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RESEARCH ARTICLE

Home energy optimization using vehicle-to-home

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Abstract

Background

Vehicle to home (V2H) involves using the energy stored in Electric Vehicle (EV) batteries to lower home energy costs by shifting energy use from high-cost periods to low-cost periods, including charging EVs overnight. This approach also helps manage grid demand peaks and decarbonize the transport and energy sectors.

Methods

This study models a home energy system, integrating grid connections, household energy demands, heating systems, EVs and photovoltaic (PV) panels. The optimization model aims to utilise the EV battery and smart electricity price tariffs to minimize home energy costs. By adopting a 3-tier (Day/Night/Peak) electricity tariff structure, the model compares the results from uncontrolled, flexible and V2H charging strategies. The sensitivity of the cost savings obtained from V2H to a range of parameters such as household, electricity usage, PV installed capacity, tariff differences and EV parameters are also investigated.

Results

By utilizing V2H strategy, the results found that V2H had the overall best savings, with the energy cost reductions up to 30% for non-commuting users and by 27.5% for commuting users. Under the 3-tier tariff structure, the growth of PV capacity leads to a decline in V2H cost savings. V2H has a 25% reduction in electricity costs without PV and a 37% reduction in electricity costs with a 6-kW PV system, compared to an uncontrolled charging strategy.

Open Peer Review

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Conclusions

Under the 3-tier tariff structure, V2H cost savings are achieved by shifting large portions of residential electricity demands into off-peak hours with low electricity tariffs, thus lowering the electricity costs and reducing the grid stress during peak hours with the better utilization of rooftop PV generation. By assuming a 4% discount rate, V2H has its Discounted Payback Period (DPP) within one decade with the initial investment cost of a bidirectional charger lower than €7000.

Plain Language Summary

This article explores the idea that EV owners could make use of the energy stored in the battery of their car to reduce their overall home energy bills. The basic idea is that the energy stored in an EV battery could be used to decrease energy bills by using the EV battery to provide power to the home during times of high electricity prices and could then charge during times of low electricity prices. This is known as Vehicle to Home (V2H). Energy cost savings can be achieved in the case where consumers are charged different prices for electricity usage during the day-time, during peak times (usually the early evening time) and during the night-time. The study assumes that household also have a rooftop PhotoVoltaic (PV) system installed which can also be used to charge the EV during the daytime. The potential cost savings depend on various factors such as household energy usage, installed PV capacity, difference between day, peak and nigh electricity costs and EV parameters. In general, there is potential for achieving significant savings on home energy costs ranging between 20% and 37% depending on the household. However, there is still considerable uncertainty regarding the initial installation costs of a Vehicle to Home system which affects the payback period. The study finds that the discounted payback period on the initial installation costs can be less than 10 years if installation costs are less than €7000.

Keywords

Vehicle-to-home (V2H); Electric Vehicle (EV); Photovoltaic (PV); Optimization model; 3-tier (Day/Night/Peak) electricity tariff; Discounted Payback Period (DPP).

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Introduction

The European Union has adopted the goal of reducing greenhouse gas emissions by at least 55% by 2030 and to become climate neutral by 2050[1]. To achieve this in the transportation sector, the automobile industry has been shifting from internal combustion engines to electric vehicles (EVs). Despite the reduction in carbon footprint, this transition brings about new challenges, particularly in terms of electricity demand and grid management. As most EV charging events occur at home, uncontrolled charging of EVs in greater numbers might put pressure on the power grid[2].

To avoid the peak electricity demand, EV charging flexibility is introduced to shift electricity demand to a preferred time, instead of charging the EV instantly when it is plugged in. The flexible charging strategy adjusts the charging time and rate in regard to the grid demand, electricity tariffs and the availability of renewable energy generation[3]. Flexible charging of EVs can reduce charging costs by 30% and grid operational costs by 10%[4]. Based on a case study of a predicted 5 million EVs in California in 2025[5], managed charging strategy was predicted to reduce renewable curtailment by up to 40% compared to uncontrolled charging strategy.

More recently, bidirectional charging strategies which allow the EV to discharge back to the power grid or the household have gained interest. This gives rise to the concepts of Vehicle to X (V2X) with vehicle-to-grid (V2G) and vehicle-to-home (V2H) strategies[6] being among the most common. Compared to V2H, V2G requires more sophisticated grid infrastructure, regulations and complex control strategies to discharge the power from multiple aggregated EVs to the grid[7]. By comparison, V2H can work "behind the meter" as an alternative controllable load/generator to offer home energy savings for EV users on a small scale, and providing a backup power supply in the case of grid outage. 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 self-sufficiency and cost reduction[8].

A heuristic method for V2H has been presented in 9 to find the optimal charging and discharging hours for an EV battery to flatten the load demand and minimize the electricity bills in a day-long period from a real-time application. Smart homes combined with small-scale distributed photovoltaic (PV) and EV can decrease daily electricity costs[10], and the study in 8 found that V2H implementation with PV could reduce daily electricity costs by 20%. 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[11]. Also, 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 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[12]. V2H applications in Netherlands[13], UK[14], and Japan[15] have also been investigated. It was found that 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[14]. Additionally, a V2H system has been found to improve the PV self-sufficiency rate in households whose annual PV generation exceeds their annual electricity demand[15]. According to the aforementioned studies, V2H cost savings are highly influenced by electricity tariffs, household demand, and PV generation. This paper aims at developing V2H models based on a non-commuting EV profile and a commuting EV profile. Results are presented for a case study using data related to Irish households. The model allows us to the study of the potential for V2H to minimize annual electricity costs and to study the impact of parameters such as PV capacity, household demand, electricity tariffs and vehicle usage on the savings. This work also quantifies the economic benefits to an EV owner by investigating the net present value (NPV) and the discounted payback period (DPP) across a range of investment costs and discount rates. The contributions of this work include the extension of quantification of cost savings due to V2H to a variable electricity tariff structure, specifically a commonly used 3 tier (Day/Nigh/Peak) tariff. The work also includes a more comprehensive sensitivity analysis by including the sensitivity of V2H savings to additional variables such as day and night tariff disparity, EV usage and allowable EV battery depth of discharge (DoD). It is found that V2H savings are largely influenced by EV usage and are most significantly affected by the difference between the day and night tariff with a +20% and -50% variations in electricity tariff difference resulting in ±60% changes in V2H savings. It is also found that, under the 3 tier tariff structure the costs savings from implementation of V2H slightly decline with an increase in installed PV capacity which is in contrast to the findings in 12 which were conducted for a flat tariff structure.

This paper is organised as follows: The Method Section describes the model configuration, data acquisition, V2H model constraints, flexible and uncontrolled charging methods and net present value methodology. Results are presented and analysed in the Results and Discussions Section with the main conclusions from the study presented in a final section.

Method

Overview of modelling approach

The methodology is based on the use of an optimization model which minimizes home energy costs over the course of one year. The model takes as input hourly profiles for home electrical energy assuming use of a heat pump for heating, generation from PV, an EV usage profile, and tariffs for import and export of electricity from/to the grid. The primary objective is to optimize the charging strategy of the EV and use of PV generation in order to optimize home energy usage so as to minimize energy costs for the home owner. Uncontrolled, flexible uni-directional charging and full flexible bi-directional (i.e. V2H) charging strategies are considered. Energy costs for a baseline model are first considered and a sensitivity analysis is performed to understand the sensitivity of the cost savings to variations in various assumed baseline parameters relating to the household and the EV. The results of the optimization are used to assess the business case for a home owner using a net present value analysis. The optimization model is implemented using the Spine modelling platform and makes use of the SpineOpt tool for the optimization[16]. The Spine modelling toolbox[17] and SpineOpt[18] are freely available to use under the GNU Lesser General Public License v3.0. Spine is a flexible open-source energy system modelling framework developed in Julia[16]. 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 optimization model to determine the EV battery state-of-charge (SOC), charging and discharging power, electric power imported from grid, etc. These inputs are described further in the section below.

Model configuration

A model in Spine is represented as a set of nodes, units and connections. In general nodes are points where energy flows are balanced and may also incorporate energy storage. Units represent energy conversions, e.g. a generator which converts the fuel to electricity. Connections represent energy flow between nodes, the physics for which can be defined in general to represent any kind of flow (electricity, gas, etc.). For the V2H model the nodes, units and connections are shown in Figure 1. 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. The model aims to optimize the energy flows, so as to minimize energy costs based on time-varying electricity tariffs with a set of predefined inputs and parameters.

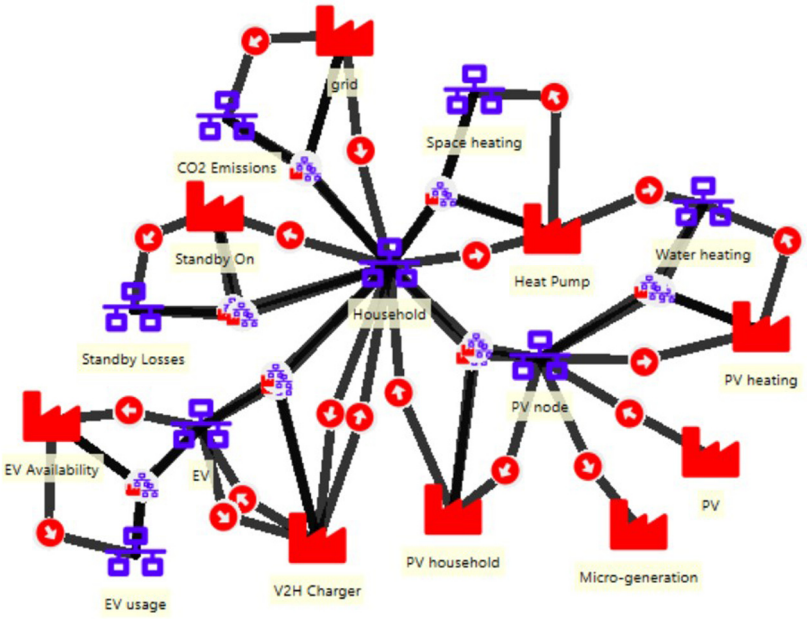


Figure 1. Configuration of V2H model.

The functions of each node and each unit are described in more detail in the following:

- **Household:** The Household node has an associated hourly household electricity demand throughout the year. This node facilitates all the flows in the model, as the electricity from the grid (Unit) or EV (Node) must pass through the Household node to reach the Heat Pump unit, the EV node, and the Standby Losses node.

- **PV system:** The PV unit determines the hourly on-site PV generation. The PV node obtains the electricity from the PV unit to distribute this electrical power to the other units or nodes. After being consumed by the household and water heating demands, the excess PV generation is supplied to a Micro-generation unit. The PV household and PV heating units facilitate the flow of electricity from PV node to Household node and to Water heating node respectively. This micro-generation unit essentially represents electricity exported to the grid from the PV system which receives a payment according to a predefined hourly export tariff.

- **HP system**: The Heat Pump unit consumes energy from the household node to meet space and water heating demands, which are denoted by the Space heating and Water heating nodes, respectively.

- **EV system**: The EV node stores energy, and has an associated battery state of charge (SOC). The V2H Charger unit defines the hourly plug-in status of the EV charger and facilitates the EV charging and discharging between the EV node and the Household node. The charger capacity and efficiency are defined in the connections between V2H Charger unit, Household and EV nodes. The EV Availability unit defines the EV (essentially whether the EV is at home or away) and also facilitates the depletion of the EV battery from driving. The EV usage node defines the hourly depletion during the time the EV is away.

- **Standby losses**: A non-constant efficiency for the V2H charger is modelled by means of standby losses and a constant efficiency. The Standby On unit determines whether EV is connected to the charger or not. The Standby Losses node determines the hourly standby losses from the EV charger at a fixed rate.

- **Grid**: The grid unit has associated the hourly electricity prices and imported electrical power to the Household node whenever the household demand is not met by either the EV or PV nodes. The CO2 emissions node defines the hourly CO2 intensity of the grid, thus yielding the hourly carbon footprint within the household.

V2H model constraints

The primary goal of the V2H model is to minimize the annual household electricity costs under a set of parameters and constraints with the objective function defined as followed:

$$min\left(\sum_{t=1}^{T}\left[p_{elec}(t)\cdot P_{grid}(t)-p_{export}\cdot P_{export}(t)\right]\right) \tag{1}$$

where $p_{elec}(t)$ corresponds the grid electricity prices, p_{export} is the constant export feed-in tariff, $P_{grid}(t)$ and $P_{export}(t)$ represent the electrical power imported from the grid and exported from the PV over all time steps t, respectively. Note vehicle to grid, i.e. export of energy from the EV battery to the grid is not allowed in this model. Hence, the V2H revenue is determined by the grid electricity imports and export from PV.

The fixed inputs include household electricity demand, HP demand, EV driving depletion, and charger standby losses, which are all supplied by PV generations, EV discharging power, or grid imports. To have the load balance, the total energy supply should be equal to the total energy consumption at a given timestamp t by:

$$\begin{aligned} &P_{grid}(t)+P_{PV}(t)+P_{EV,discharge}(t)= \\ &P_{household}(t)+P_{heatpumb}(t)+P_{EV,charge}(t)+P_{export}(t)+P_{standby}(t) \end{aligned} \tag{2}$$

where $P_{grid}(t)$ is the grid electricity demand, $P_{PV}(t)$ is the on-site PV generated power, $P_{household}(t)$ is the household electricity demand, $P_{heatpump}(t)$ is the heat-pump electricity demand, $P_{export}(t)$ is the exported power from PV, $P_{standby}(t)$ is the V2H charger standby losses, $P_{EV,discharge}(t)$ and $P_{EV,charge}(t)$ represent the amount of energy discharged from EV and charged to EV, respectively.

The standby losses $P_{standby}(t)$ is represented for V2H converter at a constant loss $P_{standby,const}$, when the EV is connected to a charging point (b_{V2H_avail} = 1) under the condition of neither charging (b_{charge} = 0) nor discharging ($b_{discharge}$ = 0):

$$P_{standby}(t)=P_{standby,const}\cdot(b_{V2H_avail}-b_{charge}-b_{discharge}) \tag{3}$$

Owing to the efficiency η, the electric power discharged from the EV and charged to the EV have been curtailed by:

$$P_{EV,discharge}(t) \cdot \Delta t = E_{discharge}(t) / \eta \tag{4}$$

$$P_{EV,charge}(t) \cdot \Delta t = \eta \cdot E_{charge}(t) \tag{5}$$

where $E_{discharge}(t)$ and $E_{charge}(t)$ represent the amount of energy discharging from the EV and the amount of energy charging to the EV battery at timestamp t, respectively, and both of them range between 0 to 7.2 kWh average for any hour.

EV depletion from driving is assumed to be a set rate per hour when it is away from home, and is represented by the energy usage from driving $E_{EV,usage}(t)$. The energy storage in EV battery $E_{EV}(t)$ at timestamp t is dependent on the energy storage at the previous timestamp $t - 1$, $E_{EV}(t - 1)$, charging power, discharging power, standby losses and EV energy according to:

$$E_{EV}(t) = E_{EV}(t-1) + \left(P_{EV,charge}(t) + P_{PV}(t) - P_{EV,usage}(t) - P_{EV,discharge}(t) - P_{standby}(t) \right) \cdot \Delta t \tag{6}$$

In this work, the SOC is constrained to operate within a given range which is set to a minimum of 30% and a maximum of 80%. A further constraint is implemented whereby, at a certain daily departure time, t_{dep}, the state of charge of the battery must at least have reached a minimum level SOC_{dep}. For the baseline model the SOC must have reached at least 70% at 7am. Thus, a binary component $b_{dep}(t)$ is set to be 1 when it is 7am (t_{dep}) every day, whilst $b_{dep}(t)$ is set to be 0 for the other hours. Hence, the constraints related to EV battery SOC are written as follows.

$$E_{EV}(t) \leq 0.8 \cdot E_{EV,max} \tag{7}$$

$$E_{EV}(t) \geq 0.3 \cdot E_{EV,max} \tag{8}$$

$$E_{EV}(t_{dep}) \geq SOC_{dep} \cdot E_{EV,max} \cdot b_{dep}(t) \tag{9}$$

where $E_{EV,max}$ represents the rated EV battery capacity and SOC_{dep} is given as 70%.

Flexible uni-directional and uncontrolledUncontrolled charging methods

Except for disallowing the EV to discharge, the flexible uni-directional charging model shares the same input data as the V2H model. The flexible charging model has a SOC range between 30% and 80%, and standby losses are also taken into consideration. Also, for the flexible charging mode, the minimum SOC must reach 70% at 7am every day.

The discharging process is also excluded in the uncontrolled charging mode. As long as the EV is plugged in, the charging process will continue until its SOC reaches 100%. The uncontrolled charging power $P_{EV,charge,uncontrolled}(t)$ is given by:

$$P_{EV,charge,uncontrolled}(t) \cdot \Delta t = min\left(\eta \cdot E_{cap}, E_{EV,max} - E_{EV}(t) \right) \tag{10}$$

Herein, the EV charger always operates at the full capacity (7.2kWh).

Both the micro-generation power $P_{micro,uncontrolled}(t)$ and the grid electricity demand $P_{grid,uncontrolled}(t)$ in uncontrolled mode are determined by the PV generation, household demand, HP demand and uncontrolled charging power as follows:

$$P_{micro,uncontrolled}(t) = \min\left(P_{PV}(t) - P_{household}(t) - P_{heatpump}(t) - P_{EV,charge,uncontrolled}(t), 0 \right) \tag{11}$$

$$P_{grid,uncontrolled}(t) = P_{household}(t) + P_{heatpump}(t) + P_{EV,charge,uncontrolled}(t) + P_{micro,uncontrolled}(t) - P_{PV}(t) \tag{12}$$

Net present values and discounted payback period

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[19]. NPV estimates the future cash flows in comparison to the initial capital investment by:

$$NPV = \sum_{n=1}^{N} (CF_n / (1+i)^n) \tag{13}$$

where CF_n is the net cash flow at year n and i is the discount rate and N is the number of years over which the investment is evaluated. The NPV in this work is evaluated over a period of 10 years. The cost of battery degradation[20] is also taken into consideration for the net cash flows generated for a given year and different discount rates ranging from 3% to 9% are considered. The V2H investment cost C_{invest} takes V2H bidirectional charger cost C_{V2H}, installation cost $C_{install}$, HEMS cost C_{HEMS}, uncontrolled charger cost $C_{uncontrolled}$, and the grant G into account by:

$$C_{invest} = C_{V2H} + C_{install} + C_{HEMS} - C_{uncontrolled} - G \tag{14}$$

The cost ranges used in this study for those components can be seen in Table 1. The grant allows to take into account a grant incentive often provided by authorities to incentivise the take up of EVs. Currently the grant offered to Irish EV users is €600[21]. For the HEMS, costs range between €91 and €560, but the cost can further reduce to €28 with the replacement of a cheaper commercial HEMS controller[22]. V2H chargers are not yet widely commercially available so the cost is somewhat uncertain. For this study is assumed that the cost for V2H bidirectional charger ranges from €1500 to €7500, and the cost for uncontrolled charger is lower than €1500[23].

The DPP determines whether the investment is worthwhile and is calculated from:

$$DPP = Y + \frac{|A|}{B} \tag{15}$$

where Y is the year before the occurrence of discounted payback period, $|A|$ is the cumulative cash flow year in the year before payback and B is the discounted cash flow in the year after payback. A V2H system is deemed to be a worthwhile investment if the DPP is within 10 years.

Case study data acquisition

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 for the V2H application in an Irish household. The baseline household electricity demand adopts the electricity demand in an average Irish household[12], which has an annual electrical consumption of 4200 kWh. Hourly HP demand data profiles are obtained from a study on 38 German households[24] scaled to the average HP electrical demand for Ireland which is 3300kWh[25].

Irish PV generation data from 2019 is taken from Renewables Ninja[26]. The baseline model assumes a PV rated capacity of 3kW with a yearly generation of 3129kWh. In this work, the baseline EV battery capacity of 57.5kWh is adopted (based on a Tesla Model Y[27]). The EV charging and discharging capacity E_{cap} is set at 7.2kWh with an efficiency of 90%. The EV charger standby losses are given at a constant of 0.05kW. In this work, EV SOC is allowed to range between 30% and 80% for V2H services, whilst at the departure hour (7am everyday), the minimum SOC must be beyond 70%.

Table 1. Ranges of investment costs.

Components	Cost range
Bidirectional charger	€1500 – €7500
Grant	€600
HEMS	€28 – €560
Installation	€500 – €3000
Uncontrolled charger	€1500

In this work, an EV non-commuter and 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[12]. For the commuter profile, Irish National Transport statistics are utilised with the average daily driving distance of 33.6 kilometres[28], by consuming an average energy usage of 0.2kWh per kilometre[27]. The electricity tariffs used for the baseline model are reflective of a typical static day/night/peak tariff from an Irish energy supplier. The electricity export tariff of 20c/kWh is also typical of a tariff available in Ireland. To summarise, the input parameters used in this work are given in Table 2, which will be applied to simulate the non-commuter and the commuter profiles.

Results and discussion

Comparative analysis of uncontrolled, flexible and V2H strategies

To provide a snapshot comparison of the impact of different charging strategies on a household Table 3 shows a breakdown of energy generation and consumption and electricity costs for uncontrolled, and optimal flexible and 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 2.

The results for the uncontrolled scenario can be considered as a reference for comparison of the two optimized charging strategies. In the case of the flexible charging the optimization 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 optimization is to use the EV battery to cover household energy demand during peak time electricity tariffs. Consequently, for the optimized scenarios for anon-commuter EV profile, PV self-consumption is increased significantly 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

Table 2. Input parameters of V2H model.

Household	
Household electricity demand p.a.	4200kWh (Non-commuter)/ 1520kWh (Commuter)
Heat pump demand p.a.	3620kWh (Non-commuter)/ 2485kWh (Commuter)
Grid electricity prices	
Day rate (08:00 –17:00, 19:00 – 00:00)	44.51c/kWh (off peak)
Night rate (00:00 – 08:00)	23.39c/kWh
Peak rate (17:00 – 19:00)	47.46c/kWh
PV system	
PV capacity	3kW
Electricity export price, (p_{export})	20c/kWh
EV system	
Max EV charging/discharging rate (E_{cap})	7.2kW (90% efficiency)
EV charger standby losses ($P_{standby,const}$)	0.05kW
EV battery capacity	57.5kWh
Travelling distance per day	33.6km (Commuter)
EV usage per km	0.2kWh (Commuter)
Max SOC	46kWh (80%)
Min SOC (08:00 - 07:00)	17.25kWh (30%)
Min SOC (07:00 - 08:00)	40.25kWh (70%)

Table 3a. 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	€

Table 3b. Results under uncontrolled, flexible and V2H charging scenarios (Commuter).

Output parameter	Uncontrolled	Flexible	V2H	Units
Household demand	2050	2050	2050	kWh
HP demand	2729	2729	2729	kWh
Standby losses	0	304.9	304.9	kWh
EV depletion	2214	2214	2214	kWh
EV charging	2236	2212	3199	kWh
EV discharging	0	0	1000	kWh
Annual throughput	4450	4426	6413	kWh
PV self-consumption	946 (27.51%)	1356 (39.44%)	1388 (40.37%)	kWh
PV export	2492	2082	2050	kWh
Grid electricity import	6344	6320	6484	kWh
Electricity costs	2042	1629	1478	€

shows less improvement, increasing from 27.51% in the Uncontrolled scenario to 39.44% in the Flexible scenario, and 40.37% 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.

The total quantity of EV charging is greatly increased in the case of V2H by about 2.5 times (for non-commuting users) and 1.5 times (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 2. 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 2, 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 3.

Despite the greatly increased charging energy for V2H in Table 3, 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 user with a commuting profile, there are a 20.22% reduction (€413) using flexible charging and a 27.54% reduction (€564) using V2H in energy costs. 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 3. 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 night time making use of the low electricity tariffs. The V2H charging strategy further reduces peak time electricity demand bringing about significant further cost savings and reducing the grid stress during peak hours. For the non-commuting profile in Figure 3(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 3(b) brings about higher peaks during the night time 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 example 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 home owner in terms of energy bill savings but also for the power grid in terms of reduction of demand during peak times.

Sensitive analysis for V2H savings

Figure 4 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

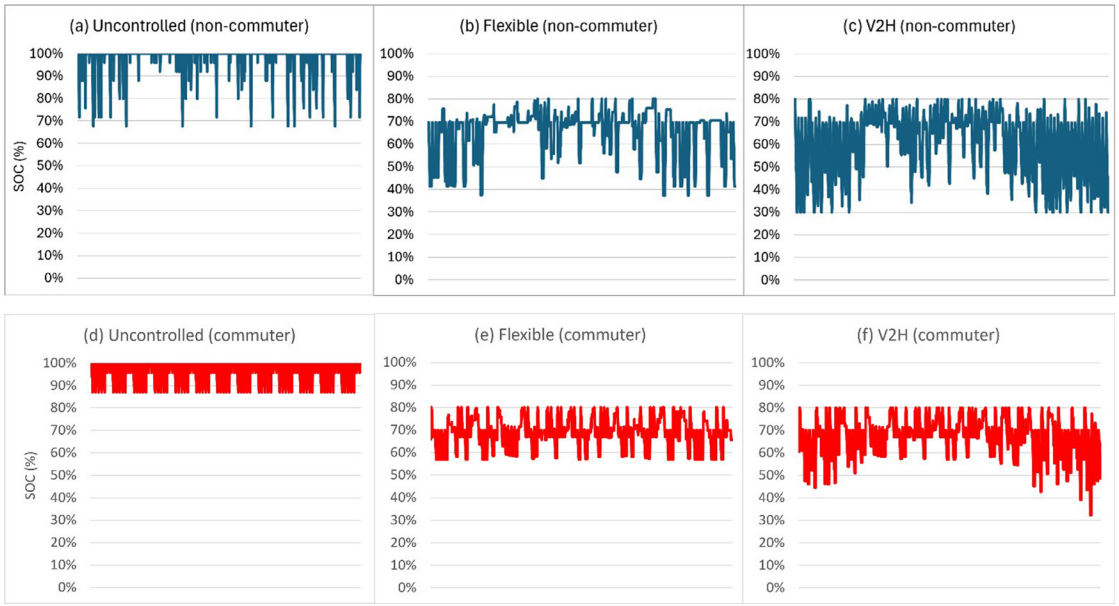


Figure 2. EV SOC for every hour throughout the year under (**a**) uncontrolled (non-commuter), (**b**) flexible (non-commuter), and (**c**) V2H charging strategy (non-commuter), (**d**) uncontrolled (commuter), (**e**) flexible (commuter), and (**f**) V2H charging strategy (commuter).

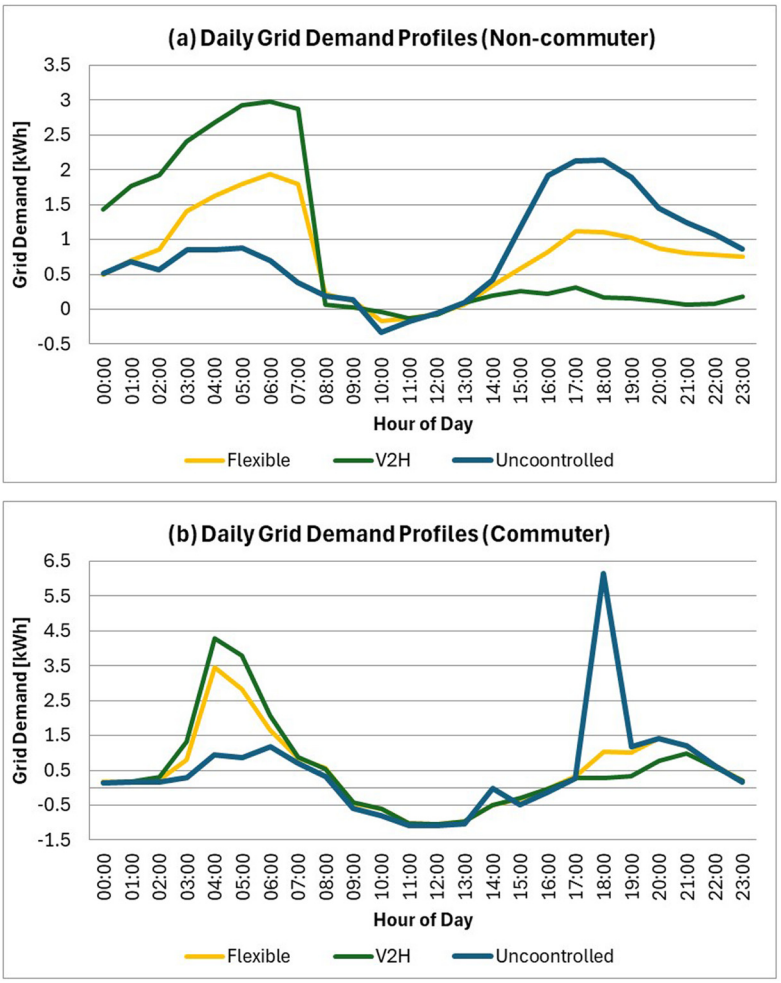


Figure 3. Averaged grid demand for each hour of the day averaged over all days of the year (**a**) Non-commuter, (**b**) Commuter.

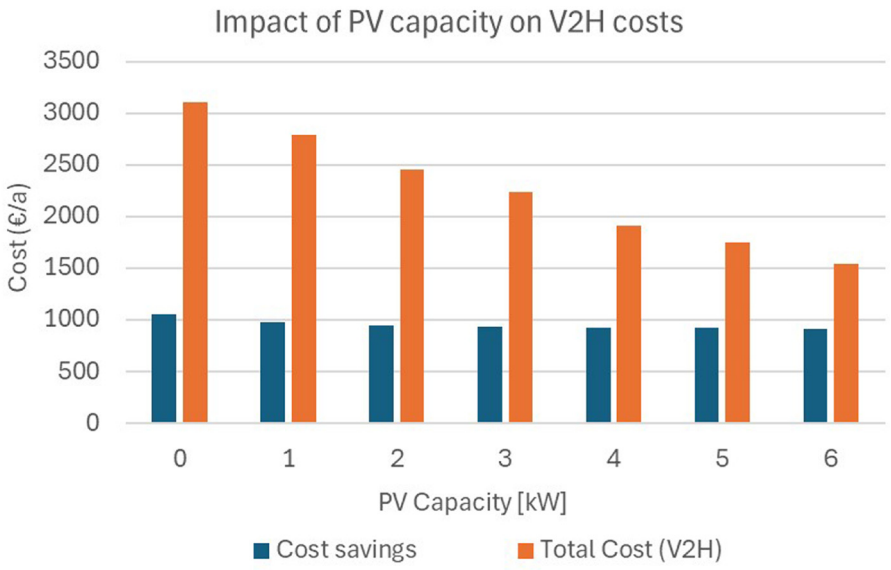


Figure 4. Impact of PV capacity on annual V2H costs.

the same installed PV capacity. With the increase of PV capacity, total electricity costs show significant declines. 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 increasing the self-consumption of the installed PV system.

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 5, in which the origin (0%, 0%) represents the base case parameter and savings using the parameters from the non-commuter profile defined in Table 1. 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 5(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 4. 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 4 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.

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. ±50% variations in household demand will lead to approximately ±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 ±60% changes in V2H savings.

Figure 5(b) shows the sensitivity analysis for parameters associated with the EV. In this graph it can be seen that increasing the allowable minimum depth of discharge (DOD) has a negative impact on V2H savings as might be expected. 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

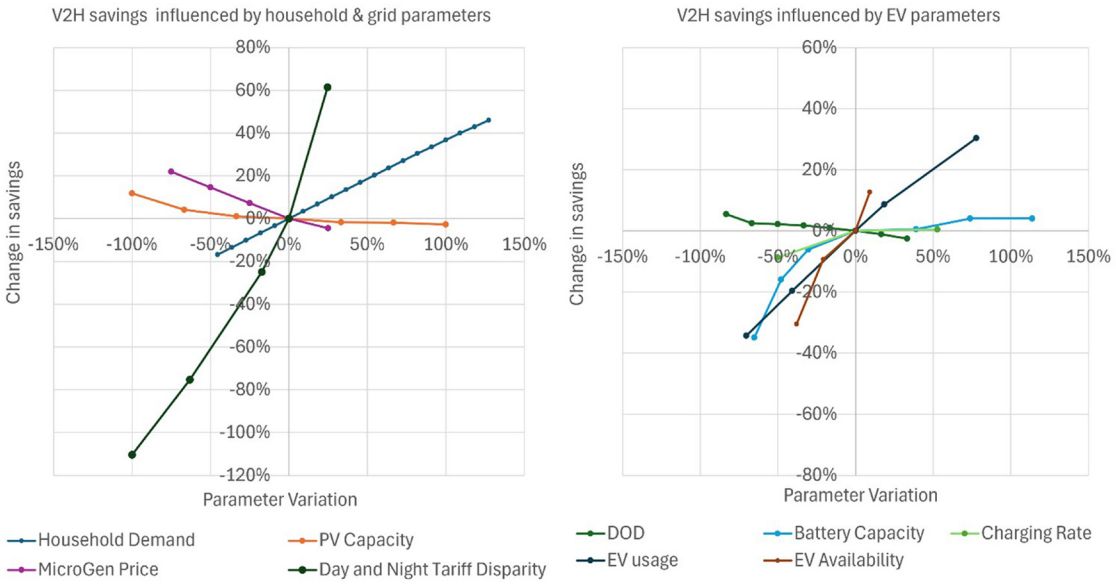


Figure 5. Impact of various parameters on V2H savings (**a**) household and grid parameter, (**b**) EV parameters (DOD refers to EV battery depth of discharge).

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, ±50% variations in EV usage will also bring about approximately ±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 5 is in contrast with the findings in Kern *et al.*[12], which found that V2H savings could increase by approximately 58.3% 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 night time. With the increase of PV capacity, however there will be fewer grid demands 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.

Net present value and discounted payback period of V2H investment

Based on the calculations from Equation (13), the NPV over a 10 year timeframe is shown in Figure 6. Because of the uncertainty associated with the cost parameters the NPV is calculated for three case studies. 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 5.

As to the calculations from Equation (15), Figure 7 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 base case reflects the conditions represented by the origin (0%, 0%) in Figure 5. Apart from the baseline case, there are three additional scenarios investigated in this sector: 1) Scenario I reflects the least favourable household conditions from Figure 5. 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 5. 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.

The DPP of 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

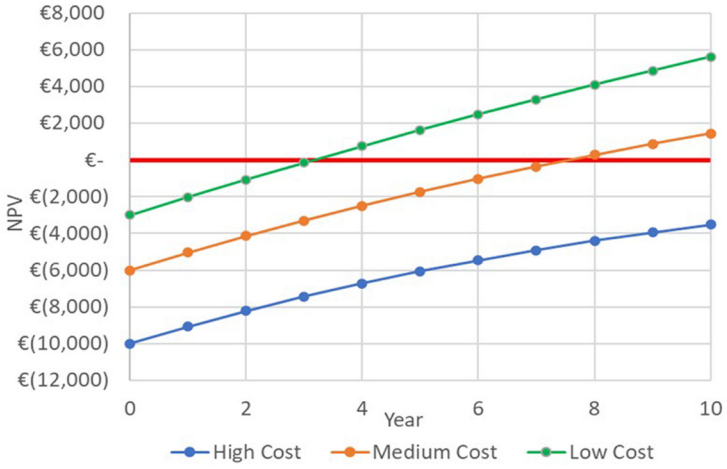


Figure 6. NPV of V2H investment over 10 years under High Cost (investment cost €3000 with 3% discount rate), Medium Cost (investment cost €6000 with 6% discount rate) and Low Cost (investment cost €10000 with 9% discount rate) Scenario cases.

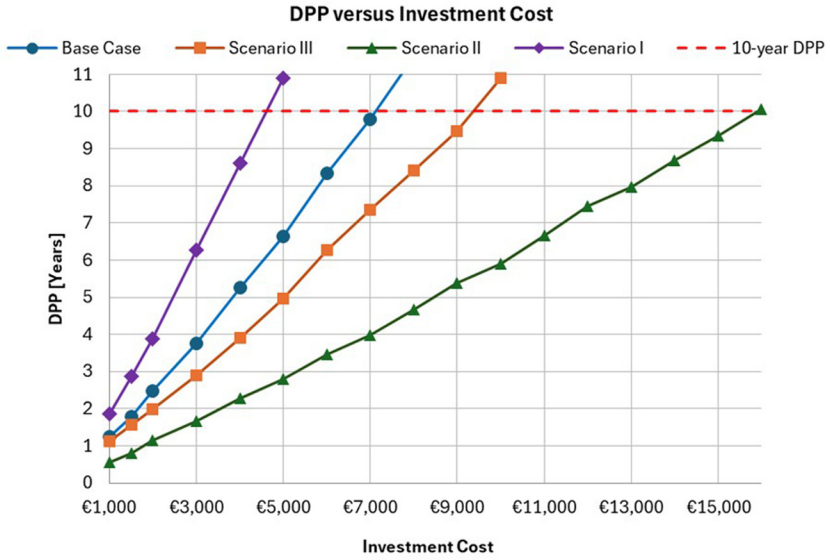


Figure 7. DPP against Investment cost for a variety of household scenarios.

2038€/a, and by comparison, Scenario I generates V2H savings of merely 98€/a. By considering the 5% inflation in electricity prices each year for the 10-year period under the Scenario III, the maximum investment cost is 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%.

Conclusions

This work has presented a V2H optimization model and used it to compare household energy savings from V2H to flexible and uncontrolled charging strategies. The savings from implementing V2H for an average non-commuting user and for an average commuting user in Ireland are found to be 939€/a and 564€/a, respectively resulting in a 30% and 35% overall reduction in household energy costs. These results are consistent with existing literature[4,12,29] with the findings of cost savings ranging from 25% to 36%.

According to the sensitivity analysis, the electricity tariff has the greatest impact on V2H cost saving, because a large difference between day and night tariffs results in EV shifting its demand into the night with cheaper prices. Household demand, EV usage and EV availability are proven to be influential on V2H savings too, whilst charging rate and DOD have minimal impact.

Under the 3-tier tariff structure, larger PV capacity has a large impact on percentage energy savings, but minimal impact on the additional savings from V2H, which is in contrast with the findings in Kern *et al.*[12], which found that the V2H cost savings increase with increased PV capacity under the flat tariff. The main reason for this comes from the difference in day and night electricity tariffs. Under a flat tariff there is no preference for shifting the grid demand to the nighttime, unlike the 3-tier tariff structure which makes substantial savings by shifting the grid demands to the nighttime. An increase in PV capacity leads to less grid demand during the day for the 3-tier tariff to shift to the nighttime.

Additionally, in 12 it was found that an average home cannot make a return on their investment of €6000 within 10 years under the flat tariff[12]. However, by applying the 3-tier tariff structure with a discount rate of 4%, the DPP under an investment cost of €7000 is less than 10 years in this work, due to the cost savings by grid demand shift to preferable low-cost nighttime.

Ethics and consent

Ethical approval and consent were not required.

Data availability

Underlying data

Zenodo: Spine model and datasets for “Home Energy Optimization using Vehicle-to-Home”. https://doi.org/10.5281/zenodo.13940359[30]

This project contains the following underlying data:

- Model output_commuter (2).xlsx
- Model_input_commuter (1).zip
- Non-commuter_spine.zip
- PV, elec, thermal_non_commuting.zip
- Recorded Results and Paramater Variation Graphs - ORE.xlsx
- Spine_commuter.zip

Data is available under the terms of the Creative Commons Attribution 4.0 International

Software availability

The identifiers and links to the repositories are:

- Spinetoolbox applied in Spine model and datasets for "Home Energy Optimization using Vehicle-to-Home"

  Source code available from: https://github.com/spine-tools/Spine-Toolbox

  Archived source code : DOI: https://doi.org/10.5281/zenodo.14638555[31]

  License : OSI approved open license software is under the licenses of LGPL-3.0 andGPL-3.0.

- SpineOpt energy system optimization tool applied in Spine model and datasets for "Home Energy Optimization using Vehicle-to-Home"

  Source code available from: https://github.com/spine-tools/SpineOpt.jl

  Archived source code : https://doi.org/10.5281/zenodo.14638823[32]

  License : OSI approved open license software is under the licenses of LGPL-3.0 and GPL-3.0.

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Open Peer Review

Current Peer Review Status: ✗ ✓

Version 1

Reviewer Report 03 June 2025

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✓ **Soumia Ayyadi**
University of Strathclyde, Glasgow, Scotland, UK

The article discuss a new topics in the literature review but more work need to be done to improve the paper.

- The introduction section needs to be reviewed to be easy in reading and following (e.g., this sentence is hard to follow 'Compared to V2H, V2G requires more sophisticated grid infrastructure' instead the authors may say V2G requires more sophisticated grid infrastructure such as ....)
- The authors need to be precise in writing their sentences (e.g., find the optimal charging and discharging hours. Instead of using charging/discharging hours you may need to say charging/discharging electricity period because the optimization targets the electricity price and not the hours of the day)
- The authors included results in the introduction instead of elaborating in the contribution. The authors need to add more details on how their work differ from the literature review? and what is the newest concept or knowledge of their work?
- Authors need to reword the overview of modelling approach subsection to clarify why they choose using Spine modelling toolbox instead of another toolbox?
- Quality of the Figure 1 needs to be improved
- b_{charge} and $b_{discharge}$ parameters are not defined
- In the equation 6 the authors assume that there are two sources of charging the EV (grid and PV). Is the charging of the EV by both sources happened at the same time? Maybe some binary parameters should be added to the equation 6.
- Add clarification for choosing a SOC minimum percentage of 30%
- subtitle “Flexible uni-directional and uncontrolledUncontrolled charging methods” the word uncontrolled is used two times
- Add references to the Table 1 to show from where you get the cost range
- Add future works in the conclusion

Is the work clearly and accurately presented and does it cite the current literature?
No

Is the study design appropriate and does the work have academic merit?
Partly

Are sufficient details of methods and analysis provided to allow replication by others?
Partly

If applicable, is the statistical analysis and its interpretation appropriate?
Partly

Are all the source data underlying the results available to ensure full reproducibility?
Partly

Are the conclusions drawn adequately supported by the results?
Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Electric vehicle smart charging, flexibility, renewable energy, and battery energy storage system

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Reviewer Report 22 March 2025

https://doi.org/10.21956/openreseurope.20567.r51533

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Yew Weng Kean
Heriot-Watt University Malaysia, Putrajaya, Malaysia

The paper on Vehicle to Home (V2H) energy systems is well written and structured, as it offer a promising study to demonstrate the potential of V2H to reduce household energy costs and enhance grid management. However, the paper on Vehicle to Home (V2H) systems lacks consideration of various real-world EV usage patterns which are crucial for assessing how these systems perform in everyday scenarios. By integrating diverse usage data, such as different commuting distances and charging habits, the study could provide a more realistic view of V2H efficiency.

The study's assumption that the EV battery doesn’t drop below 70% isn't practical for true V2H usage, where deeper discharges might be needed. This makes the setup seem more like a backup battery system rather than a dynamic V2H solution. It would be helpful to see scenarios where the battery dips below this threshold to better reflect its dual usage.

Furthermore, the paper doesn't adequately address the downsides of using EVs in V2H systems, specifically battery wear and maintenance issues from frequent charging and discharging. These factors can significantly shorten the battery's life and increase costs, which could discourage users from adopting V2H technology.

Given these substantial gaps, I recommend major revision of the paper in its current form. However, with major refinements, the paper could be reconsidered for indexing.

Is the work clearly and accurately presented and does it cite the current literature?
Yes

Is the study design appropriate and does the work have academic merit?
Partly

Are sufficient details of methods and analysis provided to allow replication by others?
Yes

If applicable, is the statistical analysis and its interpretation appropriate?
Partly

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Microgrid, smart local energy systems, renewable energy, energy optimization

I confirm that I have read this submission and believe that I have an appropriate level of expertise to state that I do not consider it to be of an acceptable scientific standard, for reasons outlined above.