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ORIGINAL PAPER

The Potential of Vehicle-to-Home Integration for Residential Prosumers: A Case Study

Marcus Brennenstuhl[1] · **Robert Otto**[1] · **Pawan Kumar Elangovan**[1] · **Ursula Eicker**[2]

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Abstract

The transition of the transport sector to e-mobility poses various challenges but also provides great flexible load and supply potential and thus enables a stronger coupling of the transport sector with other sectors. If emerging opportunities such as bidirectional charging in the context of Vehicle-to-Home and Vehicle-to-Grid applications are utilised, a previously unimagined load management and storage potential can be tapped. This can transform e-mobility from an additional burden to the grid to a grid-supporting factor that enables greater integration of renewable energies and reduces additional investments in infrastructure like grid expansion and stationary storage systems. In order to investigate this potential, within this work we examine simulation based various Vehicle-to-Home (PV self-consumption, load shifting due to flexible electricity tariff) and Vehicle-to-Grid (secondary reserve) scenarios for different driving profiles for a residential building with heat pump, PV system and optionally a small wind turbine. In addition, a charge load optimisation is carried out using a genetic algorithm. The energy quantities, saving potential and additional number of battery cycles are quantified. The results show that, despite additional battery degradation, significant financial incentives can be achieved.

Keywords Vehicle-to-Home · Vehicle-to-Grid · Bidirectional charging · Chargeload management · Heat pump · Genetic algorithm · Small wind turbine and PV self-consumption

Introduction

The coupling of the transport and electricity sectors is currently emerging due to the available technologies and political incentives, especially in the passenger car sector. It is predicted that the share of electric vehicles (BEV, Battery Electric Vehicle) and e-hybrid vehicles (PHEV, Plug-in Hybrid Electric Vehicle) in Germany will increase from 1.2% in 2020 to 24.4% in 2030. This corresponds to 11.6 million vehicles in 2030 [1]. This results in increased electricity consumption and potential bottlenecks during peak charging times. It is predicted that for BEVs (passenger cars), an additional 44 TWh of electricity per year (70 TWh for all e-mobility without rail transport) will have to be generated by 2030 [2]. Equally, this also offers enormous potential. According to Figgener et al. [3], the 1,270,000 BEVs and PHEVs registered in Germany by the end of 2021 had a cumulative battery capacity of 39.6 GWh in conjunction with a total possible AC charging capacity of 7.7 GW and a DC charging capacity of 51.8 GW with a PHEV share of approx. 50%. This means that BEVs and PHEVs already have a storage and performance potential similar to that of all pumped storage power plants installed in Germany, which have a storage potential of 39 GWh and a power generation potential of 6.2 - 6.7 GW [4, 5]. If we assume this share of PHEVs and the average battery capacity installed per vehicle would be constant up to the year 2030, then in conjunction with the predicted 11.6 million vehicles [1], this would result in an installed capacity of 457.4 GWh, an AC charging capacity of

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✉ Marcus Brennenstuhl
marcus.brennenstuhl@hft-stuttgart.de

Robert Otto
robert.otto@hft-stuttgart.de

Pawan Kumar Elangovan
pawan.elangovan@hft-stuttgart.de

Ursula Eicker
ursula.eicker@concordia.ca

[1] Center for Sustainable Energy Technology, University of Applied Sciences Stuttgart, Schellingstraße 24, 70174 Stuttgart, Baden-Wuerttemberg, Germany

[2] Canada Excellence Research Chair Next Generation Cities, Concordia University, 1455 Boul. de Maisonneuve Ouest, QC H3G 1M8 Montréal, Québec, Canada

88.9 GW (standard household wallbox), and a DC charging capacity of 598.3 GW. If only 10% of this installed storage capacity were used, 45.7 GWh would be available in 2030. For comparison, the total installed power plant based electricity generation capacity in Germany is currently 223 GW [6]. In order to capture this potential, bidirectional charging can be used, for example, in the context of Vehicle-to-Grid and Vehicle-to-Home. In the context of Vehicle-to-Grid, electricity is supplied to the electricity grid, e.g., to smooth peak loads or to provide balancing power. By Vehicle-to-Home, electricity is supplied to a building, e.g., to cover the household electricity demand or the electricity demand of a heat pump. In an emergency, this could also serve to supply power in the event of a grid failure. A BEV could supply a multi-person household with electricity for up to a week. In combination with a PV system or a small wind turbine, Vehicle-to-Home can lead to a significant increase in self-consumption and self-sufficiency [7]. This potential is also shown in connection with heat pumps. In Arnaudo et al. [8], for example, it is shown on the basis of simulations that bidirectional charging in conjunction with heat pumps can relieve the existing grid infrastructure and thus enable the integration of heat pumps. Basically, it can be said that Vehicle-to-Grid can improve the efficiency and cost-effectiveness of electricity grids and save CO2 emissions [9]. In Sovacool et al. [9], a wide range of business areas are identified that go far beyond vehicle owners and electricity suppliers as well as grid services and can represent a comprehensive value chain. In Otto et al. [10] the possibilities of bidirectional charging in the context of parking garages and a model of charge load prediction were investigated. Despite all these promising factors, there are major hurdles that prevent a wide spread utilisation. Besides the lack of standardisation, which is currently being taken care of, the fear of battery degradation and permanent damage due to additional battery cycles, as well as uncertainties considering inverter efficiencies, especially for small fluctuating loads, deter many potential users.

Battery Degradation Due to Bidirectional Charging

Battery degradation is one issue that has not yet been clarified in the context of bidirectional charging. The main problem with this topic is that no practical long-term experience is available. So far, studies have been carried out on the basis of laboratory tests and simulations, which have come to very different and sometimes contradictory conclusions. In Wang et al. [11], for example, the battery degradation for various Vehicle-to-Grid services such as control power and peak load smoothing was investigated using a semi-empirical model. In the worst case, an additional reduction in battery capacity of 3.6% was observed over a period of ten years due to the provision of balancing power, and a reduction of 5.6% due to the provision of peak load smoothing. Furthermore, the study found a degradation cost of $ 0.20 for providing two hours of balancing power, $ 0.38 for providing two hours of peak shaving, and $ 1.18 for load shifting over 24 hours. A comprehensive literature review by Thompson et al. [12], focusing on the behaviour of different battery technologies, comes to the conclusion that with regard to ageing through charging cycles, the amount of energy extracted is fundamentally more decisive than the number of cycles. However, the way in which the energy is extracted (discharge power, cell temperature) also plays an important role. Thompson et al. conclude that dedicated implementation of bidirectional charging through continuous battery monitoring and controlled charging and discharging can actually increase battery life. In Shinzaki et al. [13], a field test with a PHEV was conducted over several months, and it was shown that bidirectional charging had very little or no negative effect on the lifetime of the vehicle battery due to the relatively low energy throughput. In Lunz et al. [14], the effects of bidirectional charging were investigated in a simulation-based manner. The study concluded that bidirectional charging can significantly increase battery life expectancy due to the constant monitoring of the battery and the reduced battery charge and discharge times at high SOC. In Uddin et al. [15], investigations were carried out based on a comprehensive battery degradation model. It was also concluded that intelligent bidirectional charging can reduce battery ageing and thus the capacity loss of BEVs by up to 9.1% and the power loss by up to 12.1%. In Lehtola et al. [16], measurement data, driving data, and data from Vehicle-to-Grid operation were combined with a battery ageing model. It was found that the decisive factors that influence calendar ageing are time, temperature, and state of charge. Cycle ageing is defined by the number of cycles, the depth of discharge, and the charging rate. An important finding of this work is that at full battery capacity, the battery retains less than 80% of its initial capacity after less than 1000 cycles, whereas if the battery is used in a range between 40% and 60% of SOC, 86.7% of the original capacity is still left after 3000 cycles. This is particularly relevant with regard to cycles in the context of bidirectional charging, as only 5 kWh - 10 kWh, which corresponds to 10% - 15% of the battery capacity for common larger BEV batteries, are required for Vehicle-to-Home applications. With optimal charging management and bidirectional operation in this SOC range, cycle-related battery ageing and the resulting costs could be significantly reduced.

Inverter Efficiency

Regarding the efficiency of AC-DC inverters in BEVs in the context of bidirectional charging, a wide range of statements can be found in research publications. Thingvad et al. [17] have investigated a commercially available inverter as used in BEVs with regard to the provision of positive and negative primary control power. They came to the conclusion that efficiency varies greatly depending on the power called up or fed into the grid. They found poor efficiencies of less than 50% at low power (0 - 2 kW) and good efficiencies of 90% at nominal power for the charging and discharging processes. Basically, they conclude that there is a need for improvement in terms of efficiency for the application of bidirectional charging on a broad scale. Videgain Barranco et al. [18] investigated the charging and discharging behaviour of a Nissan Leaf ZE1 in connection with a 3-phase 10 kW CHAdeMO charging connection under laboratory conditions. Efficiencies between 77.6% at 2 kW charging and discharging power and 81.5% at 7 kW charging and discharging power were determined for combined charging and discharging for Vehicle-to-Home applications. However, a constant power extraction was assumed in this test series. In Schram et al. [19], the power-dependent efficiencies for AC charging and discharging of a Nissan Leaf and a Renault ZOE were determined. The efficiencies determined ranged from 78% for charging and discharging with 2.8 kW to 86.5% for charging and discharging with 11.0 kW. Correia et al. [20] were able to show, however, with regard to bidirectional DC charging, that a significant improvement in efficiency could be achieved by using a dedicated inverter. Measurements with a conventional inverter at 2.5 kW charging and discharging power resulted in an overall efficiency of 64.6%, and at 10 kW charging and discharging power in an overall efficiency of 80.4%. With inverters based on silicon carbide, on the other hand, 90.9% efficiency could be achieved at 2.5 kW and 91.2% efficiency at 10 kW charging and discharging power. Basically, the findings so far show that AC as well as DC inverters suffer from efficiency loss at low power levels and high power fluctuations. This is due to the fact that the inverters installed have not yet been optimised for bidirectional charging and the corresponding power spectrum. The obstacles to this are not so much on the technical level as on the economic level, since without widespread use of bidirectional charging, the costs of development and the installation of corresponding optimised inverters on the side of vehicle manufacturers cannot be justified. Nevertheless, already in the power spectrum that is relevant, e.g., for the operation of heat pumps in residential buildings (2 kW - 5 kW power input), acceptable efficiencies in the region of 80% are achieved for combined charging and discharging. Interestingly, this would make Vehicle-to-Grid or Vehicle-to-Home systems with an efficiency of 70% - 80% [21] similar in efficiency to dedicated pumped storage power plants, which have an efficiency of 70% for older plants and 83% for the newest ones [22].

Aim of this Work

Within this work, we examine the potential of an optimisation of Vehicle-to-Home and Vehicle-to-Grid scenarios on a single building level regarding PV and small wind power self-consumption, flexible electricity tariff and negative automatic Frequency Restoration Reserve (aFRR), also known as secondary reserve. For this investigation, a digital twin of a residential building with an energy efficient building standard, heat pump, PV system, and in one use case with an additional small wind turbine is created. The building and its systems are resembled as white box models and calibrated and validated based on detailed monitoring data. For each use case and two different driving profiles, a dynamic co-simulation on a yearly basis with a one minute time resolution is carried out. For each day of the year, the charge load management is optimised by a genetic algorithm and compared to normal operation without bidirectional charging and optimisation. The aim is to show the possible technical and economic benefits of bidirectional charging in the context of Vehicle-to-Home and Vehicle-to-Grid. It is shown that substantial financial gains can be made and a grid supportive role can be fulfilled even with frequent BEV usage. In addition, the impact on battery life with respect to the additional battery cycles required is examined and evaluated.

Methodology

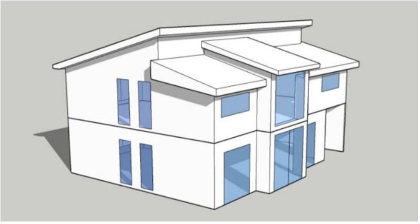
This work is based on a residential building from a positive energy settlement in the German municipality of Wüstenrot. The building that was constructed in 2013 is equipped with a heat pump connected to a cold local district heating network, two thermal buffer storage tanks, and a PV system. The detailed system parameters can be found in Fig. 1. High-resolution measurement data of all relevant energy flows was collected from this building over several years. Based on this, a white box model was created in the INSEL simulation environment, calibrated with measured data, and validated. This calibration and validation methodology is described in detail in [23]. More details about the arrangement of the cold district heating grid and the plus energy settlement can be found in [24].

Modelling and Optimisation Approach

In order to optimise the flexibility potential, the dynamic simulation model is coupled with a metaheuristic optimisation based on a genetic algorithm. The aim of this approach is to optimise the bidirectional charging and discharging of a BEV with regard to various criteria. In doing so, schedules for a certain time horizon are created and automatically updated

Fig. 1 Building system specifications

Building ID	**12**
Heat pump	Waterkotte Modell DS 5023.5Ai, 22.2 kW
Thermal buffer storage	DHW 400l; Heating 1000l
Battery storage	None
Installed PV power	13.64 kWp
PV orientation	58.4 m² (48 mod.) orientation 180°, tilt 15°; 49.5 m² (40 mod.) orientation 0°, tilt 15°
PV manufacturer and model	Solar Frontier Typ SF155-L
Residential useable area	285.13 m²
Heating demand	22,696 kWh



based on weather and demand forecast data. A time horizon of 24 hours is considered here. However, this is scaleable in terms of time, so that operation can also be optimised at significantly shorter (hourly) intervals. A genetic algorithm based on the DEAP toolbox in Python [25] is used to vary the charging and discharging states of the BEV. This is implemented as an INSEL-Python co-simulation.

Regarding the examined building, the heating demand and thus the electricity demand of the heat pump as well as the PV electricity generation are simulated dynamically. The household electricity demand is included based on measured values that were collected in 5 s intervals. The vehicle battery is also dynamically resembled in the INSEL model. The model configuration is shown in Fig. 2.

If the BEV is used (availability is determined based on specific driving profiles, see chapter "Driving Profiles") it's battery capacity is excluded from the model, and the consumed amount of energy is transferred to the modelled vehicle's battery as an energy debt, which is to be charged as efficiently as possible by the charge load optimisation. In order to reduce the settling time of the model, parts of the model are parameterised with measured values at each simulation start, which reflect the actual state of the building and it's systems. A settling time of the model of 3 hours was determined based on an iterative study. Furthermore, control intervals of 5 min are selected to ensure a high amount of flexibility without too small charge and discharge intervals. In order to consider the rebound effect, the subsequent 3 h after the 24 h optimisation are also included in the energy flow balance. Regarding mobility prediction accuracy, for simplification reasons, it is assumed that departure times are available to the optimisation algorithm in advance. In reality, this could be realised, e.g., via an app in which users specify the departure times in advance, or also by a self-learning algorithm. The charging and discharging states that are used by the optimisation are as follows:

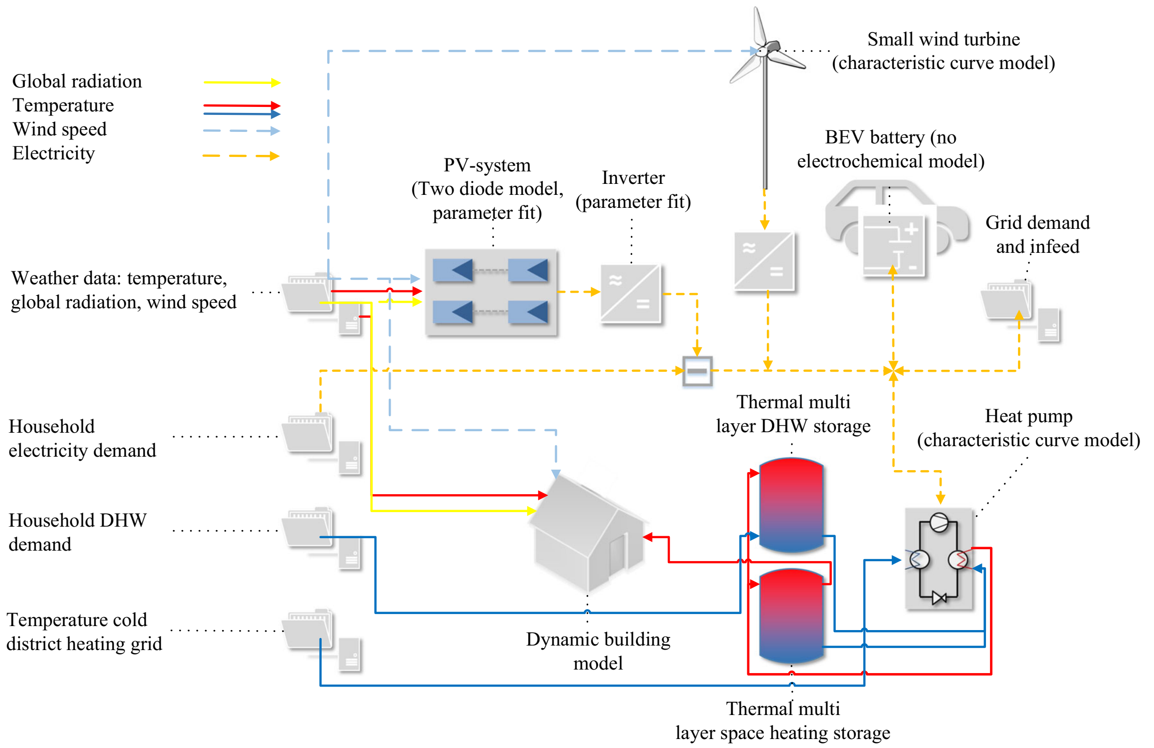


Fig. 2 Energy system model scheme

- Allow discharging by household and heat pump electricity: Yes / No.
- Allow charging by PV / small wind turbine electricity: Yes / No.
- Allow charging by grid electricity: Yes / No.

In the following scenarios, the possible daily optimisation potential is determined by the simulation. For each day of the year, a demand and generation simulation as well as an optimisation based on the weather data forecast for that day are performed. These results are then compared with the data that was measured in reality at that time.

Driving Profiles

To represent the BEV, annual load profiles are first created in one-minute resolution using a mobility generator tool developed within the Smart2Charge project, based on representative profiles from [26–28]. Profiles such as daily commuting to work or usage as a secondary car with a high rate of availability are used and investigated. The profiles generated by the mobility generator are first available as weekly profiles. To create annual profiles, these are randomised. The start or arrival time is redetermined using a Gaussian normal distribution within +/- 30 min around the original time. For each driving event, a randomly generated value between -1/5 and 1/5 of the energy quantity required according to the driving profile is added to the balance. These load profiles are then coupled with the dynamic building model. In the following, the investigated weekly driving profiles are shown with regard to BEV availability and energy consumption. Figure 3a and b show a driving profile that includes regular commuting to work, while Fig. 4a and b show a driving profile that corresponds to usage as a secondary car with a significantly higher time spent at home.

Optimisation Scenarios

Based on the previously described simulation and optimisation approach, the the following scenarios are examined and optimised:

- PV self-consumption.
- Vehicle-to-Home (PV and wind power self-consumption).
- Vehicle-to-Home (flexible electricity tariff).
- Vehicle-to-Grid (aFRR).

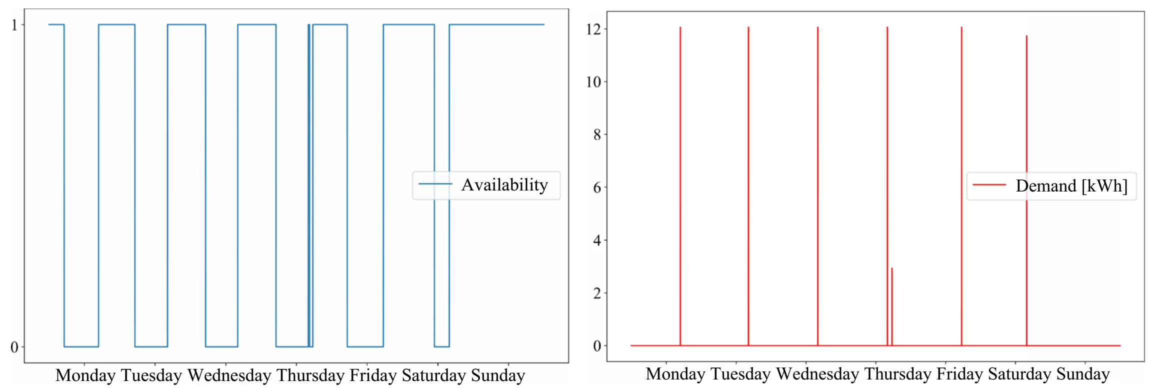
The aim thereby is to reduce peak demand, the amount of electricity that is fed into the grid and thus grid load, as well as the operation costs for the building owner.

PV Self-consumption

The goal of PV self-consumption optimisation is to minimise the cumulative amount of electricity drawn from the grid. This includes BEV electricity demand, heat pump electricity demand, as well as household electricity demand. Basically, under German regulatory conditions, it is desirable to consume as much PV electricity as possible oneself, as the household electricity price in Germany today is more than four times higher than the fixed feed-in tariff for small (smaller than 10 kWp) newly installed PV systems. This results in the following Eq. 1 as the optimisation objective function for which the result is to be minimised:

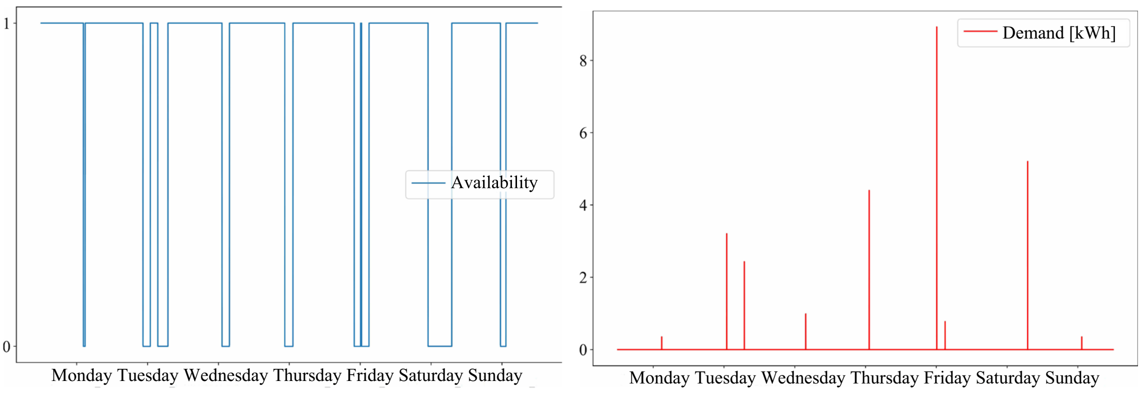
$$M = \int_{optstart+3h}^{optend} \Big((Q_{el\_Hh} + Q_{el\_HP} + Q_{el\_BEV}) * m_{tariff} - (Q_{el\_PV} * m_{PV\_togrid}) \Big) \tag{1}$$

Where M [€] is the total cost or profit from operation, Q_{el_Hh} [kWh] is the household electricity demand for each



(a) Availability (b) Demand

Fig. 3 Weekly usage and consumption profile, type work commute



(a) Availability (b) Demand

Fig. 4 Weekly usage and consumption profile, type secondary vehicle

time step, Q_{el_HP} [kWh] is the electricity demand of the heat pump for each time step, Q_{el_BEV} [kWh] is the electricity demand of the BEV for each time step, and Q_{el_PV} [kWh] is the amount of electricity from the PV system that is fed into the grid for each time step. m_{tariff} is the electricity purchase tariff [€/kWh] and m_{PV_togrid} is the feed-in tariff of the PV electricity [€/kWh].

Vehicle-to-Home (PV and Wind Power Self-consumption)

The aim of the PV and wind power self-consumption optimisation is to minimise the cumulative amount of electricity drawn from the grid. This includes the BEV electricity demand, the heat pump electricity demand, as well as the household electricity demand.

This results in the following Eq. 2 as the objective function for which the result is to be minimised.

$$M = \int_{optstart+3h}^{optend} \Big((Q_{el\_Hh} + Q_{el\_HP} + Q_{el\_BEV}) * m_{tariff} - Q_{el\_PV} * m_{PV\_togrid} - Q_{el\_Wind} * m_{Wind\_togrid} \Big) \tag{2}$$

Where M [€] is the total cost or profit from operation, Q_{el_Hh} [kWh] is the household electricity demand for each time step, Q_{el_HP} [kWh] is the heat pump electricity demand for each time step, Q_{el_BEV} [kWh] is the electricity demand of the BEV for each time step, Q_{el_PV} [kWh] is the amount of electricity from the PV system that is fed into the grid for each time step, and Q_{el_Wind} [kWh] is the amount of electricity from the small wind turbine that is fed into the grid for each time step. m_{tariff} is the electricity purchase tariff [€/kWh], m_{PV_togrid} is the feed-in tariff for PV electricity [€/kWh] and m_{Wind_togrid} is the feed-in tariff for wind electricity [€/kWh].

Vehicle-to-Home (Flexible Electricity Tariff)

In order to investigate the load shifting possibilities of Vehicle-to-Home applications in conjunction with a flexible electricity tariff, a ToU tariff is implemented in the model that uses a dynamic network fee. PV electricity generation is thus not considered in order to better evaluate the effects of the flexible tariff. The tariff approach is described in [29]. For the ToU variant with a variable network fee, a fixed price component of the grid fee is included in the calculation that is linked to the distribution grid load in order to counteract the grid load and, at the same time, increase the incentive for end customers compared to the daily variation of electricity exchange prices. This variable component is set at three price levels. 2.75 times, 1.3 times, and 0.3 times the original level of the variable component of the network fee. It is envisaged that in total, the variable network fee will be equal to the original static amount to be paid. [29]

Applying the network fee for the year 2022 and the day-ahead exchange electricity prices from calendar week 25 of 2022 using this methodology results in the ToU tariff shown in Fig. 5.

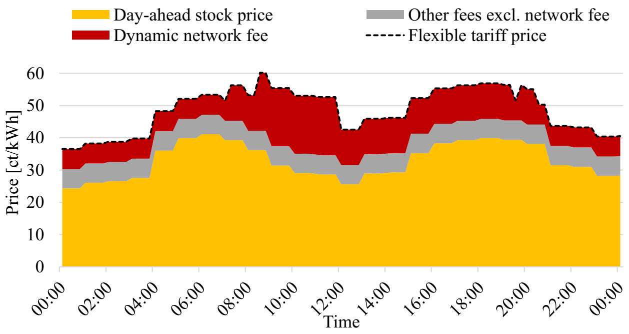


Fig. 5 Flexible ToU electricity tariff

The aim of optimising the use of a flexible electricity tariff is to minimise the use of grid electricity from periods with high tariff prices to periods with lower prices. This includes the BEV electricity demand, the heat pump electricity demand, as well as the household electricity demand. This results in the following Eq. 3 as the objective function for which the result is to be minimised.

$$M = \int_{optstart+3h}^{optend} (Q_{el\_Hh} + Q_{el\_HP} + Q_{el\_BEV}) * m_{tarif\_flex} \tag{3}$$

Where M [€] is the total cost or profit of operation, Q_{el_Hh} [kWh] is the electricity demand of the household for each time step, Q_{el_HP} [kWh] is the electricity demand of the heat pump for each time step, and Q_{el_BEV} [kWh] is the electricity demand of the BEV for each time step. m_{tarif_flex} is the flexible electricity tariff [€/kWh].

Vehicle-to-Grid (aFRR)

To determine the economic potential of BEV participation in the aFRR market, quarter-hourly aFRR demand data [30] were used for the year 2019 and merged with the corresponding price data of the aFRR power and balancing energy market (4h resolution) [30]. The assumption was made that negative aFRR can be provided for the full period that the vehicle is at home and that the electricity demand is solely fulfilled by aFRR. The revenues from participation in the power market are not included in the balance because they are assumed to be negligible in this context. The adopted participation conditions are that the lowest price is offered on the balancing energy market in order to be activated as often as possible. Thus, the case studied here represents the highest possible number of activations and thus the greatest possible flexibility that must be provided. The household, heat pump, and driving demands are fulfilled by the energy temporarily stored in the vehicle battery. This is done for all time steps where the aFRR demand is negative. For electricity purchases that fall outside of this time period, an electricity purchase price of 0.42 €/kWh is applied. During periods when the vehicle is not available, participation in the aFRR market is excluded. The cash flow is calculated according to the following Eq. 4:

$$M = \int_{optstart+3h}^{optend} \Big(Q_{el\_aFRR} * (m_{aFRR} + m_c) * (VAT + 1) + Q_{el\_tariff} * m_{tariff} \Big) \tag{4}$$

Where M [€] is the income or cost, m_{aFRR} [€/kWh] is the offered aFRR balancing energy marked price, mc [€/kWh] is the sum of surcharges and taxes of 0.135 €/kWh (see also Table 1), m_{tariff} is the standard electricity tariff amounting to 0.42 €/kWh, Q_{el_aFRR} is the amount of delivered aFRR electricity [kWh] and Q_{el_tariff} [kWh] is the amount of tariff electricity purchased. The VAT is assumed to be 19%.

Results

Vehicle-to-Home: PV Self-consumption

In the following, two different driving profiles (first car, commuting to work, and secondary car with less frequent use) are investigated for optimising PV self-consumption. The aim is to keep the SOC in the range between 40% and 60%, which enables a high cycle tolerance and thus low battery degradation.

Driving Profile First Car, Commuting to Work, 80 kWh Storage Size, 10 kWh Storage Usage

Table 2 shows the monthly cost reduction resulting from the optimised operation and the avoided electricity purchase costs. Opt means the predicted improvement, Meas Opt means the improvement that would occur taking into account the forecast uncertainty with regard to global radiation, ambient temperature, electricity consumption, DHW demand and the associated electricity consumption of the heat pump. As expected, there is a significant savings potential of up to 32.5% in the summer months and in the transitional period, taking into account the forecast deviation. in the winter months, the optimisation achieves negligible results due to the low PV yield.

For this use case, the calculated annual cost savings without taking the forecast deviation into account is 303.1 €. Taking the forecast deviation into account, it is 242.0 €. The number of battery cycles would be 45.5 with optimised Vehicle-to-Home operation and 31.7 without. This would

Table 1 Surcharges and taxes for electricity purchase as of September 2022

EEG reallocation charge	No longer required as of 07/01/2022
CHP surcharge	3.78 €/MWh
§19 StromNEV-reallocation	4.37 €/MWh
Offshore apportionment of liability	4.20 €/MWh
Reallocation charge for switchable loads	0.03 €/MWh
Network fee	80.80 €/MWh
Electricity tax	20.05 €/MWh
VAT	21.51 €/MWh
Total	134.74 €/MWh

Table 2 Monthly cost reduction through Vehicle-to-Home, with optimisation of PV self-consumption (driving profile of first car, commuting to work)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Opt	0.1%	3.7%	8.6%	18.0%	28.2%	52.3%	50.8%	48.6%	22.5%	8.2%	0.5%	0.0%
Meas Opt	0.1%	3.4%	8.2%	21.4%	32.5%	21.2%	21.4%	31.5%	18.7%	9.0%	1.2%	0.0%

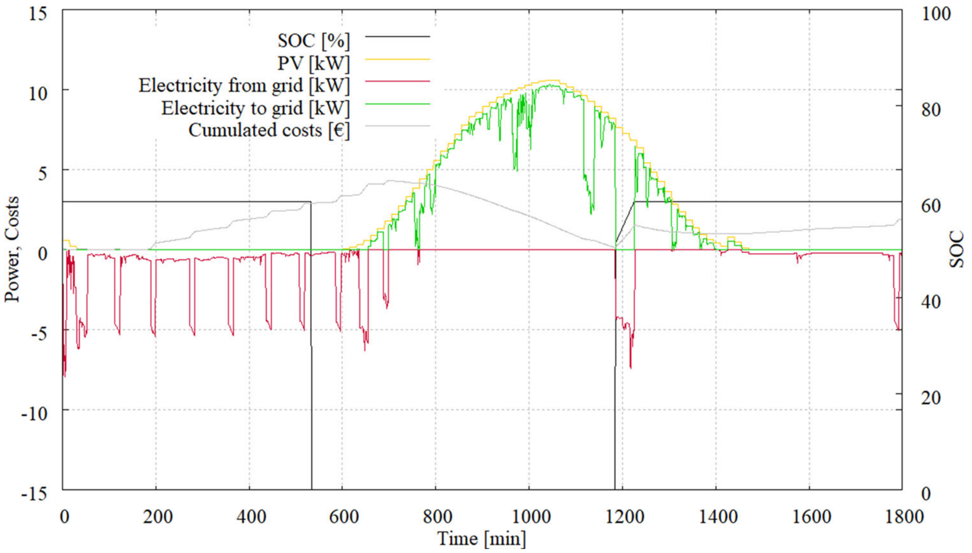
correspond to 13.8 additional cycles. The optimised operation could save the purchase of 661.1 kWh of grid electricity. Assuming a life span of 3,000 cycles, which might be possible with this mode of operation, and a price of 20,000 € for a replacement battery, this would result in 92.2 € of damage to the battery. Increasing the usable capacity to 20 kWh resulted in a further reduction of purchased grid electricity of 29%. This would save 344.5 € per year, taking into account the forecast uncertainty. The number of charging cycles increases by another 3.5 cycles to 49. However, when using 20 kWh and thus 25% of the SOC, it is no longer possible to keep the SOC in the optimal range for the battery, which can increase the cycle-related degradation of the battery. Figures 6 (normal operation) and 7 (optimised operation) show the difference between normal and optimised operation for one weekday in the transition period. The driving profile here defines that during a large part of the time with PV yield, the vehicle is not available. Nevertheless, a significant part of grid power consumption can be avoided through optimisation. In the morning hours, for example, the heat pump is powered by the vehicle battery. After returning from the work trip, the battery is recharged with the remaining available PV electricity. All in all, the SOC can be kept in the ideal range between 40% and 60% despite the provision of heat pump and household electricity and a journey of approx. 50 kilometres. It can also be seen that the operating costs are significantly reduced by the reduction in grid electricity consumption and that a slight profit can even be achieved in the balance of fed-in and purchased grid electricity on the day shown.

Driving Profile Secondary Car, 80 kWh Storage Size, 10 kWh Storage Usage

Table 3 shows the monthly cost reduction resulting from the optimised operation and the avoided electricity purchase costs. As expected, there is a significant savings potential of up to 52,1% in the summer months and in the transition period, taking into account the forecast deviation. in the winter months, this operational optimisation results in only a small improvement due to the low PV yield.

For this use case, the calculated annual cost savings without taking the forecast deviation into account is 547.7 €. Taking the forecast deviation into account, this is 484.2 €. The forecast deviation therefore plays a smaller role here due to the greater availability of the vehicle battery and thus a greater flexibility. Taking the forecast deviation into account, the number of battery cycles would be 48.6 with Vehicle-to-Home operation and 18.2 without. This would correspond to 30.4 additional cycles. The optimised operation could save the purchase of 1380.1 kWh of grid electricity. Assuming a battery life of 3,000 cycles, which might be possible with this mode of operation, and a price of 20,000 € for a replacement battery, this would result in 202.7 € of damage to the

Fig. 6 Daily energy and cost balance driving profile commuting to work



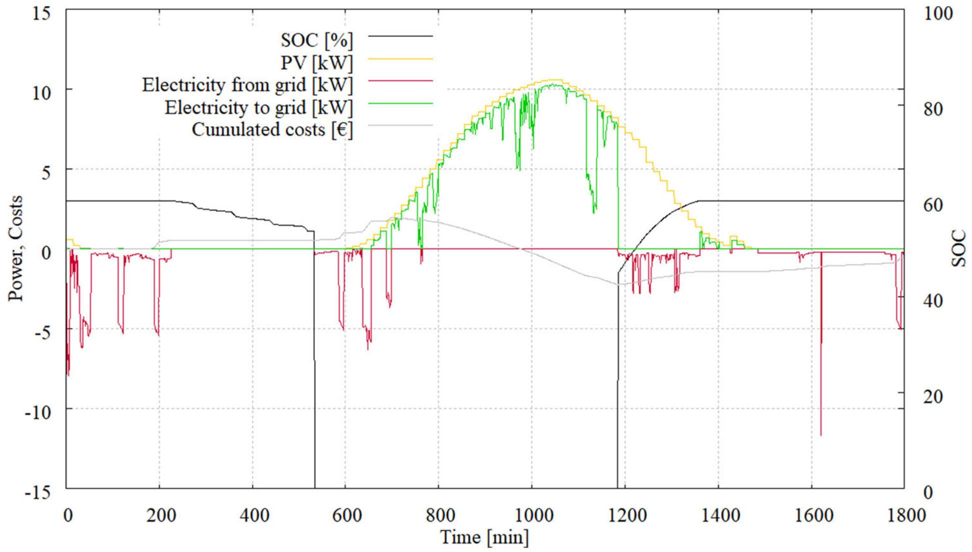


Fig. 7 Daily energy and cost balance driving profile commuting to work, Vehicle-to-Home, PV self-consumption optimised

battery. Increasing the usable capacity to 20 kWh did not result in any significant improvements for this driving profile with regard to the increase of PV self-consumption. The grid power consumption remained about the same, which implies that 10 kWh is sufficient. However, since the model only includes a period of 27 hours in the balance (24 hours of optimisation and 3 hours to include rebound effects), it is possible that constellations occur in which the use of a larger part of the vehicle battery could make sense in order to bridge several days with low PV yield. Figures 8 (normal operation) and 9 (optimised operation) show the difference between normal and optimised operation for one weekday in the transition period. Due to the driving profile, the vehicle is not available twice during the time of PV power generation and must be recharged in between. Through optimisation, a significant part of grid power consumption can be avoided. In the morning hours, for example, the heat pump is powered by the vehicle battery. In total, the SOC can be kept in the ideal range between 40% and 60% despite the provision of heat pump and household electricity, as well as two shorter trips. It is also shown that operating costs are significantly reduced by the reduction of grid electricity consumption and that a profit can even be achieved.

Vehicle-to-Home (PV and Wind Power Self-consumption)

In the following, as in the previous chapter, two different driving profiles (first car, commuting to work, and secondary car with frequent leisure use) are investigated for the use of 10 kWh and 20 kWh of the vehicle battery for optimising PV and wind electricity self-consumption.

Driving Profile First Car, Commuting to Work, 80 kWh Storage Size, 10 kWh Storage Usage

Table 4 shows the monthly cost reduction resulting from the optimised operation and the avoided electricity purchase costs. Opt means the predicted improvement, Meas Opt means the improvement that would occur taking into account the forecast uncertainty with regard to global radiation, ambient temperature, electricity consumption, DHW demand, and the associated electricity consumption of the heat pump. As expected, a significant savings potential of up to 35.0% can be seen in the summer months and in the transitional period, taking into account the forecast uncertainty. Compared to pure PV self-generated electricity optimisation, there is greater potential in the winter months and in the transitional period due to the seasonally relatively independent wind power production. In summer, the forecast uncertainty increases due to the stronger influence of user behaviour in the context of DHW demand.

For this use case, the calculated annual cost savings without considering the forecast deviation is 537.5 €. Taking the forecast deviation into account, this is 341.5 €. The number of battery cycles would be 57.1 with operational optimisation and 31.7 without operational optimisation. This would

Table 3 Monthly cost reduction through Vehicle-to-Home, with optimisation of PV self-consumption (driving profile secondary car)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Opt	0.2%	9.4%	18.6%	41.0%	51.0%	52.6%	47.7%	66.9%	42.0%	13.0%	0.7%	0.3%
Meas Opt	0.1%	11.3%	19.1%	49.6%	52.1%	32.1%	25.3%	46.3%	38.4%	17.0%	1.3%	0.4%

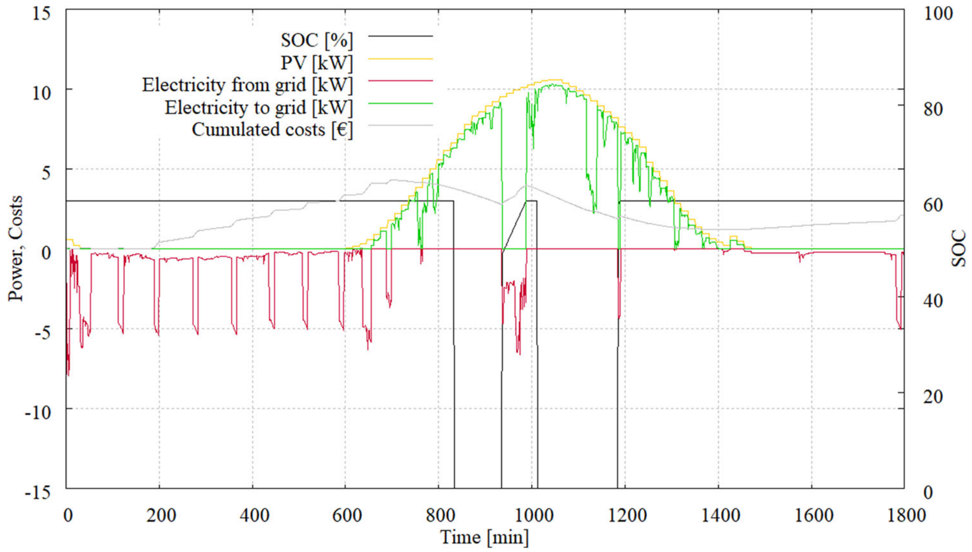


Fig. 8 Daily energy and cost balance driving profile secondary car

correspond to 24.9 additional cycles. Optimised operation could save an additional 956.4 kWh of purchased grid electricity. Assuming a battery life of at least 3,000 cycles, which might be possible with this mode of operation, and a price of 20,000 € for a replacement battery, this would result in 166.0 € in damage to the battery. Increasing the usable capacity to 20 kWh resulted in only a slight improvement for this driving profile with regard to PV and wind power self-use. The grid electricity consumption could be reduced by a further 12%. This would save 350.3 € per year, taking into account the forecast uncertainty. The number of charging cycles increases by a further 4.9 cycles to 62.0. In regard to the slight improvement that can be achieved and the fact that it is no longer possible to keep the SOC in the optimal range for the battery when using 20 kWh, it does not make sense to increase the utilised battery capacity. Figures 10 (normal operation) and 11 (optimised operation) show the difference between normal and optimised operation for a weekday in the transition period. The driving profile here defines that the vehicle is not available for almost the entire period of the PV yield. The wind power production is more continuous throughout the day. Nevertheless, part of the grid power consumption can be avoided and postponed through optimisation. In the morning hours, for example, the heat pump is powered by the vehicle battery. After returning from the work trip, the battery is recharged with the remaining available PV, wind, and grid power. In total, the SOC can be kept in the ideal range between 40% and 60% despite the provision of heat pump and household electricity and a journey of approx. 50 kilometres. The operating costs decrease due to the reduction of grid power consumption.

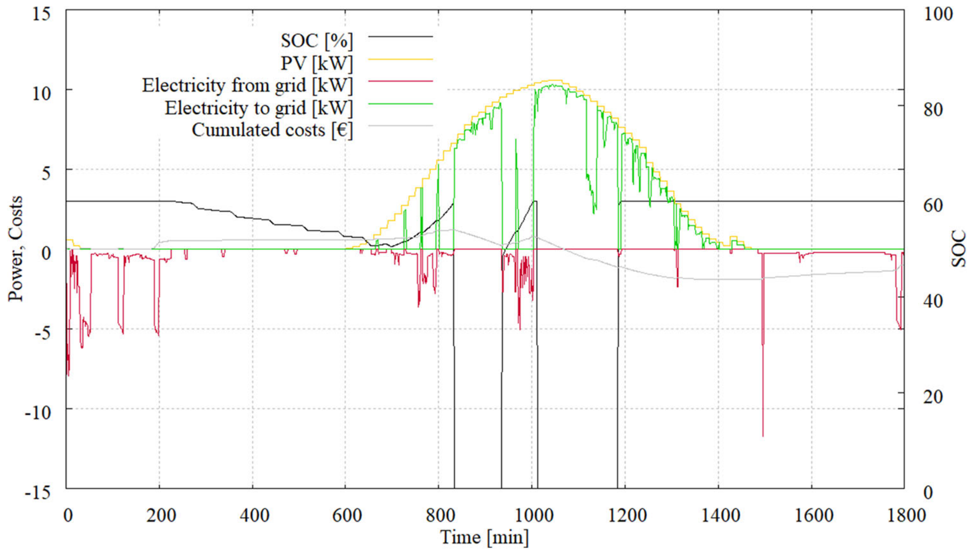


Fig. 9 Daily energy and cost balance driving profile secondary car, Vehicle-to-Home, PV self-consumption optimised

Table 4 Monthly cost reduction through Vehicle-to-Home, with optimisation of PV and wind self-power consumption (driving profile first car, commuting to work)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Opt	5.9%	12.5%	14.5%	27.0%	43.0%	66.6%	73.4%	51.0%	27.7%	10.2%	3.8%	0.2%
Meas Opt	2.6%	11.1%	15.5%	30.3%	35.0%	33.2%	22.3%	31.9%	22.5%	10.6%	4.1%	0.2%

Driving Profile Secondary Car, 80 kWh Storage Size, 10 kWh Storage Usage

Table 5 shows the monthly cost reduction resulting from the optimised operation and the avoided electricity purchase costs. As expected, there is a clear savings potential of up to 45.7% in the summer months and in the transitional period, taking into account the forecast uncertainty. In the winter months, this operational optimisation results in only a small improvement due to the low PV yield.

For this use case, the calculated annual cost savings without considering the forecast deviation is 838.9 €. Taking the forecast deviation into account, this is 647.6 €. Compared to the commuting driving profile, this shows a significantly greater potential. The number of battery cycles would be 70.8 with operational optimisation and 18.2 without operational optimisation. This would correspond to 56.0 additional cycles. Optimised operation could save the purchase of additional 1761.2 kWh of grid electricity. Assuming a battery life of at least 3,000 cycles, which might be possible with this mode of operation, and a price of 20,000 € for a replacement battery, this would result in 376.0 € in damage to the battery. Increasing the usable capacity to 20 kWh resulted in a slight improvement for this driving profile with regard to PV self-consumption. The grid electricity consumption decreased by 10% with a cost saving of 671 € and 74.6 battery cycles, which corresponds to additional 3.8 battery cycles. Figures 12 (normal operation) and 13 (optimised operation) show the difference between normal and optimised operation for one weekday in the transition period. Due to the driving profile, the vehicle is unavailable twice during the period of PV power generation and must be recharged in between. During these periods, there is also a higher wind power production. Through optimisation, a part of the grid electricity can be avoided. Thus, for most of the day, the demand of the heat pump is fulfilled by the vehicle battery. This is recharged with PV, wind, and grid electricity. In total, the SOC can be kept in the ideal range between 40% and 60% despite the provision of heat pump and household electricity, as well as two shorter trips. The cumulative operating costs decrease.

Vehicle-to-Home (Flexible Electricity Tariff)

In the following, two different driving profiles (first car, commuting to work, and secondary car with frequent leisure use) and use of 10 kWh of the vehicle battery are investigated for optimised charging and Vehicle-to-Home operation in conjunction with a flexible ToU electricity tariff with the aim to keep the SOC in the range between 40% and 60% to enable a high cycle stability and thus low losses due to battery degradation.

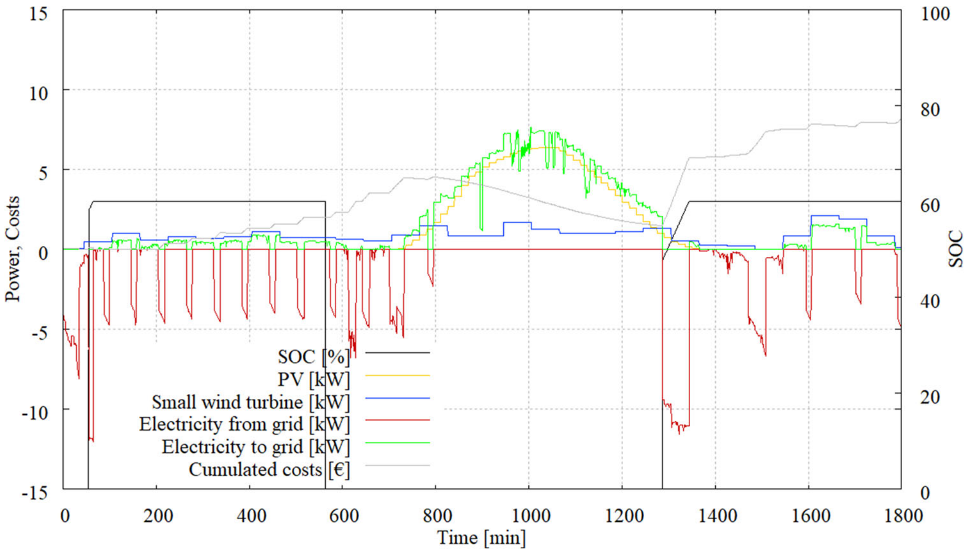


Fig. 10 Daily energy and cost balance driving profile first car, commuting to work

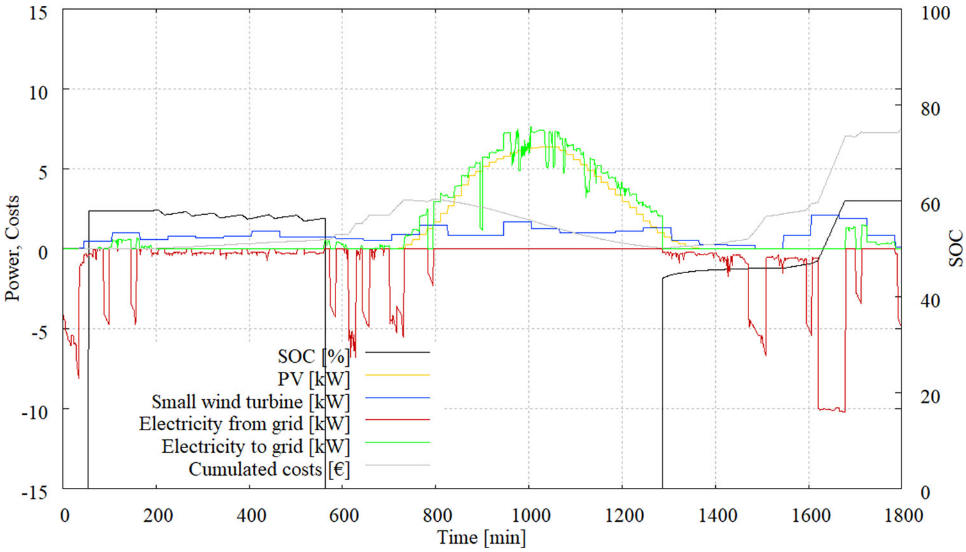


Fig. 11 Daily energy and cost balance driving profile first car, commuting to work, Vehicle-to-Home, PV, and wind power self-consumption, optimised

Driving Profile First Car, Commuting to Work, 80 kWh Storage Size, 10 kWh Storage Usage

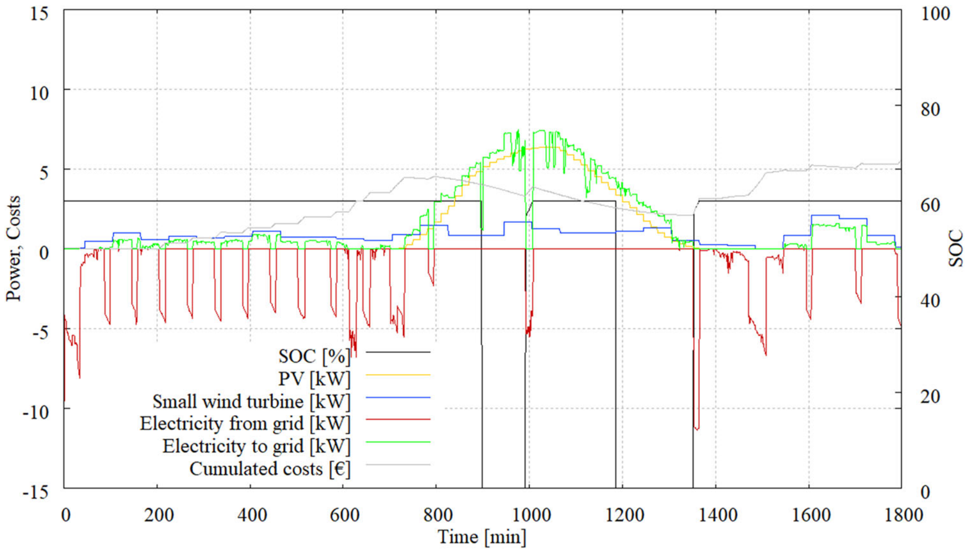
Table 6 shows the monthly cost reduction resulting from the optimised operation and the avoided electricity purchase costs. This shows a savings potential of up to 4.1%, taking into account the forecast uncertainty. These low values, compared to those archived with PV and wind self-consumption optimisation, can, on the one hand, be attributed to the somewhat lower financial potential of the ToU tariff and, on the other hand, to the higher absolute costs without power generation by PV. A direct comparison of the percentage improvement with other scenarios examined in this work is therefore not meaningful. This also explains the seasonal differences in Table 6, as in the winter months the electricity consumption is higher due to the heat pump operation and thus the relative improvement is lower.

For this use case, the calculated annual cost savings without considering the forecast deviance is 320.5 €. Taking the forecast deviation into account, it is 201.4 €. The number of battery cycles would be 49.8 with operational optimisation and 31.7 without operational optimisation. This would correspond to 18.1 additional cycles. With optimised operation, 1467.1 kWh of grid electricity could be shifted to times of lower grid load. This is approx. 15% of the total grid electricity consumption of the building and BEV. Assuming a battery life of at least 3,000 cycles, which might be possible with this mode of operation, and a price of 20,000 € for a replacement battery, this would result in 120.1 € of damage to the battery. Increasing the usable capacity to 20 kWh results in a notable improvement for this driving profile in combination with a flexible electricity tariff. The amount of electricity shifted could be increased by 81% to 2657.9 kWh and the cost savings almost doubled to 396.5 €, taking into account the forecast uncertainty. The number of cycles increased by 15.1 to 64.9, which would correspond to a battery damage of 221.3 €. This larger potential when increasing the used battery size compared to the Vehicle-to-Home use of PV and wind power is due to the fact that the potential is not limited by the maximum amount of electricity generated daily, but by the maximum demand, which is shifted to times of a lower tariff price. Since the demand is usually larger than the generation for the installed generation plants, using a larger part of the BEV battery is more recommendable. Figures 14 (normal operation) and 15 (optimised operation) show the difference between normal and optimised operation for a weekday in the transition period. Due to the driving profile, the vehicle is not available during the day. It is shown that the charging of the battery storage of the BEV is postponed after the journey to times of low tariff prices. The heat pump operation in the morning is normal because the tariff price is low at this time. At the beginning, during the settling period (3 h) of the model, and at the end, during the period in which the rebound effect is considered (3 h), there is no optimisation and thus no use of the vehicle battery. In total, despite the provision of heat pump and household electricity as well as the demand of

Table 5 Monthly cost reduction through Vehicle-to-Home, with optimisation of PV and wind self-consumption (driving profile of second vehicle)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Opt	7.8%	25.6%	29.1%	51.4%	67.7%	64.0%	54.2%	69.2%	47.8%	18.5%	3.5%	0.8%
Meas Opt	5.9%	25.1%	30.0%	56.0%	45.7%	35.0%	18.5%	41.0%	43.6%	23.0%	4.5%	1.7%

Fig. 12 Daily energy and cost balance driving profile secondary car



the BEV, the SOC can be kept in the ideal range between 40% and 60% when utilising 10 kWh of the vehicle battery. It can also be seen that operating costs are reduced by purchasing electricity at more favourable conditions.

Driving Profile Secondary Car, 80 kWh Storage Size, 10 kWh Storage Usage

Table 7 shows the monthly cost reduction resulting from the optimised operation and the avoided electricity purchase costs. This shows a savings potential of up to 7.1%, taking into account the forecast uncertainty.

For this use case, the calculated annual cost savings without considering the forecast deviation is 482.8 €. Taking the forecast deviation into account, this is 444.5 €. The forecast deviation therefore plays a smaller role here due to the greater availability of the vehicle battery and the associated flexibility. The number of battery cycles would be 61.3 with operational optimisation and 18.2 without operational optimisation. This would correspond to 43.1 additional cycles. With optimised operation, 3460.0 kWh of grid electricity could be shifted to times of lower grid load. This is approx. 33% of the total grid electricity consumption of the building and BEV. Assuming a battery life of at least 3,000 cycles, which might be possible with this mode of operation, and a price of 20,000 € for a replacement battery, this would result in 287.3 € of damage to the battery. Increasing the usable capacity to 20 kWh results in a notable improvement for this driving profile in combination with a flexible electricity tariff. The amount of electricity shifted could be increased by 29% to 4470.1 kWh, and the cost savings almost doubled

Fig. 13 Daily energy and cost balance driving profile secondary car, Vehicle-to-Home PV, and wind power self-consumption, optimised

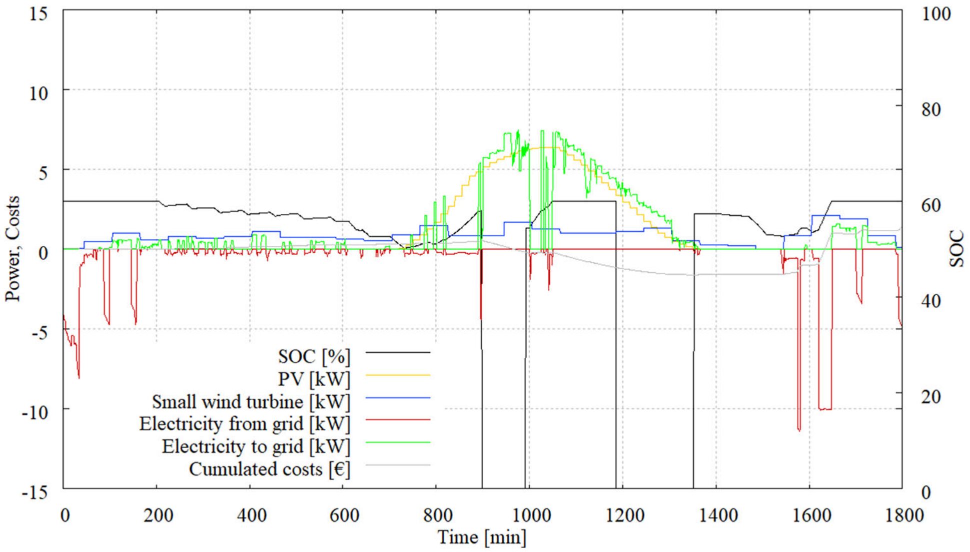


Table 6 Monthly cost reduction through Vehicle-to-Home, when optimised in conjunction with a flexible electricity tariff (driving profile first car, commuting to work)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Opt	5.5%	5.7%	5.8%	5.9%	6.0%	6.0%	5.7%	5.8%	5.1%	4.8%	4.2%	4.0%
Meas Opt	3.8%	3.9%	3.9%	4.0%	4.1%	4.0%	3.8%	3.9%	3.6%	3.4%	3.0%	2.2%

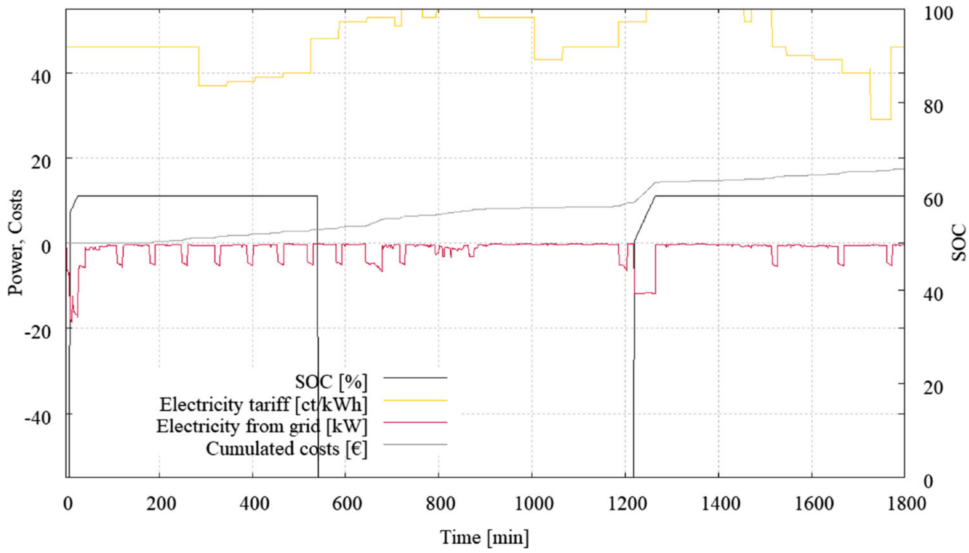


Fig. 14 Daily energy and cost balance driving profile first car, commuting to work, flexible electricity tariff

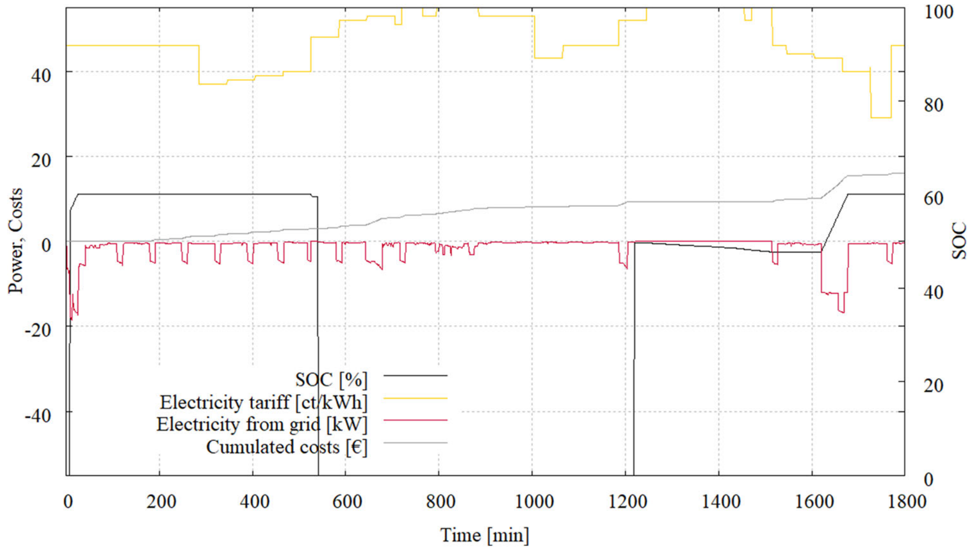


Fig. 15 Daily energy and cost balance driving profile first car, commuting to work, Vehicle-to-Home, optimised for flexible electricity tariff

Table 7 Monthly cost reduction through Vehicle-to-Home, when optimised in conjunction with a flexible electricity tariff (driving profile secondary car)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Opt	8.4%	8.6%	8.8%	8.9%	8.9%	9.0%	8.9%	8.8%	8.3%	7.6%	7.1%	6.5%
Meas Opt	6.5%	6.7%	6.9%	7.0%	7.0%	7.1%	6.8%	6.7%	6.3%	5.5%	4.6%	3.7%

to 650.2 €, taking into account the forecast uncertainty. The number of cycles increases by 11.2 to 72.5, which would correspond to a battery damage of 362.0 €. Figures 16 (normal operation) and 17 (optimised operation) show the difference between normal and optimised operation in the transition period. The driving profile makes the vehicle available for a large part of the time. It is shown that the battery storage is loaded at times of low electricity tariff prices in order to cover the household and partly the heat pump electricity demand. Heat pump operation in the morning is fed by tariff electricity as long as the tariff price is low. After that, it is covered by the vehicle battery. In total, despite the provision of heat pump and household electricity as well as the demand of the BEV, the SOC can be kept in the ideal range between 40% and 60%. It is also shown that operating costs are reduced by purchasing electricity at more favourable conditions.

Vehicle-to-Grid (aFRR)

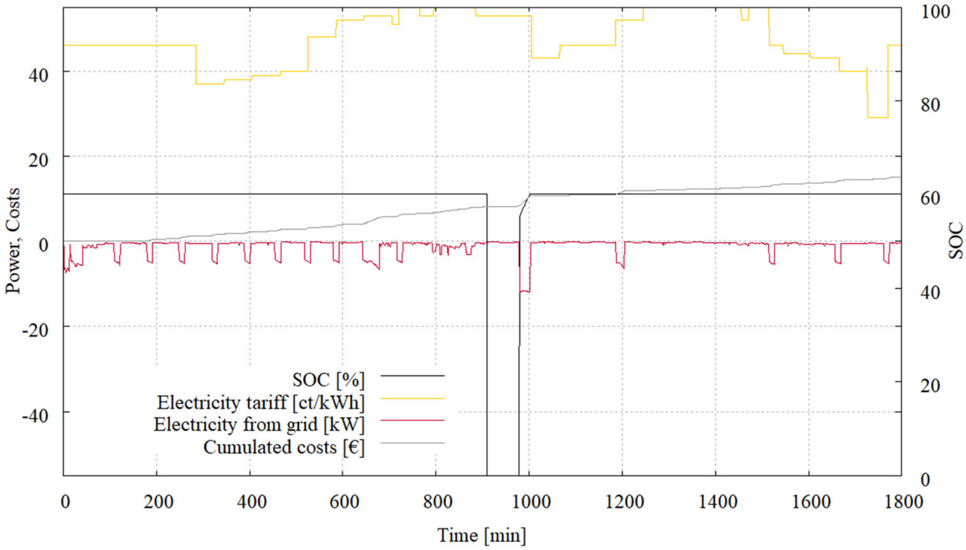
In the following, two different driving profiles (first car, commuting to work and secondary car with frequent leisure use) are investigated with regard to the provision of negative aFRR power. The charge control system is designed to keep the SOC between 40% and SOC 60% in order to achieve a high cycle stability and thus lower losses due to battery degradation. However, the lower SOC limit may be undershot by BEV driving. For each driving profile, the daily initial SOC, which corresponds to the targeted SOC at the end of the day, and the charging power are varied to find the combination that offers the greatest flexibility and can thus meet all negative aFRR activations on as many days as possible.

Driving Profile First Car, Commuting to Work, 80 kWh Storage Size

The results of varying the charging power and the daily start and end capacity of the vehicle battery, sorted by the least number of days on which the negative aFRR activations cannot be met, are shown in Fig. 23. The best case here is a daily initial SOC of 40% in conjunction with 2 kW of charging power. In this case, not all aFRR activations could be fulfilled on 35 days. Only three of these days are on weekends. On 28 days, the final capacity of the vehicle battery would be higher than the next day's required initial capacity, which on the one hand means that additional power has been stored that would further improve the economics, but on the other hand may also result in limiting the potential of providing negative aFRR the next day. Table 8 shows the monthly cost reduction that results from obtaining negative aFRR and electricity purchase costs that are avoided as a result. This shows a savings potential of up to 30.4%, taking into account forecast uncertainty. The seasonal differences can be explained by the fact that in the winter months, the electricity consumption is higher due to the heat pump operation, and therefore the relative improvement is lower.

For this use case, the calculated annual cost savings without considering the forecast deviation is 1387.5 €. Considering the forecast deviation, this would be 1154.0 €. The number of battery cycles would be 85.9 with aFRR activations and 31.7 without. This would correspond to 54.6 additional cycles. Assuming a battery life of at least 3,000 cycles, which might be possible with this operating mode, and a price of 20,000 € for a replacement battery, this would result in 364 € of damage to the battery. However, it is not possible to stay consistently in the range between 40% and 60% with this driving profile. If the upper limit of a maximum

Fig. 16 Daily energy and cost balance driving profile secondary car, flexible electricity tariff



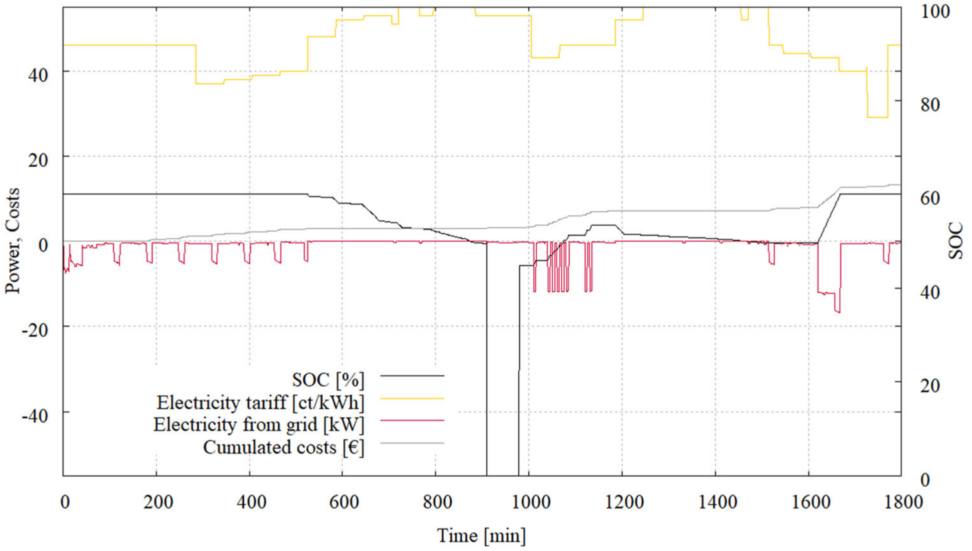


Fig. 17 Daily energy and cost balance driving profile secondary car, Vehicle-to-Home, optimised for flexible electricity tariff

SOC of 60% is met, the SOC drops to as low as 30% on some days due to the additional energy demand of driving. This could be compensated by purposeful charging before the start of the trip, but this would mean a higher tariff electricity demand. In Figs. 18 (normal operation) and 19 (aFRR fulfilment), the difference between normal and operation with aFRR fulfilment is shown for a weekday in the transition period. Due to the driving profile, the vehicle is not available during the day. It can be seen that much of the grid electricity demand can be replaced by providing negative aFRR. Similarly, with the charging power reduced to 2 kW, the SOC of the vehicle battery is consistently in the optimal operating range. It is also shown that operating costs are significantly reduced by obtaining electricity through negative aFRR.

Profile Secondary Car, 80 kWh Storage Size

The results of varying the charging power and the daily start and end SOC of the vehicle battery, sorted by the least number of days on which the negative aFRR activations cannot be met, are shown in Fig. 24. The most favourable case is represented by a daily initial SOC of 40% in conjunction with 2 kW of charging power. In this case, not all aFRR activations could be fulfilled on 21 days. On 42 days, the final SOC of the vehicle battery would be higher than the required start SOC of the next day, which on the one hand means that additional power has been stored that would further improve the economic efficiency, but on the other hand may also lead to a limited potential of providing negative aFRR on the next day. Table 9 shows the monthly cost reduction that results from obtaining negative aFRR and thus avoiding the purchase of tariff electricity. This shows a savings potential of up to 40.7%, taking into account the forecast uncertainty. The seasonal differences can be explained by the fact that in the winter months, the electricity consumption is higher due to the heat pump operation, and thus the relative improvement is lower.

For this use case, the calculated annual cost savings without considering the forecast deviation is 1709.2 €. Including the forecast deviation, this would be 1490.5 €. The number of battery cycles would be 91.4 with aFRR fulfilment and 18.2 without. This would correspond to 73.2 additional cycles. Assuming a battery life of at least 3,000 cycles, which might be possible with this operating mode, and a price of 20,000 € for a replacement battery, this would result in 488.0 € in damage to the battery. However, even with this driving profile, it is not possible to consistently stay within the range between 40% and 60%. If the upper limit of a SOC of 60% has to be met, on some days the SOC drops to as low as 35% due to the additional energy demand of the trips. This could be compensated by purposeful charging before the start of the trip, but this would mean a higher tariff electricity demand. In Figs. 20 (normal operation) and 21 (aFRR fulfilment), the difference between normal and operation with aFRR fulfil-

Table 8 Monthly cost reduction from Vehicle-to-Home and Vehicle-to-Grid operation when providing negative aFRR (driving profile first car, commute to work)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Opt	12.5%	17.8%	22.2%	21.0%	19.0%	30.3%	27.1%	30.4%	29.0%	25.6%	18.6%	21.2%
Meas Opt	11.8%	18.1%	20.7%	20.8%	20.9%	30.4%	22.4%	30.2%	24.0%	24.7%	17.1%	17.6%

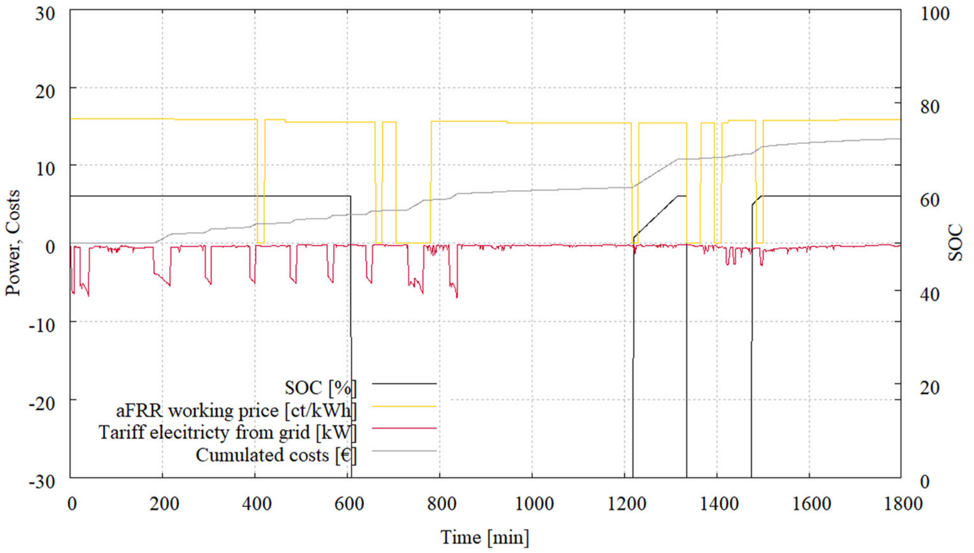


Fig. 18 Daily energy and cost balance driving profile first car, commute to work, Vehicle-to-Home and Vehicle-to-Grid

ment is shown for a weekday in the transition period. Due to the driving profile, the vehicle is unavailable twice during the day for shorter periods of time. It can be seen that a large part of the tariff electricity consumption, especially that caused by the cycling of the heat pump, can be replaced by providing negative aFRR. However, the SOC drops to as low as 38% due to the two trips. It can also be seen that the operating cost drops significantly by providing negative aFRR.

Discussion

The model-based investigation of optimised charge and discharge load management for different Vehicle-to-Home and Vehicle-to-Grid application scenarios shows that the forecast uncertainty of heat pump and household power demand as well as of PV power generation plays a measurable but subordinate role. This can be mainly attributed to the flexibility offered by the vehicle battery (capacity, activation speed, maximum charging, and discharging power). For all scenarios investigated, it is also shown that the revenue is greater than the determined potential damage to the vehicle battery due to additional cycles. An overview of the potential savings of the individual variants with and without additional costs due to battery degradation is given in Fig. 22. Here, the variant of participating in the negative aFRR balance energy market offers the greatest financial potential but also the greatest planning uncertainty since the actual number of activations that will occur and the expected prices are difficult to predict.

In this context, it should also be taken into account that, with the determined cycle numbers, the BEV would have to be in operation for more than 10 years with a conservative life expectancy of 1000 cycles, and for more than 20 years with

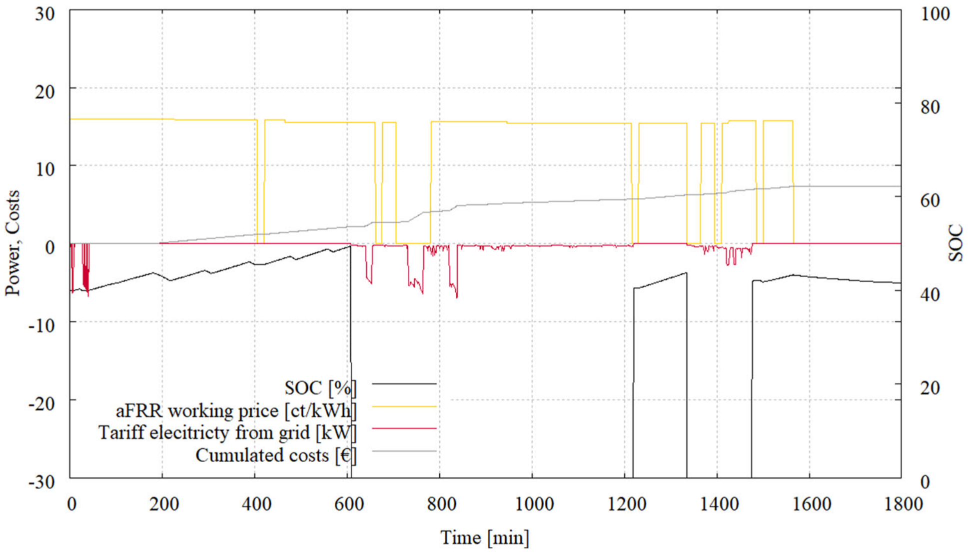


Fig. 19 Daily energy and cost balance driving profile first car, commute to work, Vehicle-to-Home, and Vehicle-to-Grid optimised for providing negative aFRR

Table 9 Monthly cost reduction from Vehicle-to-Home and Vehicle-to-Grid operation when providing negative aFRR (driving profile secondary car)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Opt	14.9%	23.8%	28.7%	27.9%	29.1%	42.6%	37.9%	41.6%	36.0%	35.9%	22.5%	17.9%
Meas Opt	14.3%	25.6%	28.4%	28.1%	31.4%	40.7%	36.7%	40.6%	29.8%	35.8%	20.5%	20.2%

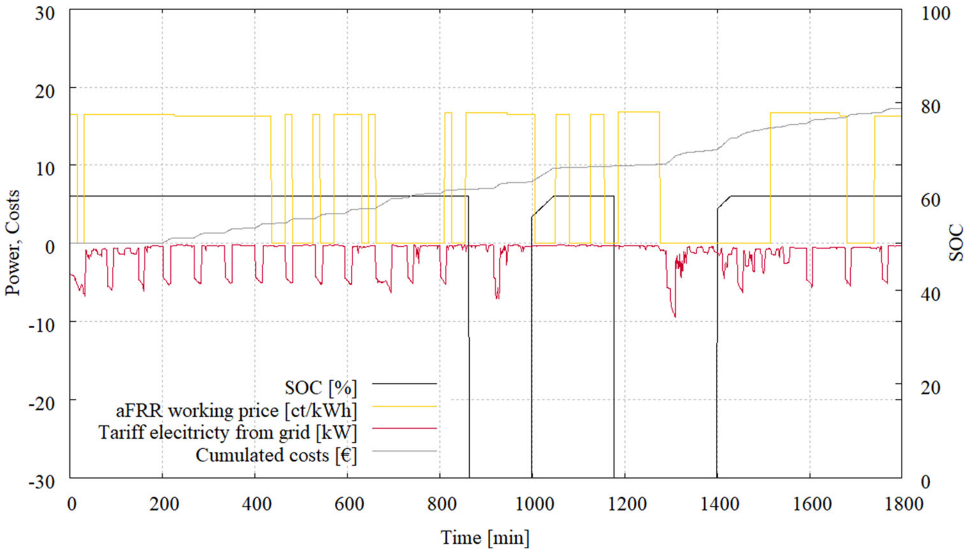


Fig. 20 Daily energy and cost balance driving profile secondary car, Vehicle-to-Home and Vehicle-to-Grid

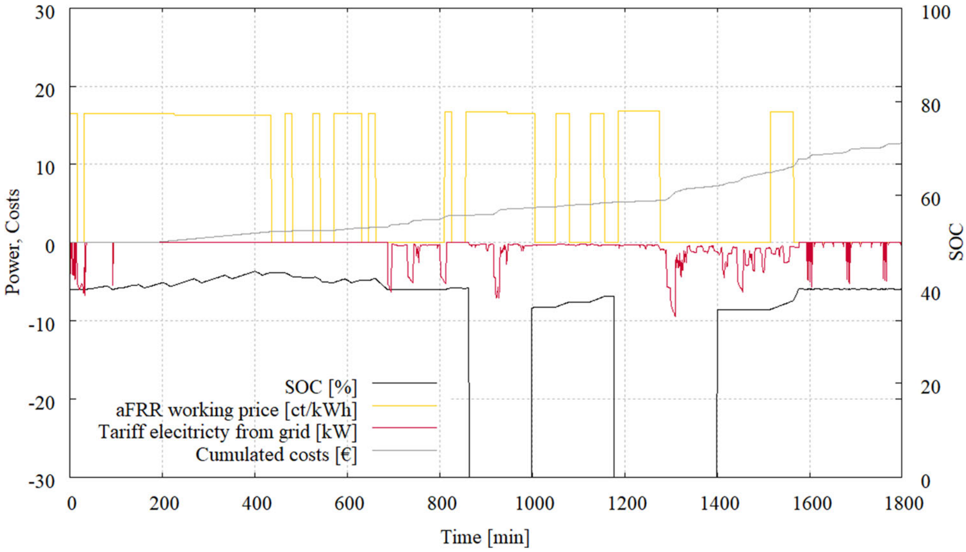
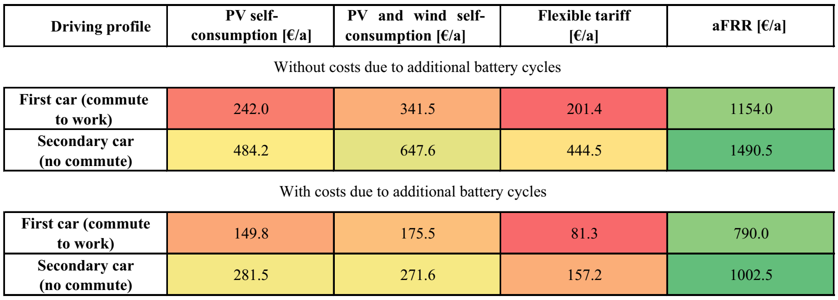


Fig. 21 Daily energy and cost balance driving profile secondary car, Vehicle-to-Home and Vehicle-to-Grid optimised for providing negative aFRR

Fig. 22 Annual cost reduction from various Vehicle-to-Home and Vehicle-to-Grid applications



Driving profile	PV self-consumption [€/a]	PV and wind self-consumption [€/a]	Flexible tariff [€/a]	aFRR [€/a]
Without costs due to additional battery cycles				
First car (commute to work)	242.0	341.5	201.4	1154.0
Secondary car (no commute)	484.2	647.6	444.5	1490.5
With costs due to additional battery cycles				
First car (commute to work)	149.8	175.5	81.3	790.0
Secondary car (no commute)	281.5	271.6	157.2	1002.5

a more optimistic life expectancy of 2000 to 3000 cycles, until the battery capacity drops below 80%. In this period, the vehicle is already depreciated on the balance sheet, and it is questionable whether the costs incurred by the additional cycles must be included in the balance. According to the German Federal Motor Transport Authority, 91.7% of passenger cars on Germany's roads in 2021 were less than 20 years old [31] and the German Federal Ministry of Finance specifies a useful life of 6 years for passenger cars in its tables of depreciation for wear and tear (AfA) [32]. At the same time, it is possible that supervised operation of the vehicle battery in the range of the optimum SOC can even positively influence its service life and offset the negative effects of the additional cycles.

Vehicle-to-Home (self-consumption):
With optimised charge and discharge load management with respect to PV self-consumption and the combined PV and wind self-consumption, a significant annual savings potential is shown that is mainly dependet on the driving profile and the availability of the BEV. At the same time, if the additional battery ageing is taken into account, the savings potential would be approximately halved. An increase of the used storage capacity to 20 kWh compared to the 10 kWh investigated brings only a slight improvement. The forecast uncertainty has a greater impact in terms of yield reduction for driving profiles with greater absence durations due to the lower flexibility. The forecast uncertainty of small wind generation was not considered. This might be counteracted in a real implementation by using rule-based logic or model predictive control (MPC).

Vehicle-to-Home (flexible electricity tariff):
The usage of a flexible electricity tariff in combination with optimised charge and discharge load management leads to significantly more cycles with similar cost savings compared to the optimised self-consumption use case. This can be explained by the fact that a significantly larger amount of energy is shifted, but the financial incentive is lower compared to self-consumption. In terms of grid supportive operation, however, this variant is recommendable. Thus, depending on the driving profile, 15% - 33% of the total grid electricity demand of building and BEV could be shifted to times of low tariff prices and thereby low grid stress. With regard to the used capacity of the vehicle battery, a utilisation of a larger share than the considered 10 kWh is reasonable. In order to limit the use of the vehicle battery to the range between 40% and 60% of the SOC, a maximum of 16 kWh should be used in the considered case of an 80 kWh vehicle battery.

Vehicle-to-Grid (aFRR):
This variant offers the greatest potential, financially speaking, but it is highly dependent on the bidding strategy. In reality, vehicles would be activated less often, resulting in lower savings but also less flexibility needed and a lower cycle load. At the same time, to participate in the aFRR market, the minimum power of 1 MW requires a pool operation equivalent to more than 500 vehicles at the determined optimal charging power of 2 kW. This would also imply additional costs for an aggregator and platform infrastructure. Equally, however, a pool operation can compensate for situations where a vehicle cannot fulfil all activations and thus avoid compensation payments. Basically, the study showed that a rather low charging power is useful to provide more flexibility and thus to be able to fulfil all aFRR activations. The study did not take into account the aFRR power market price since the revenues achievable with this use case do not play a significant role.

Conclusion

In this research, we examined the potential of bidirectional charging for different Vehicle-to-Home and Vehicle-to-Grid applications in the context of a residential building with heat pump, PV, and in one use case, small wind power generation. In particular, the potential of optimised bidirectional charging with regard to PV and small wind power self-consumption, a flexible ToU electricity tariff, and negative automatic Frequency Restoration Reserve (aFRR) was investigated. The examined use cases and applications have shown that there is significant potential regarding (optimised) bidirectional charging in the context of Vehicle-to-Grid and Vehicle-to-Home operations on a technical as well as on an economical level. It has been shown that, regarding self-consumption of PV and wind power in between 150 € and 272 € could be saved per year when the damage to the vehicle battery due to additional cycles is included. The implementation of a ToU electricity tariff was able to create an incentive to shift up to one-third of the building's demand to hours of less net load. However, it proved to be more difficult to provide sufficient financial incentives compared to the other use cases. Out of the examined use cases the participation in the negative aFRR market offered the highest financial potential. Thereby only the participation in energy balance market made a relevant economical sense. Gains in aFRR power market were minor also because the aim of this use case was not to provide reserve power with an existing power plant but to obtain electricity cheaply. Interestingly, only a fraction of the BEV stock predicted until 2030 would be sufficient to fulfil a large part of the negative aFRR tendered in Germany. This could be extended to the additional provision of positive aFRR, which was not considered in this study since the primary goal here was to consume surplus electricity. In future research, it would be interesting to expand this study to other internationally important markets. It would also be beneficial to consider the influence on economic efficiency through additional parameters such as demand (kW) and power factor (PF) as components of charge. In addition, it would be compelling to examine the effect of an additional stationary battery storage on the results.

This study is only a simulation-based investigation. In order to transfer these results into practice, various assumptions, such as charging behaviour (response speed, ramp up speed), inverter efficiency, and battery ageing, need to be further investigated in field trials to better understand them and validate the benefits identified here. Also, unforeseen usage of the BEV that might impact the savings potential has not been considered so far. To tap the full potential of bidirectional charging, general conditions must be changed. Uniform standards for bidirectional charging must be finalised and rolled out sooner than later to prevent the majority of the future BEV stock from being sold incompatible. Also, the awareness and education of BEV customers regarding battery ageing must be targeted. In addition, better inverters must be installed by the car manufacturers that provide higher efficiencies at low power levels (e.g. 0 - 3 kW).

Appendix A: Vehicle-to-Grid (aFRR)

Fig. 23 Vehicle-to-Grid parameter variation: profile first car, commute to work, 80 kWh storage size

Daily start charge state [% SOC]	aFRR power [kW]	Cost reduction [€]	Days without aFRR fullfilment	Addictional battery cycles
40%	2	1388	**35**	54
43%	2	1170	**52**	58
40%	1	844	**58**	31
40%	3	1666	**58**	62
45%	2	1034	**71**	58
48%	2	1008	**72**	61
43%	3	1481	**73**	63
45%	3	1354	**81**	63
50%	2	961	**83**	61
43%	1	622	**91**	34
53%	2	915	**94**	62
48%	3	1235	**98**	59
40%	4	1448	**112**	53
45%	1	504	**112**	36
55%	2	809	**118**	59
48%	1	458	**127**	37
50%	3	1026	**128**	52
43%	4	1253	**130**	51
53%	1	446	**133**	42
50%	1	446	**134**	39
55%	1	435	**140**	43
58%	1	407	**141**	45
58%	2	664	**152**	53
45%	4	1026	**162**	45
53%	3	832	**163**	47
48%	4	848	**183**	39
40%	5	921	**195**	33
50%	4	740	**198**	36
43%	5	810	**204**	31
55%	3	594	**205**	36
45%	5	702	**215**	29
48%	5	528	**240**	23
53%	4	449	**246**	24
58%	3	391	**249**	28
50%	5	384	**263**	18
55%	4	309	**270**	20
53%	5	297	**282**	15
58%	4	200	**301**	14
55%	5	200	**303**	11
58%	5	97	**323**	6
60%	3	13	**337**	6
60%	2	12	**338**	7
60%	1	2	**346**	1
60%	4	1	**346**	2
60%	5	4	**346**	1

Fig. 24 Vehicle-to-Grid parameter variation: profile secondary car, 80 kWh storage size

Daily start charge state [% SOC]	aFRR power [kW]	Cost reduction [€]	Days without aFRR fullfilment	Addictional battery cycles
40%	2	1709	**21**	74
43%	2	1455	**31**	77
45%	2	1344	**39**	80
40%	1	986	**40**	40
48%	2	1273	**48**	82
50%	2	1211	**63**	82
40%	3	1900	**65**	85
43%	1	731	**69**	43
43%	3	1754	**73**	88
53%	2	1134	**78**	82
45%	1	617	**83**	47
45%	3	1574	**92**	83
50%	1	541	**109**	51
55%	2	945	**113**	77
48%	1	549	**114**	46
53%	1	518	**118**	52
48%	3	1383	**120**	77
58%	1	493	**123**	58
55%	1	503	**125**	54
58%	2	778	**151**	69
50%	3	1140	**155**	68
40%	4	1332	**164**	62
43%	4	1220	**174**	60
53%	3	907	**184**	58
45%	4	1077	**190**	56
48%	4	952	**205**	51
55%	3	624	**227**	46
40%	5	855	**232**	40
50%	4	735	**234**	41
43%	5	709	**244**	35
58%	3	460	**256**	37
45%	5	588	**261**	30
53%	4	497	**265**	31
48%	5	445	**276**	25
55%	4	347	**287**	24
50%	5	336	**292**	20
53%	5	242	**306**	15
58%	4	191	**308**	16
55%	5	187	**313**	13
58%	5	130	**324**	10
60%	2	19	**329**	12
60%	3	11	**337**	7
60%	1	2	**345**	1
60%	4	2	**346**	1
60%	5	5	**346**	2

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Declarations

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