Simulation tool of Vehicle-to-Home concept for different scenarios

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***Abstract.***  *This paper presents a simulation tool to explore V2H strategies using realistic input data on PV, home demand, EVs, and tariffs. Users can test scenarios by adjusting season, location, vehicle type, and behavior. Results are visualized along with key performance indicators. A case study showed that larger EV batteries do not always improve performance under short connection times. Expert testing confirmed the tool’s usability and relevance for both analysis and education.*

***Key words:*** *Vehicuk-to-home(V2H), simulation tool, battery size impact, context-aware energy management*

# Introduction

The increasing share of renewable energy in power systems calls for greater flexibility. At the same time, electric vehicles (EVs) emerge as a growing but still underused source of distributed energy storage. As transportation becomes increasingly electrified, the correlation between traffic patterns and electricity demand is also intensifying, revealing new interactions between the energy and mobility sectors [3,4].

 Among Vehicle-to-X (V2X) solutions, Vehicle-to-Home (V2H) stands out as a promising approach. It enables bidirectional energy exchange between an EV and a home, turning the vehicle into both a flexible storage unit and a support system for the home [1,2]. This synergy between the home and the vehicle opens new opportunities for improving energy self-sufficiency reducing electricity bills and easing stress on the electrical grid.

 In recent years, a growing number of simulation tools have been developed to support energy system analysis and the integration of distributed energy resources. However, few of these tools are specifically designed to explore V2H strategies in realistic residential contexts. Existing platforms such as HOMER Energy, GridLAB-D, or OpenDSS focus on broader energy systems or grid-level analysis Academic studies often rely on custom-built models in MATLAB or Simulink, but these remain difficult to access and reuse outside specific research environments [5].

 To address this gap, we developed V2Hsim, a lightweight and open-source simulation tool tailored for evaluating residential V2H scenarios and energy strategies. The tool allows for quick UCs testing, supports educational use, and enables comparisons across countries, seasons, and home profiles. It features a visual, parameter-driven interface that based on inputs, calculates key performance indicators (KPIs) such as flexibility, savings, and energy self-sufficiency.

 In this paper, we present the simulation tool and explain its structure and internal logic. Additionally, we explore a set of test use cases representing different levels of correlation between home demand and EV connection. We compare how the EV battery size affects system performance including energy autonomy, flexibility, and cost savings and discuss the results of internal testing and expert feedback. Finally, we reflect on the broader value of such tools for both research and education and suggest directions for future development.

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Figure 1: V2H concept and energy flow diagram

# V2Hsim simulation tool and methodology

We developed a Python-based simulator, V2Hsim, designed to model 24-hour energy exchange between components in a V2H system with an hourly resolution. An interactive version of the tool is available online at [appv2h.streamlit.app](https://appv2h.streamlit.app), the interface is presented in Figure 2. The system includes four components: home electricity demand, photovoltaic power plant (PV), the EV. The energy grid is represented through hourly energy prices (peak, mid-peak, and off-peak tariffs) and used to compute the net load curve when local production and storage are insufficient.

 Further section 2 describes the simulator’s structure in detail, starting with the input data and modelling assumptions, followed by the rule-based simulation algorithm. Additionally, the outputs, the calculated KPIs, and the visualization of the tool is presented. Finally, we present the typical UCs that can be explored through the tools interface.

## Input data and assumptions

For the simulation the tool uses realistic and context-specific input data. The used input data is presented on the Figure 2 For PV generation, we compute hourly profiles for each month and for selected country and consequently city, using irradiance data from PVGIS, assuming a panel efficiency of 20.5 %. These values are scaled according to the installed peak power, which typically ranges from 9 to 15 kWp depending on the selected city. The simulator includes five cities Ljubljana, Paris, Copenhagen, Lisbon, and Athens. PV generation profile is automatically adjusted to reflect each location’s solar potential and seasonal variation.

  Home electricity demand is defined using five behavioural profiles from the literature [6], such as “Morning Glory” or “Evening Users”. Each profile captures a 24-hour consumption pattern, expressed as a normalized hourly distribution (sum = 1), and is then scaled by multiplying each hourly value by the chosen total daily energy demand.

 Users can also choose between different EV types, with battery capacities ranging from 40 to 80 kWh. We assume that the EV is connected to the charging station (CS) 11 kW.They also need to define connection times (arrival and departure) to reflect typical routines or operational constraints in fleet usage. In addition to connection times, users must specify the EV’s state of charge (SoC) at plug-in and the desired SoC at plug-out, which defines the battery’s availability for energy exchanges during the connection window.

 Electricity prices and tariffs follow a three-block time-of-use structure off-peak, mid-peak, and peak defined for each city. The energy grid constrains are predefined in the tool. These dynamic prices guide charging or discharging decisions when PV production is insufficient and enabling cost optimization under realistic energy market conditions more about the decision process you can read in section 2.2.

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Figure 2: General structure of the V2Hsim simulation tool. Inputs feed a rule-based algorithm that computes energy flows, SoC, and key performance indicators.

## Rule based algorithm

The V2Hsim follows a rule-based algorithm that prioritizes energy self-consumption in the V2H concept. PV energy is first used to meet home demand. If additional energy is needed, the EV battery may discharge to support the home, as long as three constraints are respected: the power exchanged cannot exceed 11 kW, the battery SoC must be between 20 % and 100 %, and the user-defined target SoC at departure must be reached. When surplus PV or low-cost electricity is available, the EV charges to meet desired SoC at plug out.

 The EV can only interact with the system during its connection period, defined by the selected arrival and departure times. All the input parameters used in this logic are defined in Section 2.1.

 The simulation produces hourly values for the SoC and for energy flows between the PV system, the home, the battery, and the grid. It also computes KPIs, such as the energy charged and discharged (in kWh), the contribution of PV and EV to home demand, and the utilized flexibility, defined as the energy that the EV provided (discharged) to support the home and consequently reduce costs. Simplified presentation how the algorithm works is presented in Figure 4.

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Figure 3: Simplified decision tree of the rule-based algorithm

## Outputs and KPIs

The simulator outputs a combined visual and numerical summary. As shown in Figure **2**, the main chart displays four hourly curves over a 24-hour period: electricity demand (black), PV production (orange), battery flow (yellow), and EV state of charge (blue dashed). Battery flow is positive when charging and negative when discharging. Green and red dots mark the EV’s arrival and departure times, and the background color reflects local time-of-use pricing and grid tariffs: green (off-peak), white (mid-peak), and red (peak). Visualization on Figure 2 illustrates how the system reacts to solar input, demand, EV battery status, and grid tariffs.

On the right, a summary panel displays calculated KPIs, including:

* energy charged to the EV (from PV or grid),
* energy discharged from the EV,
* activated flexibility (EV support to the home),
* PV usage during EV connection period,
* Energy self-sufficiency
* Savings compared to a home without V2H

The outputs of the V2Hsim tool are also presented on the Figure 3.

## Uses cases

This section presents the UCs selected for demonstration and user testing to evaluate the simulation tool’s performance and usability. Selected UCs are presented in the table 1. Each scenario represents a typical residential V2H setup with varying vehicle connection times and SoC parameters, reflecting different user behaviours and needs. These cases help validate the tool’s capacity to model realistic V2H interactions and provide meaningful feedback on its practical application.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| UC | Arrival  Time | SOC at plug in | Departure  Time | SOC at plug out |
| UC1 "workday home” | 4AM | 40% | 8AM | 80% |
| UC2 “weekend home” | 7PM | 50% | 11AM | 90% |
| UC3 “work employee’s car” | 4AM | 20% | 8AM | 90% |

Table 1. Definition of the three test use cases (UCs).

UCs presented in table 1 encompass typical daily schedules and battery management strategies, allowing users to explore the impact of connection windows and SoC targets on energy flows, cost savings, and flexibility. They also serve as a basis for gathering user feedback on the tool’s interface and outputs, contributing to its iterative improvement (Section 4).

# Case study of the EV battery size impact

To assess how battery size influences V2H performance, we conducted a comparative analysis using two vehicle configurations under identical conditions. The test scenario simulated a summer day in Paris, following UC2 (table 1), with a 9 kWp PV system.

 The only difference between the two scenarios was battery capacity: a small EV (Renault Zoé, 40 kWh) versus a large EV (BMW iX3, 80 kWh), both connected to the CS with 11 kW charging and discharging power. Although the BMW charged significantly more energy overall (38.9 kWh vs. 22.9 kWh for the Zoé), both vehicles achieved similar performance results, they discharged exactly 6.9 kWh to support the home, achieved the same activated flexibility score of 45.4%, and utilized PV production similarly during connection (24.11 kWh), with 19.21% directly covering home consumption. Self-sufficiency was identical at 86.3% as can be seen from the Figure 5.

 Interestingly, the smaller EV battery produced slightly higher cost savings (€0.92 versus €0.88), mainly due to lower reliance on the grid. These results show that for short connection durations and moderate solar input, increasing battery size does not necessarily improve performance. Charging needs and connection times dominate system behaviour, leaving excess activated flexibility potential unused. Without longer availability or greater PV generation, oversizing the battery can lead to underutilized flexibility. This similarity in performance is clearly illustrated in Figure 5.

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Figure 5: Impact of 40kWh and 80 kWh EV battery capacity size on KPIS for the UC (Paris, summer weekday).

# Internal testing with domain experts

To evaluate the simulator, five researchers and engineers from the University of Ljubljana, experts in energy systems but not involved in the tool’s development, participated in a structured user testing

 After a short introduction, they explored a predefined scenario set for Ljubljana during summer, using the “Evening users” home profile and a 12 kWp PV system. Using this setup as a baseline, participants then tested three UC defined in table 1, which differed only in EV connection times and SoC This allowed them to observe how small behavioural changes such as arriving earlier or aiming for a higher final charge and consequently SOC could influence system performance.

 Throughout the simulations, users examined both graphical outputs (energy flows, SoC evolution etc.) and key KPs (flexibility, energy self-sufficiency and cost savings). They then completed a short survey covering both factual aspects and subjective impressions.

 A summary of the responses is shown in Figure 5. Among the three tested UCs, UC1 was by far the most appreciated. It was the most frequently selected scenario across all dimensions: flexibility, energy self-sufficiency, cost savings, and overall preference. This consensus suggests that users found UC1 to offer the best compromise between effective energy exchange with the EV, strong solar integration, and economic benefit. Its early morning connection window and relatively low initial SoC may have allowed the system to maximize EV battery usage without compromising the desired SOC at plug out.

 In contrast, UC2 and UC3 received fewer positive mentions. They were rarely identified as the most performant scenario on any single KPI, and even less frequently chosen as the best configuration overall. While some participants acknowledged their specific features such as the low initial SoC in UC3 or the long connection period in UC2, mentioned did not translate into a strong perceived advantage. This suggests that small variations in timing and SoC targets can significantly affect system performance, but do not always yield better outcomes.

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Figure 6: User perception the three tested UCs

Overall, the simulator was positively received. Users appreciated the clarity of the visuals, the ease of use, and the ability to observe how different parameters affect results. Suggestions included adding tooltips for KPIs, enabling result export in table format, and extending the simulation window beyond 24 hours. One participant emphasized the tool’s potential for teaching energy activated flexibility and user behaviour in academic settings.

# Conclusion

This paper presents a V2Hsim simulation tool designed to explore V2H strategies across different EV profiles and specifications, cities, seasons, and home demand profiles. Through a simple visual interface, it graphically presents the results and calculates KPIs such as activated flexibility, savings, and energy self-sufficiency, supporting both technical assessment and educational use.

 Initial testing with domain experts confirmed its usability and conceptual consistency. Participants were able to interpret key trends, identify performance variations across scenarios, and provided constructive suggestions for future improvement. These insights contributed directly to refining the interface and validating the overall approach.

 A case study on battery size showed that, under short connection times, larger EV battery capacities do not necessarily enhance performance. This highlights the tool’s ability to test realistic trade-offs and challenge assumptions.

 The simulator stands out for its flexibility, ease of use, and ability to support non-specialists in exploring V2H scenarios. Future developments may include multi-day simulations, EV fleet aggregation, and real-time data integration, enhancing the tool’s value for research and educational us

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