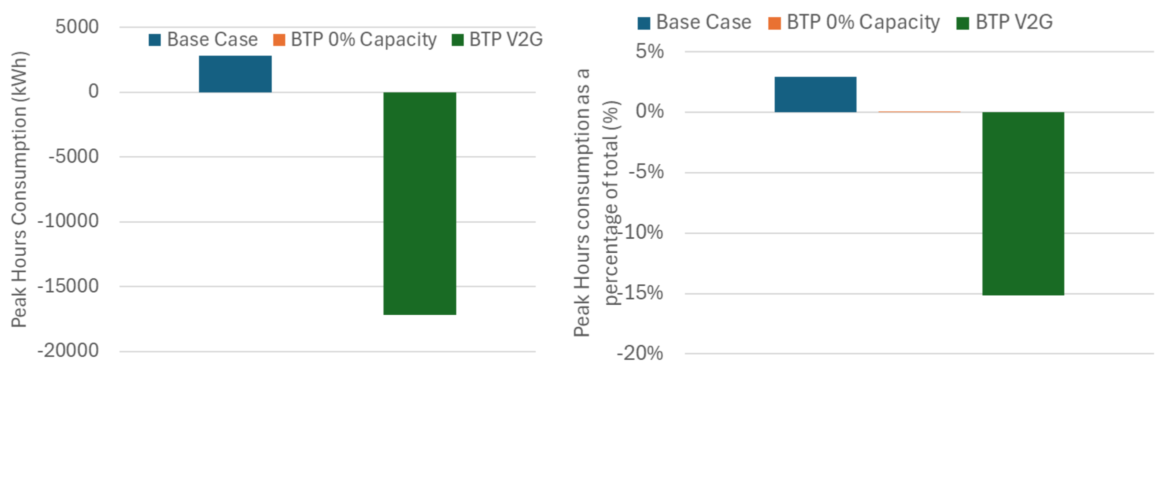

(a) (b)

Figure 18 Reduction in peak hour consumption resulting from participation in BTP programme for unidirectional and bidirectional V2G schemes. (a) shows the peak hours consumption in kWh, (b)

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shows the peak hours consumption (positive) or export (negative) as a percentage of total consumption.

4.7 Summary

Overall, there is significant advantage to participation in this peak shaving scheme, with the payments from the scheme contributing to an 8% reduction in overall fleet charging costs in the case of uni-directional charging. Assuming that exports from V2G were also allowed under the scheme, then charging cost reductions would be significantly higher at 20%. Implementation of bidirectional charging does significantly increase the revenue per vehicle earned from the scheme, however it would be likely also to incur significant extra costs in terms of upgrading charging systems. For example, in this specific case study the savings from charging cost reductions amounted to approximately €5600 per year for the fleet of 28 delivery vans using 24 charge points. The economic feasibility of implementing V2G is therefore highly dependent on the additional extra costs associated with upgrading the charging system. Ag

It is also worth noting that this scheme is relatively simple in its implementation involving only the DSO and Flexibility Providers, where the flexibility provider may be a single commercial electricity customer or an aggregator. In the case where the contract is directly with an electricity customer then all revenue goes to the customer. In the case where an aggregator aggregates multiple customers then revenue will be split between the aggregator and the electricity consumer. In this case therefore revenue need only be shared between one or two stakeholder making the economic case for the stakeholder more attractive.

As with many of these schemes, the BTP programme is a pilot project and the payments for the demand response are relatively high in order to motivate entities to participate. It is unclear if the payments being provided are sustainable in the long term. This lack of longer-term visibility of payments creates an uncertainty which would be a major disincentive for making investments in bi-directional charging costs.

6. Summary and Conclusions

Previous studies in the literature on the economics associated with smart, flexible EV charging reveals a wide range of revenue estimations depending on the use cases. Estimates range from negative revenue (no economic benefits) to values in the range of several thousand euro per EV per year. The variations can be largely attributed to the differences in the exact conditions under study, such as the grid services being provided and the payments (in the case of V2G), electricity tariff structures, the charging power of the EVs and EV battery capacity . However, one aspect is clear; for EV owners, there are almost always significant economic benefits associated with moving charging to low cost times (assuming a variable electricity pricing tariff) and these economic benefits are generally enhanced by moving from unidirectional to bidirectional charging. Therefore, use cases such as Vehicle to Home

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(V2H) would seem to offer significant economic opportunities for EV and homeowners. As regards Vehicle to Grid (V2G) the situation is less clear with some studies suggesting negative revenues depending on the grid service being provided and the assumptions regarding payments etc. In general studies seem to indicate that the provision of services such as secondary frequency control and load levelling offers the best potential for positive economic benefits.

There are large scale demonstrations in FLOW project which address the use cases of provision of frequency support and congestion management to the system. An important point to note is that the practical implementation of these grid services from aggregated EVs involves a range of stakeholders, including EV owners, Charge Point Operators, Electric Mobility Service Provider and Balancing Service Provider as well as the system operator (DSO or TSO) depending on the service. Feasibility of the service would require that there be some economic advantage to all the stakeholders. The renumeration models for the various stakeholder are to be investigated further in WP7 towards the end of the demonstrations.

The simplest use case for bidirectional charging, involving the least number of stakeholders is the V2H use case. When combined with variable electricity tariffs this provides significant opportunities for homeowners to optimise their home energy bills by discharging from the EV battery during peak price times. The detailed analysis for the case study based on data from Ireland suggests the potential to reduce electricity bill by somewhere in the range of 20% to 30% depending on the conditions. These savings should provide a significant economic incentive for homeowners to adopt bidirectional V2H charging, while also providing an added incentive for purchasing an EV. Of course, the savings need to be offset against the initial investment costs, which for a bidirectional charger may be two to three times more than a conventional unidirectional charger. The analysis for the Irish case study suggests that investment costs up to €9000 could be tolerated to ensure a payback period of less than 10 years. It is worth noting that the implementation of V2H also results in a significant shift in the energy demand associated with EV charging away from peak hours, which is advantageous to the power system in terms of reducing peak hour generation requirements.

The economics of V2G have been investigated in some more detail by taking a case study based on an EV fleet participation in a demand response (peak shaving) programme in Ireland. This particular scheme is relatively simple in its implementation involving a minimum number of stakeholders, i.e. only the DSO and Flexibility Providers, where the flexibility provider may be a single commercial electricity customer or an aggregator. Therefore, revenue need only be split between one or two actors making the economic benefits more attractive. The analysis suggests that overall there is significant advantage to the EV fleet owner from participation in this peak shaving scheme, with the payments from the scheme contributing to an 8% reduction in overall fleet charging costs in the case of unidirectional charging. Assuming that exports from V2G were also allowed under the scheme, then charging cost reductions would be significantly higher at 20%. Although the implementation of bidirectional charging significantly increases the revenue per vehicle earned from the scheme, it would be likely also to incur significant extra costs in terms of upgrading charging systems. For example, in this specific case study the savings from charging cost reductions amounted to approximately €5000 per year for the fleet of 28 delivery vans using 24 charge points. The economic feasibility of implementing V2G as opposed to just unidirectional charging control is therefore highly dependent on the additional extra costs associated with upgrading the charging system.

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8. Appendix A: Details of Battery Degradation Cost Calculations

The cost of battery degradation can be split into that which is caused by calendar ageing and that which is caused by cycling ageing. Battery degradation cost was not included as an optimisation variable within this model and instead was calculated after the optimisation run in post-processing.

The total estimated cost due to calendar ageing over the lifespan of the battery was divided by each hour, in order to determine an hourly cost of degradation. Thingvad et al. (2021) describes the percentage of battery degradation with respect to SOC, ambient temperature, and the age of the battery. Taking a typical EV manufacturer's warranty of 8 years to be the expected lifetime, this equates to 5.15% calendar degradation of the battery over its lifetime, or $7.35\text{x}10^{-5}$ %/h. Equation 1 divides this expected degradation by the allowable lifetime degradation (20%) and multiplies it by the cost of replacing the battery (82.80 €/kWh multiplied by the aggregation capacity at a given time). This resulted in an hourly calendar degradation cost of 3.045 · 10−4 €/h, per kWh of battery capacity.

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$$\mathbb{C}_{deg,cal,t} = \mathrm{C}_{battery} \cdot E_{EV,t}^{max} \cdot \frac{d_{cal,t}}{d_{lifetime}} \qquad \text{Equation 1}$$

where

$$d_{cal,t} = \frac{f(SOC) \cdot e^{-\frac{E_a}{RT}} \cdot \sqrt{D}}{h_{lifetime}}$$

given	$C_{battery}$	= 82.80	[€/$kWh_{capacity}$]
	$d_{lifetime}$	= 20	[%]
	D	= 8 · 365	[days]
	$h_{lifetime}$	= 8 · 365 · 24	[hours]
	SOC	= 55	[%]
	T	= 10	[°C]
	E_a	= 24.5	[kJ/mol]
	R	= 0.008314	[kJ/mol K]

and

$$f(SOC) = \begin{cases} -1.04\,x^{\wedge}2 + 89.72\,x + 1224.6 \;\; if\; SOC < 50 \\ 10.35\,x^{\wedge}2 - 1083.6\,x + 31447 \;\; if\; 50 \le SOC < 70 \\ 2.64\,x^{\wedge}2 + 409.55\,x + 22035 \;\; if\; SOC \le 70 \end{cases}$$

In order to calculate the impact that any additional energy throughput will have on the lifespan of the EV batteries, a further equation from Thingvad et al. was used to determine the degradation cost per kWh of energy throughput. Equation 2 describes the cost of cycling degradation as a function of ambient temperature, charging rate (C_{rate}), energy throughput, and battery capacity, again dividing the expected degradation by the allowable degradation and multiplying the result by the cost of battery replacement for the entire aggregation (Battery cost in €/kWh capacity multiplied by total aggregation capacity in kWh). As the C-rate varies depending on the charger, a degradation cost ($C_{deg,cyc,t}$) was calculated for each individual charger used in the case study models.

$$\mathbb{C}_{deg,cyc,t} = C_{battery} \cdot E_{EV,t}^{max} \cdot \frac{d_{cyc,t}}{d_{lifetime}} \qquad \text{Equation 2}$$

where

$$d_{cyc,t} = (\beta_1 T^2 + \beta_2 T + \beta_3)\left(e^{(\beta_4 T + \beta_5)(C_{rate})}\right)\left(\beta_6 \cdot \frac{(P_{EV\rightarrow Charger,t} + P_{Charger\rightarrow EV,t})}{2E_{EV,t}^{max}}\right)$$

given	$C_{battery}$	= 82.80	[€/$kWh_{capacity}$]
	$d_{lifetime}$	= 20	[%]
	β_1	= $8.58\text{x}10^{-6}$	[K^{-2} Ah^{-1}]
	β_1	= - $5.10\text{x}10^{-3}$	[K^{-1} Ah^{-1}]
	β_1	= 0.7589	[Ah^{-1}]
	β_1	= - $6.70\text{x}10^{-3}$	[K^{-1} C_{rate}^{-1}]
	β_1	= 2.344	[C_{rate}^{-1}]
	β_1	= 1.5	[Ah $Cycle^{-1}$]
	T	= 10	[°C]

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