Bidirectional Charging (Vehicle-to-Home) in Home Energy Management Systems: Exploring Potentials with a Simulation Tool

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ABSTRACT

The home will become the most important link between heat, electricity and mobility. For instance, the concept of Vehicle-to-Home (V2H) allows to use the average long parking times of electric vehicles for energy management applications in the household. In this study, we focus on developing a simulation model in the Home Energy Management System (HEMS) to explore the impact of bi-directional charging on household energy supply. Different scenarios of bi-directional charging could be simulated. For example, the degree of self-sufficiency of bi-directional systems could be increased by more than 10% compared to unidirectional systems. The results of the simulations show that bi-directional charging has the potential to increase the home self-sufficiency of photovoltaics energy and indirectly to reduce the load from the energy grid. It is important to say that the potential strongly depends on individual user behaviour, the possible charging technology and the presence of the vehicle on site.

KEYWORDS

Bidirectional charging, Battery electrical vehicle (BEV), Home Energy Management (HEMS), Vehicle-to-Home (V2H), Simulation tool, Self-sufficiency

INTRODUCTION

The home will become the most important link between heat, electricity and mobility. This is illustrated by the fact that between 2015 and 2020 in Europe, the installation of heat pumps increased by 81% [1], the installation of photovoltaic systems increased by 313% [2] and the registration of battery electric vehicles (BEV) increased by 1,170% [3]. By transforming the energy system away from a centralized and fossil-based energy supply to a decentralized and more renewable energy system, there are already a large number of opportunities in the household to use energy sustainably and smartly.

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Households are no longer just consumers, but also producers of energy, so-called prosumers. Self-consumption and the flexibilization of households will play an important role in the future. Digital and smart technologies such as Home Energy Management Systems (HEMS) are needed to play this active role. The task of the future HEMS is to optimize the self-consumption of self-generated energy and to make the best possible use of it in terms of energy and economy [4].

In particular, the issue of bi-directional energy flows is becoming increasingly important. The Vehicle-to-Home (V2H) concept allows the average extended idle time of electric vehicles to be used for energy management applications in the home. Related concepts include Vehicle-to-Grid (V2G) and Vehicle-to-Vehicle (V2V), where V2H involves storing excess energy, for example from a personal photovoltaic system, in the vehicle battery and feeding it back into the home grid (AC/DC) rather than the public grid when needed. This approach significantly increases the self-consumption and autonomy of the household.

The principle V2H, for example, is to control the charging processes of the Wallbox with the aim of increasing the self-consumption rate and saving costs [5, 6]. It is therefore an important component of the HEMS. The electric vehicle can be seen as an additional storage or consumer in the system. Furthermore, other functions are possible, such as emergency power generation or grid-serving applications in the context of V2G. In addition to intelligent load flow control, the HEMS will also have to take into account user preferences, such as arrival and absence times (or arrival and departure times).

First of all, bi-directional charging was researched in initial pilot projects [7, 8], and the findings were used to validate the results, see page 3. Furthermore, load profiles for household loads, heat loads (heat pumps) and production profiles (photovoltaics) were collected. Based on the findings from the literature, a simulation model was developed that considers the dynamic interactions between the electric vehicle and the system components in the household.

Similar studies have been carried out in the urban sector, focusing on simulation of larger sites for buses and BEVs of an entire city, which also looked at different smart charging strategies [9]. The developed tool is more concerned with existing technology that is already possible today, without smart charging strategies that would require a variety of technical solutions, such as smart metering infrastructure. This also excludes smart charging, e.g. through multi-agent systems for V2H applications in HEMS, as [10] has investigated. The developed tool will be used to simulate a single-family household with average consumption and electrical system components for a modern house, such as a heat pump and an electric vehicle. In the first stage of development, the focus is on private households, as these are the most electrified (in new buildings also with coverage of heat generation).

In this study, we focus on developing a simulation model in the Home Energy Management System (HEMS) to explore the impact of bi-directional charging on household energy supply. Bi-directional charging allows electric vehicles not only to take energy but also to feed energy back to supply other consumers. The study addresses the following research question:

- *What are the effects of a bi-directional charging system in the V2H-System of a single-family home on the degree of self-sufficiency and self-consumption rate?*

In this context, the following chapters summarise the research results from empirical projects as well as the necessary basics for the creation of the V2H model, such as the required load profiles, and describe the methodology.

MATERIAL AND METHODS

This chapter first presents the results of empirical research projects. This is followed by a more detailed description of the simulation tool and the underlying load profiles, as well as the resulting reference model used for the sensitivity analysis.

State of Research V2H

In order to use bi-directional charging within the V2H concept, technical and infrastructural prerequisites are required. To realise V2H, both the electric vehicle and the home need to be equipped with appropriate technology. This includes a bi-directional Wallbox (charging device) and appropriate connections in the vehicle. In addition to the Wallbox, the BEV must also be suitable and support bi-directional charging; the ISO/IEC 15118-20 standard defines bi-directional charging for vehicles and wallboxes [11].

The main findings of the bi-directional field tests are summarised below. These findings were used to validate the results of the simulation tool.

The feasibility of bi-directional charging has been tested for the first time in Germany in two empirical research projects. These are the *BDL project* [7] and the follow-up project *Bi-clEVer* [8], which was carried out with, among others, the car manufacturer *BMW* and the energy supplier *E.ON SE*. In this project, two real households near Munich (Germany) were equipped with a V2H system. In summary, the following results were achieved, among others: [7]

- Bi-directional charging is technically feasible and can be implemented with the Combined Charging System (CCS) standard [7].
- Self-sufficiency level with BEV and PV system of 24%, with the addition of bi-directional charging functionality increased to 51% and including a home storage system, a self-sufficiency level of 59% was achieved [8].
- The key factors influencing the efficiency of bi-directional charging are the electricity consumption in the household, the performance of the PV system and the user behaviour [7].
- Less important factors are the capacity of the vehicle battery and the charging power. [7].

In summary, the level of self-sufficiency in the real-world environment could be almost doubled. Other business models and opportunities will be explored in the future, such as time-of-use (ToU) and dynamic tariffs facilitated by bi-directional vehicle capabilities. These include ensuring grid stability, energy trading and arbitrage trading based on different electricity prices throughout the day [8].

The results of the studies are a valuable contribution to the creation of the simulation model.

Modelling approach and framework conditions

Once the current state of research has been explored and evaluated, the technical fundamentals of bi-directional charging will be explored. The findings on the technical structure and operation of V2H systems will be used as a basis for the development of a simulation tool. This will be used to simulate a reference household with a V2H system.

The simulation tool will make it possible to show the effects of a V2H concept on different parameters such as self-consumption rate and degree of self-sufficiency, as well as the potential energy savings. The tool has been developed using Excel VBA (Visual Basic for Applications) and offers the possibility to vary relevant parameters, e.g. home storage capacity, user and producer load profiles, as well as BEV with different Wallbox settings and user behaviour data.

The developed simulation tool includes a photovoltaics system for self-consumption use, a home battery storage, household consumer appliances, a heat pump, a Wallbox and battery electric vehicle with bi-directional functionality. In Figure 1 below schematically shows the main HEMS components in a V2H system with a smart Wallbox according to ISO 15118-20.

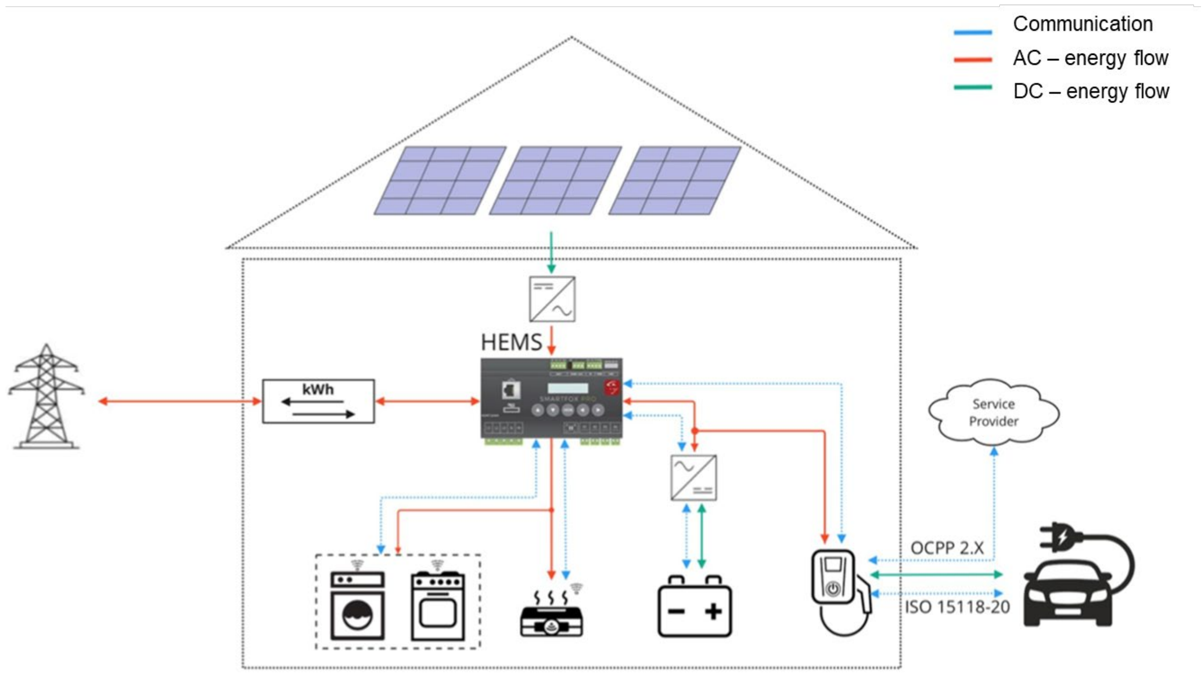

Figure 1. Schematic representation of the components in a V2H system with load flows and communication paths (own illustration, Icon HEMS [12])

In the simulation, all the above system components are considered as a black-box. The black-box method is *"an useful way of roughly structuring complex systems with an initially unknown internal structure"* [13]. In this process, input and output parameters are simplified and used for modelling. Other influencing parameters such as specific user behaviour or driving behaviour, are not included in this model via profiles and are set statically.

The load profiles and database used are described in more detail in the next chapter Reference household and database. This includes synthetic and real load profiles. The output of the tool should be the self-consumption rate and the degree of self-sufficiency, which are defined as follows.

The **self-consumption rate** describes the share of the generated solar electricity that is used either at the same time by electricity consumption or for charging the battery storage [14] (also for the BEV). The higher the self-consumption, the less electricity is fed into the grid, see equation (1) amount of energy for electricity fed into the grid ($E_{Grid\ feed\ in}$) and amount of energy for PV electricity produced ($E_{PV\ production}$) in kilowatt hours.

$$Self\ consumption\ rate\ [\%] = 1 - \frac{E_{Grid\ feed\ in}\ [kWh]}{E_{PV\ production}[kWh]} \quad (1)$$

The **degree of self-sufficiency** indicates the proportion of electricity consumption that is supplied by the photovoltaic system (including storage) [14]. This is achieved either by direct consumption of the solar power generated or by discharging the battery storage. The higher the degree of self-sufficiency, the less energy is taken from the grid, see equation (2) amount of energy for electricity purchased from the grid ($E_{Grid\ demand}$) and amount of energy for annual electricity consumption ($E_{Annual\ electricity\ consumption}$) in kilowatt hours.

$$Self\ sufficiency\ [\%] = 1 - \frac{E_{Grid\ demand}\ [kWh]}{E_{Annual\ electricity\ consumption}\ [kWh]} \quad (2)$$

The decision scheme and logic in the simulation is described in the following bullet points as an example, over 29 cases are considered in the programme, In the process, some use cases could be applied from [6, 15].

- The charging processes are programmed so that the BEV only recharges from the photovoltaic surplus when the home storage is full.
- The BEV is only charged from the grid to reach the minimum State of Charge (SoC).
- The BEV can only be discharged when the SoC is greater than the present minimum SoC of the BEV to ensure some mobility.
- Overall, the home storage is prioritised over the BEV, except when the BEV needs to be charged to the minimum SoC, in which case it is charged from the grid or the stationary battery storage.

In most cases, a current of six amps is required to charge the BEV with solar energy (solar charging) from the photovoltaic system [16]. In practice, this means: Surplus charging (solar charging) only works from a production power of 1.38 kW (single-phase). If three-phase charging is used, a power of approximately 4.14 kW (3 x 1.38 kW) is required for charging. Otherwise the BEV will not charge. This means that for many days of the year, at least for smaller photovoltaic systems, there will be limited time windows available for charging.

The scenarios were created through this hurdle of minimum solar charging power, see Table 3 in chapter Scenarios.

Reference household and database

The simulation of the V2H system is based on a reference household consisting of a modern single-family house with the following systems and configurations, see parameters and values in Table 1.

Table 1. Summary of energy parameters of the reference household

Component	Parameter	Values and units
Household	Number of Person	4 Persons
	Electricity consumption	4,719 kWh/a
Heat pump	Heat demand	6,401 kWh/a
Photovoltaic system	Power	10 kW_p
	Production	10,400 kWh/a
	Orientation	South
	Inclination angle	30°
Battery storage	Capacity	10.24 kWh
	Min. State of Charge (SoC)	10%
	Min. Charging Power	500 W
	Max. Charging Power	5.75 kW
Battery Electric Vehicle	Capacity	58 kWh
	Min. State of Charge (SoC)	30%
	Min. Charging Power	1.38 kW [1]
	Max. Charging Power	11 kW
	Daily consumption	7.5 kWh
	Absence times	08:00 – 17:00 h (during the week)
		16:00 – 18:30 h (at the weekend)
Wallbox	Min. Charging Power	1.38 kW [1]
	Max. Charging Power	11 kW

In addition to the generator profile from the photovoltaic system, various consumption profiles (household consumption, heat pump) and characteristics (electric vehicles) have also been collected. This makes it possible to change modular household parameters or load profiles. The bi-directional BEV charging function was also taken into account. In the simulation tool, different parameters (usage times, charging power, consumption, capacity of the battery from vehicle or home storage) can be adjusted.

[1] The minimum charging power is 1.38 kW for 1-phase AC charging and 4.14 kW for 3-phase AC charging (determined by PWM) according to IEC 61851-1 [17].

Furthermore, the reference scenario consists of a consumption profile of four people (two adults and two children) based on the Type: CHR44 from the *Load Profile Generator* Version 10.8.0 [18]. The generation profile has been simulated using *PV*SOL* premium 2022 Release 7 [19] and, like most load profiles, is based on the reference year 2021.

The heat pump is based on a thermal energy demand of 13,860 kWh/a for a single-family house with a floor area of 132 m², based on [20] and the thermal load profile „*HEF33*" [21]. The heat demand has been converted into electrical demand using the coefficient of performance (COP) for an air-to-water heat pump, a conversion tool was used for this purpose [22].

A minimum range was adjustable to ensure mobility at all times. This was set by default at 37 km/day [23] and an average consumption of 20 kWh/100 km, which corresponds to a daily consumption of approximately 7.5 kWh per day.

The use of standard load profiles is avoided as far as possible, as these cannot reflect the stochastic profile of individual consumers. For this reason, the load profile for the electric vehicle with V2H functionality is developed for this application. All load profiles are stored at 15-minute resolution.

The absence of the BEV is based on the activity log generated by the *Load Profile Generator* for the 4-person household. This shows that the working person works nine hours a day and leaves the house between 08:00 and 09:00 AM. [18] Weekend absences are assumed to be 2.5 hours per day. This results in the selected absence times of the BEV, see Table 1 for weekdays and weekends.

RESULTS

Firstly, the results and functions of the simulation tool are demonstrated using the results of the reference household. Secondly, the scenarios are derived and the results of the scenarios are presented individually, thus forming the sensitivity analysis.

Features of the simulation tool

The core evaluation of the simulation tool displays seven graphs, showing an example of a full year (2021) and one week, one weekday (Tuesday) and one weekend day (Sunday) for summer and winter respectively. Any day or week can be selected from the raw data. The energy assessment in the tool includes the following key figures:

- Total demand for all electrical consumers (household, heat pump, BEV)
- Total production of photovoltaic yield, amount of energy fed into the grid, self-consumption rate and degree of self-sufficiency
- Storage quantities such as discharged energy (home storage and BEV) and number of full charge cycles

In the following, the simulation results for the reference model (from chapter Reference household and database) are presented as an example for a summer day. The following parameters are displayed in Figure 2 over time: Photovoltaic power (Power PV), grid cover, BEV power, stationary storage power, BEV SoC and storage SoC. The power is displayed as an area and can be read on the vertical primary axis. The SoC in percent is displayed as a line and can be read on the vertical secondary axis.

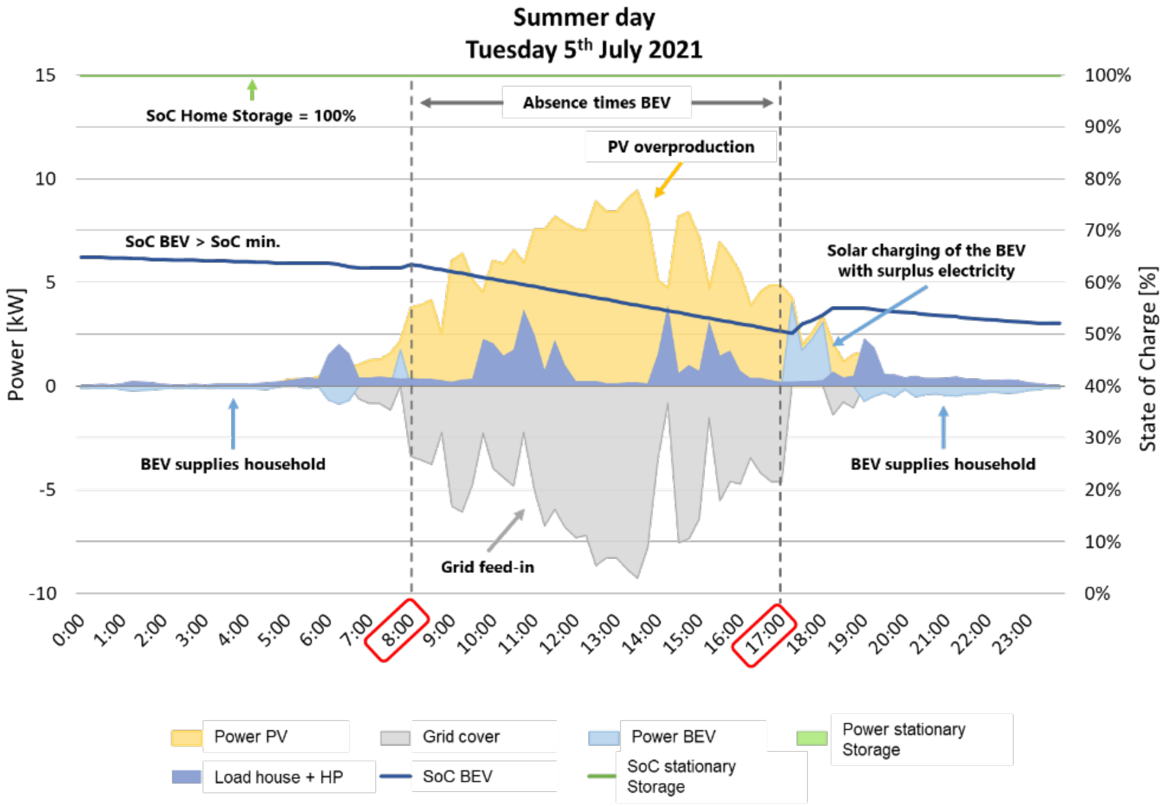

Figure 2. Reference scenario simulation results with evaluation graph of power and SoC curves on a Tuesday 5th July 2021

Table 2 shows the most important energy parameters of the results of the simulation. It should be noted that the values given refer to the reference household.

Table 2. Simulation results for the reference household (in brackets the change compared to the reference household without bi-directional charging)

Parameter	Values
Demand BEV	4,610 kWh/a (0.0%)
Demand Grid	7,590 kWh/a (-9.5%)
Feed-in	3,323 kWh/a (+4.1%)
Discharged Energy BEV	411 kWh/a (-)
Discharged Energy Home storage	1,565 kWh/a (-29.1%)
Self-sufficiency	52% (+10.6%)
Self-consumption rate	68% (-1.4%)

Figure 2 clearly shows that with bi-directional charging there is a problem with the availability of photovoltaic generation over time. Furthermore, Table 2 shows that compared to a unidirectional system, self-sufficiency can be increased by more than 10% compared to the reference household.

On the other hand, Figure 3 shows a comparable winter day. The BEV does not discharge because it does not have enough battery capacity.

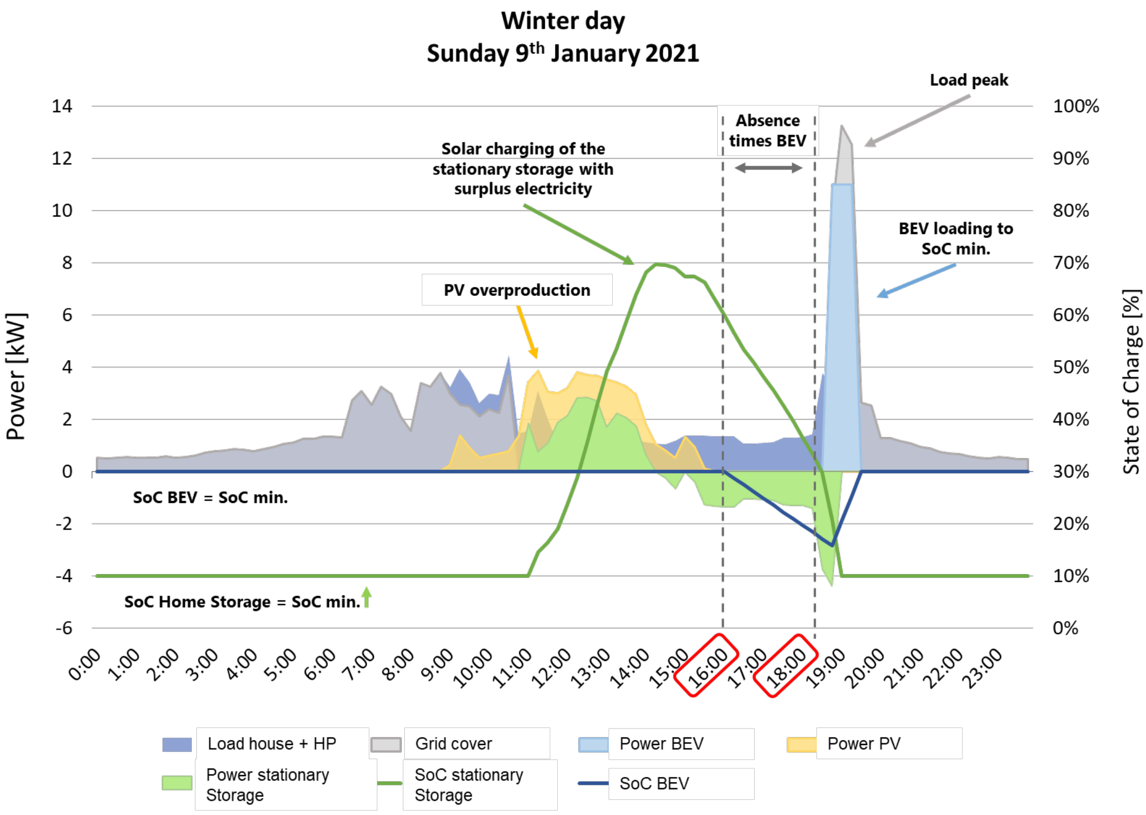

Figure 3. Reference scenario simulation results with evaluation graph of power and SoC curves on a Tuesday 9th January 2021

Scenarios for sensitivity analysis

The standard case for the simulation is a reference household consisting of a detached house with photovoltaic system and battery storage. In addition, several scenarios have been created where the following parameters, see Table 3, have been investigated. The sensitivity analysis scenarios were always compared and described in relation to the reference household, thus showing the effect of V2H functionality.

Table 3. Drawing up different scenarios for a single-family house Reference house

Scenario	Description	Parameter range
BEV battery capacity	Variation of BEV battery size and different min. and max. charging power	- Small 52 kWh - Medium 58 kWh - Large 79 kWh
Charging and discharging power	Variation of charging and discharging power (single-phase and three-phase)	- Slow 1.38 kW - Medium 4.14 kW - Fast 11 kW
Times of use (BEV availability)	Set different static attendance times, using the example of typical employee times	- Fulltime employee (9 hours away) - Part-time employee (6 hours away) - Home-office employee (1 hour away)

BEV battery capacity. The BEV battery capacity was varied in three sizes (small, medium and large) using commercially available BEV storage sizes. Increasing the battery capacity of the BEV has no particular effect on the degree of self-sufficiency. Only the amount of energy discharged by the BEV increases slightly with BEV capacity, as can be seen in Table 4. Furthermore, the effect is amplified compared to the changes in the reference household without bi-directional charging, see percentage changes to the reference household without bi-directional charging in the brackets.

Table 4. Sensitivity analysis BEV battery capacity variation (in brackets the change compared to the reference household without bi-directional charging)

Parameter	Variation of BEV battery capacity		
	Small 52 kWh	**Medium** 58 kWh	**Large** 79 kWh
Demand BEV	4,376 kWh/a (-5.1%)	4,610 kWh/a (0.0%)	5,429 kWh/a (+17.8%)
Demand Grid	7,596 kWh/a (-9.5%)	7,590 kWh/a (-9.5%)	7,589 kWh/a (-9.5%)
Feed-in	3,346 kWh/a (+4.8%)	3,323 kWh/a (+4.1%)	3,300 kWh/a (+3.4%)
Discharged Energy BEV	393 kWh/a (-)	411 kWh/a (-)	452 kWh/a (-)
Discharged Energy Home storage	1,595 kWh/a (-27.7%)	1,565 kWh/a (-29.1%)	1,494 kWh/a (-32.3%)
Self-sufficiency	51% (+8.5%)	52% (+10.6%)	54% (+14.9%)
Self-consumption rate	68% (-1.4%)	68% (-1.4%)	68% (-1.4%)

Charging and discharging power. Variation of the charge and discharge power from single phase to three phases, see also page 5 Choice of charge power.

The following relationships and impacts are summarised in bullet points:

- Bi-directional charging reduces grid consumption demand compared to unidirectional charging. The greatest reduction is achieved at the lowest charging power (more energy can be charged into the car).
- The higher the charge power, the greater the Grid feed-in, as less energy can be charged into the car.
- As the bi-directional charging power increases, the amount of energy delivered by the BEV decreases.
- On the other hand, the energy discharged from the home battery increases as the charge power increases.
- At 11kW bi-directional charging power, no energy is discharged from the BEV to the household.
- The degree of self-sufficiency slowly decreases as the charge power increases, because the lower the charge power, the less is fed into the grid and the more can be charged into the car.

The effects are also transferable with the change values compared to the reference household without bi-directional charging (see values in brackets). The degree of self-sufficiency also decreases slightly with increasing charging power, so that less PV electricity can be charged into the car.

Table 5. Sensitivity analysis BEV charging power variation (in brackets the change compared to the reference household without bi-directional charging)

Parameter	Variation of Charging power		
	Slow 1.38 kWh (single-phase)	**Medium** 4.14 kWh (three-phase)	**Fast** 11 kW (three-phase)
Demand BEV	4,610 kWh/a (0.0%)	4,610 kWh/a (0.0%)	4,610 kWh/a (0.0%)
Demand Grid	7,590 kWh/a (-9.5%)	7,699 kWh/a (-8.2%)	7,832 kWh/a (-6.7%)
Feed-in	3,323 kWh/a (+4.1%)	3,370 kWh/a (+5.5%)	3,563 kWh/a (+11.6%)
Discharged Energy BEV	411 kWh/a (-)	256 kWh/a (-)	0 kWh/a (-)
Discharged Energy Home storage	1,565 kWh/a (-29.1%)	1,794 kWh/a (-18.7%)	2,192 kWh/a (-0.7%)
Self-sufficiency	52% (+10.6%)	51% (+8.5%)	50% (+6.4%)
Self-consumption rate	68% (-1.4%)	68% (-1.4%)	66% (-4.3%)

Times of use. Set different static presence times. As an example, three typical types of worker have been defined and corresponding periods of absence during which the BEV is not available.

Table 6 clearly shows that the longer availability of the BEV has a positive effect on the amount of energy discharged from the BEV to the household.

It is also interesting to note that household storage and BEV storage show competing behaviour. As the availability of the BEV increases, the self-consumption rate rises to 75%, which means that more solar electricity can be consumed directly, but the degree of self-sufficiency stagnates.

Table 6. Sensitivity analysis BEV availability time of use (in brackets the change compared to the reference household without bi-directional charging)

Parameter	**BEV availability** (Time of Use)		
	Fulltime employee Times of absence 08:00 – 17:00 h (during the week) 16:00 – 18:30 h (at the weekend)	**Part-time employee** Times of absence 08:00 – 14:00 h (during the week) 16:00 – 18:30 h (at the weekend)	**Home-Office employee** Times of absence 18:00 – 19:00 h (during the week) 16:00 – 18:30 h (at the weekend)
Demand BEV	4,610 kWh/a (0.0%)	4,610 kWh/a (0.0%)	4,610 kWh/a (0.0%)
Demand Grid	7,590 kWh/a (-9.5%)	7,352 kWh/a (-8.3%)	7,475 kWh/a (-6.8%)
Feed-in	3,323 kWh/a (+4.1%)	2,915 kWh/a (-11.1%)	2,609 kWh/a (-20.4%)
Discharged Energy BEV	411 kWh/a (-)	688 kWh/a (-)	999 kWh/a (-)
Discharged Energy Home storage	1,565 kWh/a (-29.1%)	1,247 kWh/a (-40.3%)	876 kWh/a (-58.1%)
Self-sufficiency	52% (+10.6%)	53% (+8.2%)	53% (+8.2%)
Self-consumption rate	68% (-1.4%)	72% (+5.9%)	75% (+10.3%)

DISCUSSION

The simulation tool can be used to simulate a V2H system for a modern single-family household, allowing energy assessments and analyses to be carried out. By adjusting a number of parameters, such as BEV battery capacity, charging power, daily BEV consumption and BEV absence times, it is possible to perform a variety of different analyses.

Compared to the pilot studies in Chapter State of Research V2H, some statements and results on the degree of self-sufficiency could be confirmed by the simulation tool. The only finding that could be rejected was that the charging power has little effect. The lower the bi-directional Wallbox can charge the BEV, the more energy can be temporarily stored and returned to the household. Therefore, the thresholds should take into account the barriers to solar charging. Otherwise, the car will not be charged. This means that, at least for smaller photovoltaic systems, there are limited charging windows for many days of the year. In this case, the best charging strategy is grid-supplementation, where even low photovoltaic power is used and supplemented with power from the grid. If you use a Wallbox with automatic phase switching, you can switch between single-phase and three-phase charging depending on the available photovoltaic power. This can significantly extend the charging windows in variable weather conditions or at off-peak times.

As part of a sensitivity analysis, various parameters were varied in scenarios and compared with the pre-defined reference household. The parameters examined included the battery capacity of the BEV, the charging power of the bi-directional charging and the time availability of the vehicle.

Other parameters to be investigated could be the effect of photovoltaic power and orientation. For the investigation of technical loads, such as peak loads, high time resolution modelling of load profiles at the second level would be interesting. Technical wear and tear due to battery aging could not be demonstrated in the simulation because the energy amounts and full charge cycles were considered low, as the loads in normal household operation are too low for the BEV.

Central to the simulation are the underlying load and usage profiles, which in part have static effects on the simulation due to the choice of certain parameters, such as the daily BEV consumption. For this reason, further development should attempt to create or use dynamic driving profiles for BEVs. The results of the simulation only show that the availability of the BEV has the greatest influence on the degree of self-sufficiency. In the future, variable electricity tariffs (time-of-use tariffs) could also be interesting for households without a photovoltaic system to charge their BEV intelligently or to use it for new business models in the sense of V2G to market their battery capacity.

Further development of the tool will include more options for selecting load profiles and better adaptation to individual household scenarios. It will also be possible to store more dynamic user profiles for consumption and driving behaviour, making the simulations even more realistic.

CONCLUSION

The results of the simulations show that bi-directional charging has the potential to increase the self-sufficiency of renewable energy (in this case photovoltaics) in the household, to reduce electricity costs and indirectly to reduce the load from the energy grid. It is important to say that the potential strongly depends on individual user behaviour, the possible charging technology and the presence of the vehicle on site.

Different scenarios of bi-directional charging could be simulated and compared e.g. with a unidirectional system. For example, the degree of self-sufficiency of bi-directional systems could be increased by more than 10% compared to unidirectional systems.

In addition, various parameters could be adjusted and analysed through a sensitivity analysis. The parameters of vehicle battery capacity, charging power and daily availability were varied using typical employee working hours as an example.

This study contributes to the scientific literature by presenting a simulation model for bi-directional charging in modern Households with the V2H concept. The results provide important insights for households and the simulation model can be a decision support tool for the choice and sizing of system components in the HEMS. In addition, the study provides input for further research and development in the field of electromobility and home energy management systems.

In summary, V2H applications through bi-directional charging offer added value for single-family homes with a PV system and increase the level of self-sufficiency. Furthermore, the potential increases as the number of BEVs increases, so bi-directional BEVs offer a huge potential for end users and the grid.

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NOMENCLATURE

Symbols and Acronyms

BEV	Battery Electric Vehicle
COP	Coefficient of performance
$\mathbf{E}_{\textbf{Grid feed in}}$	Amount of energy for electricity fed into the grid
$\mathbf{E}_{\textbf{PV production}}$	Amount of energy for PV electricity produced
$\mathbf{E}_{\textbf{Grid demand}}$	Amount of energy for electricity purchased from the grid
$\mathbf{E}_{\textbf{Annual electricity consumption}}$	Amount of energy for annual electricity consumption
HEMS	Home Energy Management System
PV	Photovoltaic
SoC	State of Charge
V2H	Vehicle-to-Home
V2G	Vehicle-to-Grid
V2V	Vehicle-to-Vehicle

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