Modeling and simulation of electric vehicles as battery storage in an energy flexible factory

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Abstract:

Germany's federal government has set ambitious targets for the decarbonization of the transport sector with six million electric vehicles by 2030. Furthermore, the expansion of renewable energy systems leads to a need for adaptation to fluctuating electricity generation. The vehicle-to-grid approach unites these developments and uses the batteries of electric vehicles for the stabilization of power grids. Similarly, vehicle batteries connected to the charging infrastructure of factories can be used to support the energy procurement of companies. So-called vehicle-to-factory is an approach to use the vehicle batteries available in a company car park as cumulative energy storage for manufacturing companies. This paper shows that the targeted use of charging and discharging processes in electric vehicles within the framework of an energy flexible factory can significantly increase the energy flexibility of companies. For this purpose, a simulation model has been developed in Matlab/Simulink, which consist of three main modules: A controller, which determines the sequence of the simulation steps, a battery module that maps the charging and discharging processes of the batteries, and a trading module that calculates the costs and profits of purchase and sale of electricity. The simulation model is applied using real data from a manufacturing company.

Keywords: Energy flexible factory, Industry, Energy-oriented production planning, Energy management, Self-consumption, Peak loads, Energy storage, Vehicle-to-grid (V2G), Vehicle-to-factory (V2F), Electric mobility, Transport sector, Charging systems, Modeling, Simulation, Matlab, Simulink

1 Motivation

With the national electromobility development plan, Germany's federal government set itself ambitious goals in 2009. According to this plan, there should be one million electric vehicles on german streets by 2020 and six million by 2030 [1]. However, the current numbers are below the set goals. In 2018 around 335,000 hybrid and electric vehicles were in use in Germany. Based on the total number of 46.5 million German vehicles, this corresponds to a

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share of 0.7% [2]. Nevertheless, the progress report of the National Platform for Electromobility is optimistic about the future. Germany is joining the international lead markets for electric vehicles. The package of measures of the federal government and industry has contributed significantly to this. Germany had the highest growth rate worldwide in 2017 with 54,617 new registrations. According to forecasts by experts of the National Platform for Electromobility, the goal of one million electric vehicles will be reached in 2022. In addition, Germany is one of the leading international providers of electromobility. In the important international automotive markets the German automakers already reach a higher or at least comparable market share with their electric vehicles compared to their conventional vehicles. [3] With the increasing electrification of the transport sector, battery storages of electric vehicles are available when the vehicles are not in use. The vehicle-to-grid approach (V2G) and the vehicle-to-home approach (V2H) use the battery capacity to support the electric power grids [4] respectively to increase the self-consumption in the household sector [5]. Vehicle-to-factory (V2F) is a solution in which the vehicle batteries available in a company car park can be used as a flexibility option for manufacturing companies. Due to the increasing complexity of the energy markets, the importance of energy management for industrial companies with the goal of a reliable and cost-effective power supply is constantly increasing [6]. Various current research studies are exploring how the production processes of energy flexible factories can be adapted to a volatile energy supply [7-11]. 42% of small and medium-sized German companies have implemented measures in the field of electromobility or in planning. The results of the survey by the German Chamber of Industry and Commerce are an indication that electric vehicles and charging systems will be an important concern for companies in the years ahead. [12] This paper shows that the targeted use of charging and discharging processes in electric vehicles within the framework of energy-oriented production planning can significantly increase the energy flexibility of companies. The state of the art in the field of vehicle storage usage is described in section 2. Section 3 presents the methodological approach to the simulation model and its functions. The results of the exemplary application of the model are shown in section 4. Section 5 reflects the results and concludes with an outlook.

2 State of the art

In order to participate profitably in the electricity market, it is one of a manufacturing company's central targets to develop and offer energy flexibilities. This can be achieved by increasing the flexibility of the production processes on the consumer side or the power source on the generator side [13,14]. Battery storage facilities offer special potential with regard to independence in energy supply [15]. They can be used in a variety of ways and have both high energy densities and high efficiencies. In the industrial environment the following typical applications are well established: Uninterruptible power supply, optimization of self-consumption, minimization of peak loads, load shifting and offering grid services. Within the scope of this work, the two goals of optimizing self-consumption and minimizing peak loads are to be examined in particular. The self-consumption rate of self-generated electricity in industrial companies is currently at 20%–30% without storage and can be increased up to 75% by adding a storage unit [16]. The combination of solar power systems with battery storage is especially suitable here, in order to store the surplus energy produced during the day and make it available during high-priced times in mornings and evenings. The services and capacities required depend strongly on the specific process variables and corporate objectives.

Ultimately, the decisive factor is the achievable economic efficiency, which is determined by the difference between the energy costs saved through additional purchases and the costs associated with an investment in storage technology. For the minimization of peak loads, on the other hand, the crucial factor is the performance price of the power supply, which depends on the maximum load of consumption. A smooth load profile is therefore desirable in terms of reducing electricity costs [16]. In order to avoid a superposition of power-intensive processes to peak loads and the following effect on the energy price, the required additional power can be provided by storage facilities. An intelligent energy management system can be used to determine the maximum level of peak load and to control the operation of the storage system. Studies by Fraunhofer IWU show a potential of 60%–80 % of reduction in peak loads through storage integration [16].

As part of the electrification of the transport sector, it is assumed that there will be a large availability of mostly unused battery capacity in future scenarios. A sector coupling between the transport and energy sector through vehicle-to-grid enables both a stabilisation of the power grid and an improved resource utilisation of the vehicle batteries. Currently, battery-powered cars account for 0.7% of the total vehicle population [17]. Due to political efforts, technical progress, especially in the field of batteries, and ongoing investments in charging infrastructure, a strong increase is expected by 2030 [18].

The initial idea to transfer V2G to a commercial application is already mentioned in the first publications by Kempton & Tomić. In [19] they describe the situation of the vehicle fleet of a delivery service. While the cars are in daily use, for example from 9:00 a.m. to 5:00 p.m., there are still 16 hours left every day to offer system services to the power grid.

In 2016, Beier et al. published studies comparing an in-house fleet of electrified vehicles with a stationary battery storage system regarding their suitability for the integration of renewable energies in a factory [20]. For this purpose, various shift plans for the use of electric vehicles were simulated. In the best case, the storage capacity of parked and leaving cars fluctuates hourly between 70 and 80% of the maximum. By contrast, in the worst case only 10% of the storage capacity is available between 8:00 a.m. and 4:00 p.m. because all vehicles are used for delivery services. Accordingly, the results show that a stationary battery storage system can increase the degree of energy self-sufficiency of a company the most (14%). A storage system based on an electric vehicle fleet can achieve a 10% improvement in the case of high availability. The losses result from the requirement that the electric vehicles must be fully charged at the end of a period. This means that they can no longer be used as mobile storage in the time required for the charging process. In addition, the vehicles are often absent during the phases of high feed-in from renewable energy, in particular photovoltaics (PV), since they are used for fleet services depending on the shift schedule.

In [20] Beier et al. also point out that the increased number of cycles in particular must be taken into account in a final economic and ecological evaluation. They correlate both with an increasing degree of self-sufficiency and increasing battery wear. Apart from this, it is particularly interesting that the charging cycles are not evenly distributed across the electric vehicle models. The resulting error caused by simulation of a "virtual battery" must be considered when developing such simulation models.

Betz & Lienkamp are also investigating vehicle-to-grid models based on electric vehicle integration into the corporate fleet. The studies in [21] focus on the intelligent linking of fleet, energy and load management. It aims to reduce CO_2 emissions as well as the acquisition and operating costs of the fleet. Due to the lack of constant availability of the fleet vehicles, this research team is adding a stationary energy storage to the simulation. The authors also discuss the developed availability model in more detail. Considering local photovoltaic generation and stationary battery capacity, the optimal composition of the corporate fleet of electric vehicles and combustion engines is investigated.

In this paper the concept of vehicle-to-factory shall be investigated. The expression is to be understood as the implementation of V2G in the context of a production site. The vehicles used as mobile battery storage belong, for example, to the workforce or to the company as company cars. In contrast to the work of Betz et al. and Beier et al., however, the focus is on cars that are used by employees for their commuting routes to the workplace and not for business trips. In combination with local power generation, this will ensure the spatial and temporal availability of power and battery capacity. In this context, the installation of a solar power system is especially suitable for industrial power generation. By means of the targeted utilization of surplus generation, synergy effects can be exploited and the lack of controllability of renewables can be compensated with a storage system. In summary, it can be stated that vehicle-to-factory is a particularly suitable application of V2G for the following reasons.

- Vehicle availability: The EVs are available constantly and at times of high PV-generation.
- Planning reliability: Both the times and the battery capacities are known.
- Organisational effort: The existing legal relationship to employees simplifies administration.
- Clear objective: The use of storage capacity is defined without contradiction.

Applying the V2G-concept to the industrial field seems interesting according to the above mentioned advantages. After a first proof of concept in [22] this paper is aimed at further analysis of its feasibility and viability.

3 Methodological approach

Developing the simulation model can be divided into three main steps:

1. Typical characteristics of V2G-models are identified from literature and requirements for the V2F-simulation are defined.
2. The specifications from 1. are realized in a general simulation model.
3. Exemplary data is collected, assumptions are determined and the model is executed and validated.

3.1 Requirement specification

In order to identify the main characteristics of a V2G-simulation, first, a literature research is conducted. Based on the findings, the following requirements are specified:

A balancing battery model updating the defined target values based only on calculations with the input variables without taking into account the underlying physico-chemical processes is considered sufficient. As in [23,24] the individual vehicle batteries are to be specifically selected and controlled instead of combining them into a virtual storage system. This, in consequence, allows to map the charging cycles of every vehicle. The Monte Carlo method is used to determine the initial state of charge (SoC) after arrival at the workplace [24,25]. It facilitates the consideration of stochastic variables and thus, the minimization of their falsifying effect on the model. In order to protect the battery and to guarantee the vehicle owner a permanent minimum of flexibility, limits for the (un)charging processes have been defined in many studies [25-27]. In this work, a minimum charging level of 20% should not be passed, while the maximum charging level is not restricted. Since in reality the charging capacity decreases significantly with increasing state of charge [24], a linear mapping of the charge load curve as in [15] is rejected. Instead, actual measured charge load curves are integrated into the model.

3.2 Model and functions

The simulation model is developed in Matlab/Simulink and consists of three essential modules as shown in Figure 1: the Stateflow® controller, which determines the sequence of the simulation process, a battery module, which maps the charging and discharging processes of the batteries, and a trading module, which calculates the electricity costs and profits.

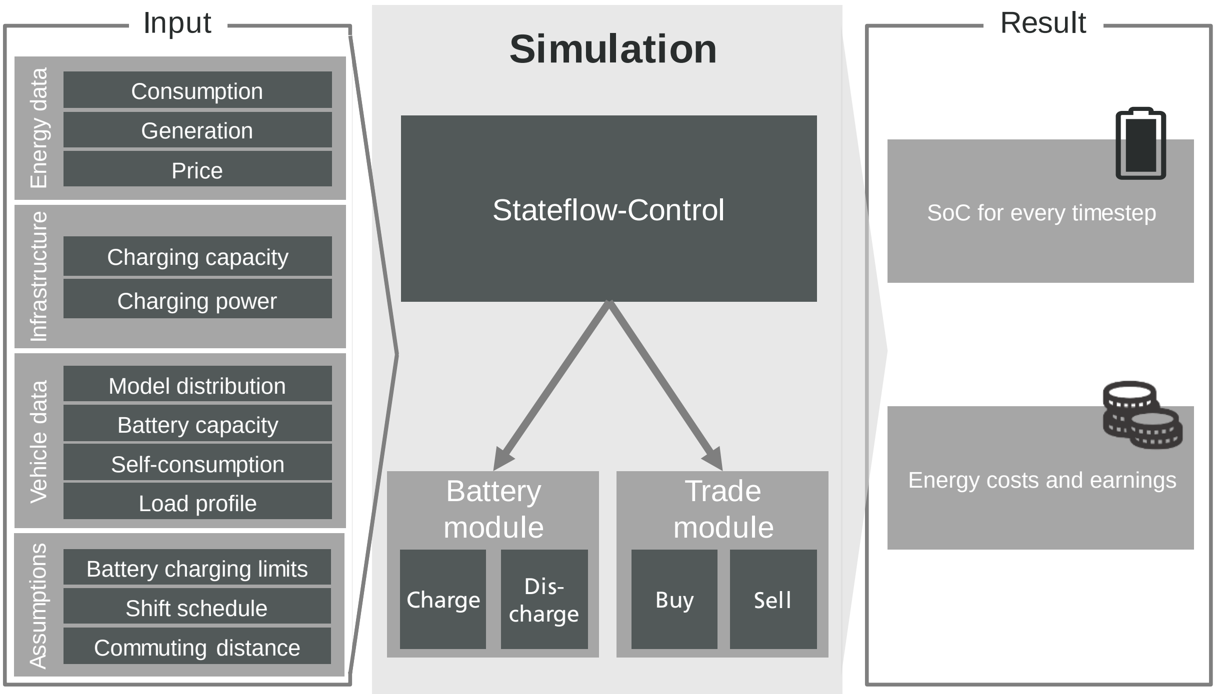

Figure 1: Structure of the simulation modell (middle) with its inputs (left) and target figures (right)

3.2.1 Control

For one day, the decision logic according to Figure 2 looks as follows: In the initialization phase, all important functions and variables are retrieved, such as the calculation of the initial state of charge. The model is then in the night state, i.e. before 8:00 a.m. and before the electric cars are available in the company's parking lot. By incrementing the counter in this step, the difference between the generation of the solar system and the energy demand of the factory (residual load) for the respective time step is determined. As there is no storage available yet, the electricity demand can only be purchased on the market. The model jumps back and forth between the states "night", in which the residual load is determined, and "trade", in which the determined residual load is covered, until the day begins (right in the picture). As soon as the counter reaches the 08:00 am limit and, thus, all electric vehicles have arrived at the parking lot, the state of charge of the batteries is checked (left in the picture). If not all batteries are empty when the residual load is negative (more power required than generated) or, analogously, if not all batteries are full when the residual load is positive, the transition condition to the storage state is fulfilled. Here it must be noted that "empty" and "full" refer to the defined charging limits and do not necessarily describe the physical-chemical state of charge. If the charge limits have already been reached, the residual load is covered again in the trade state, i.e. purchased or sold according to its sign. This matching takes place in each time step between the states “day”, “battery” and “trade” until 4:00 p.m. Then the control returns to the fictitious night mode and trades the requirements on the market. At 12:00 p.m. the variable “day” is incremented by one unit in the state “end” and there is an unconditional transition back to the initialization phase, from where the next day begins.

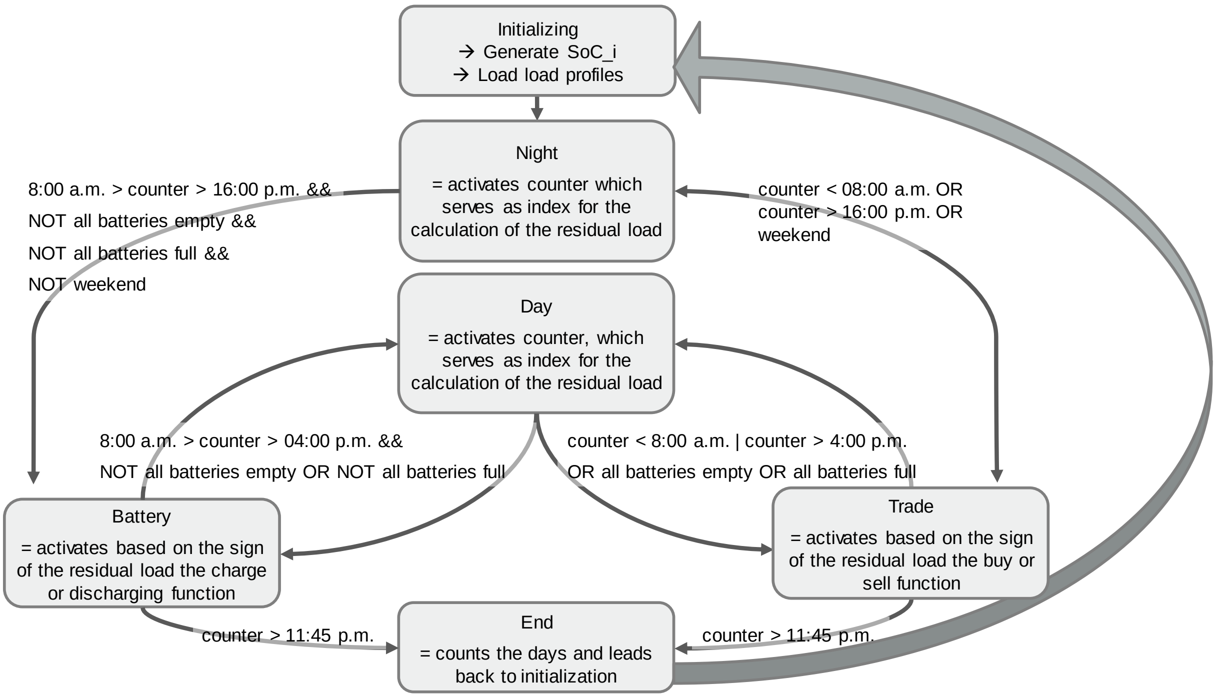

Figure 2: Flow chart presenting the decision-making logic of the Stateflow®-control

Two different control models are implemented in order to consider the two selected use cases described in section 2. They differ in their decision logic of the battery module control as follows:

- In order to **maximize the self-consumption rate**, the decisive factor is the battery charging status. Whenever power is available in excess and not all batteries are full, it is stored. Accordingly, whenever power is required and not all batteries are empty, it is taken from the vehicles’ accumulators.
- In order to **reduce peak loads**, the decision criterion is the height of the load. Only if it exceeds a certain limit, the energy is obtained from the batteries. In this way, the achieved power price can be kept within defined limits. The upper limit of the load is freely selected here to 80 kW.

3.2.2 Battery module

When the battery module is activated, first, an index is generated, which makes it possible to control a specific vehicle represented by an element in a data vector. To take into account the increase of the SoC over the charging time, charging load curves are measured at a charging station and integrated into the model. For each vehicle model there are three possible load profiles, one of which is randomly selected in each charging process. Within the charging function, the development of the state of charge over time is determined using two central methods. The time course is represented by a while loop, which is run until one of the following three criteria is reached.

- The time must not exceed 15 minutes. This is derived from the data characteristics of the energy data. It is available as quarter-hour power values. Since the battery capacity is an energy quantity and the energy content is the product of power P and time t, the power values must be converted into the corresponding quarter-hour energy values.
- The amount of energy charged into the battery reduced by the efficiency of the inverter must not exceed the amount of energy available.
- The sum of the charged energy and the energy already contained in the battery must not exceed the maximum battery capacity.

Within the defined limits, the target value of the state of charge is calculated by a so-called Look-Up-Table facilitating to look up interpolated values in an n-dimensional table. It links the vectors of the time and energy values of the actual measured charge load curve according to an interpolated graph. It can then output the corresponding energy value E at any time t, contained in the battery after the charging time. Consequentally, the current state of charge of the indexed vehicle can be determined.

3.2.3 Trade module

The trade module calculates the costs or profits arising from trading the required or surplus electricity. It distinguishes between a sell- and a purchase-function. The latter will buy electricity if no energy can be drawn from the vehicle batteries due to the time of the day or the charging status. To do this, the amount of energy required is converted into kWh and then multiplied by the electricity price. In the case that all batteries are fully discharged during a discharging process, the required residual energy can be purchased. The energy already discharged from the batteries is then subtracted from the energy demand of the individual time step. In addition, the electricity price, which refers to a quarter of an hour, is reduced by the proportion of the time step that has already elapsed in the charging process.

3.3 Data acquisition and definition of assumptions

As can be derived from Figure 1, various data inputs were integrated into the model in order to perform an exemplary application. This section gives an overview of the type and source of the selected data.

3.3.1 Energy data

A medium-sized company serves as data source for obtaining the real world energy data. The company has a production plant with an annual energy requirement of approx. 300 MWh.

Furthermore, they have electricity generation from a photovoltaic system with an annual yield of around 290 MWh.

Although the annual amount of energy demand and production are almost identical, the performance curves show a clear difference in terms of temporal availability. Consumption remains relatively constant throughout the year, with deviations due to a fluctuating monthly order situation. In contrast, PV generation shows a seasonal increase in the summer months. Nevertheless, the maximum values of the yield performance are above the maximum consumption in both summer and winter. However, solar energy does not only depend on the seasons, but especially on the times of the day. Although consumption also fluctuates according to the rhythm of the day, it is not zero even at night, unlike energy generation from PV. This results in excess energy availability during the day and a lack of energy at dawn and at night.

For the economic evaluation of the V2F approach, the average electricity price for industrial customers with an annual demand of > 160 MWh was also taken into account. According to [28] it currently amounts to 17.7 ct/kWh. For a feedback of excess PV generation into the grids, profits of 7 ct/kWh are assumed, which are customary in the industry.

3.3.2 Vehicle data

For simplification, it is assumed that there is one representative electric model per vehicle class on the company car park with the following distribution: 20% top class model (Tesla Model S), 40% middle class (BMW i3), 40% small car (Smart EQ fortwo). The characteristics of the charging station, which recorded actual measured load curves (see next section), also limit the number of vehicles considered here. This means that a maximum of eight vehicles can be charged simultaneously. Relative to the size of the car park with 100 spaces, the proportion is 8%.

3.3.3 Charging data

The charging characteristic of a lithium-ion battery is not linear but first rises steeply and then decreases again as the state of charge increases. In order to reproduce a charging process as close to reality as possible without making the battery module of the simulation too complex, charging load profiles measured on a high-performance charging pole were integrated into the model. However, the charging station only records in rough time intervals and provides only limited information on battery size and initial state of charge. Resulting inaccuracies cannot be avoided. From the available charge load curves, three are selected for each model. In order to prepare the data for simulation, the interpolated charge graphs are integrated step by step over time using a function. For each limit value of 0.01 time units, an area value of the curve is calculated and thus represents the energy output. These energy values are stored in a vector and serve together with the time vector as input variables. For the discharging process, a linear course of the discharge power is assumed. Analogous to charging, the charging current is constant during discharge, but is not regulated over time. Therefore, the charging power only decreases with decreasing battery voltage. Since, as described in more detail later on, the battery is not discharged below 20% in this model, the course of the discharge power should be approximated linearly. The possible discharge powers 11, 20 and 50 kW were implemented, whereby the model randomly selects one of the powers in each time step analogously to charging.

3.3.4 Commuting data

The Monte Carlo method was used to determine the state of charge of the vehicle battery when the employee arrives at his workplace. It is assumed that the employees leave home with a vehicle that is fully charged overnight (SoC = 100%). The following relationship then results for the state of charge of a battery after distance x: [29]

$$SoC = SoC_i \pm \eta * x$$

SoC = State of charge

SoC_i = Initial state of charge

η = Self-consumption of the vehicle

x = Commuting distance

Data from the German Mobility Panel of the Karlsruhe Institute of Technology (KIT) [30] were used as the basis for the distance x, which in this model corresponds to the commuting distance to the workplace. It is a long-term study to characterize the everyday mobility of German private households. Data are collected on the duration, distance and cause of car journeys, which can then be evaluated according to the commuting distance to the workplace. Following [23], a normal distribution of the commuting distance was applied. The mean value μ_{dist} is therefore 16.39 km and the standard deviation σ_{dist} is 22.92 km.

The Monte Carlo module generates normally distributed distances, which are stored in case of a positive value. Using the formula shown above, the SoC is calculated for each random value and then summarized to an average value. Thus, the highly variable characteristics of the commuting distances of the employees are taken into account and represented stochastically.

3.3.5 Assumptions

In order to control the large number of variable influences, various assumptions have been made, which are summarized below:

- The employees charge their vehicles overnight and start from home with the batteries fully charged.
- They reach the workplace at 8:00 a.m. and provide their vehicle for a full 8-hour shift until 4:00 p.m.
- A total of eight electric cars are parked in the company parking lot, including two Tesla, three BMW i3s and three Smart EQs. This corresponds to an 8% share of electrified vehicles.
- In order to keep enough distance buffers for the journey home and to conserve the battery, the battery should never be discharged below 20% SoC. The discharge capacity is linear.
- An industry reference value of 0.9 is estimated for the efficiency of the charging column inverter.
- If the company has to buy electricity from the market, 17.7 ct/kWh are due after [28]. Revenues of 7 ct/kWh are assumed for the sale of one kilowatt hour of solar electricity.

4 Results of the exemplary application of the model

The simulation was carried out for two exemplary industrial applications of battery storage: the increase of self-consumption and the minimization of peak loads. In addition, one summer and one winter month were simulated to investigate the seasonal fluctuations. The calculation time of the model is just under two minutes. Most of it is used for compilation, during which the load cycles of the electric vehicles are charged.

It is shown that the implementation of V2F can significantly increase the self-consumption rate both in winter (13.6%) and in summer (4.3%) as shown in Figure 3.

Without the introduction of a V2F system, the large output of the PV system can generate electricity gains of around € 830 in July. Electricity costs for purchases, especially at night or on cloudy days, amount to € 1,175, while sales of surplus solar electricity reach € 2,005. This revenue can be slightly increased to € 850 by implementing V2F, although the amount of electricity sold drops by about 5%, which leads to decreased revenues of € 1,850. However, at the same time, the electricity purchase volume decreases by the same proportion, which reduces electricity costs to € 1,000.

In November, the electricity costs minus the proceeds from the sale of PV electricity amount to € 3,855 without the use of V2F. By introducing the self-consumption increase based on vehicle batteries, costs can be reduced by around € 410 to € 3,446. Taking into account the lower revenue from the sale of electricity, this results in a cost reduction of € 210.

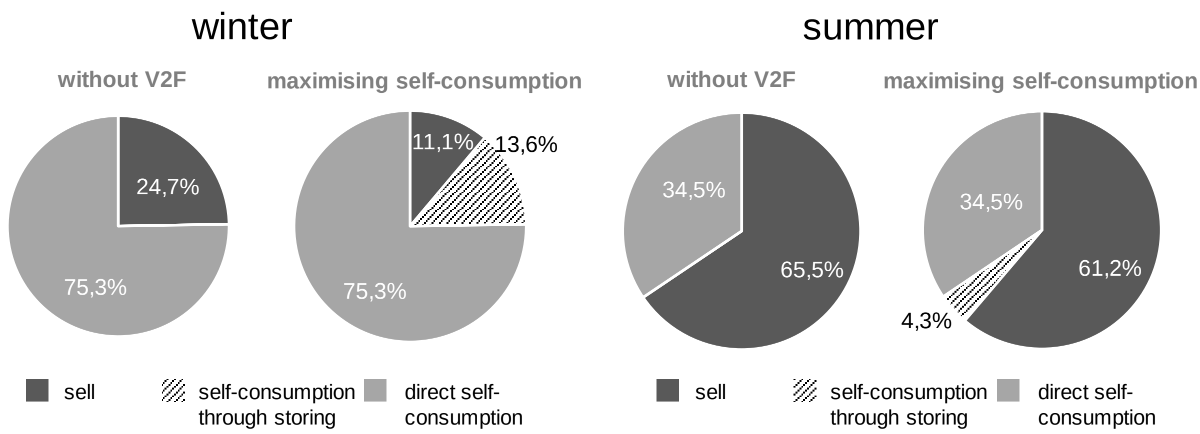

Figure 3: Increasing the share of solar self-consumption in an exemplary winter (left) and summer (right) month

The implementation of V2F with the goal of minimizing peak loads does not show the desired effects on the basis of the specific application case. This is not due to the method but to the load profiles of the exemplary company. Most of the peak loads that occur at the production plant of the medium-sized company are outside the times the electric vehicles are available. Therefore, an implementation should be checked individually. The load profile should be examined in terms of flexibility, for example to enable a shift of the load peaks into the times of storage availability. It would also be conceivable to adapt the working shift plan to an energy-oriented production planning in order to combine the advantages of V2F and flexible production processes.

5 Conclusion and outlook

The exemplary application of the model shows that by implementing V2F, the self-consumption rate can be significantly increased both in winter (13.6%) and in summer (4.3%). The monetary valuation was based on the current average price for the electricity purchase of German industrial companies. The expected increase in volatility in electricity prices and lower feed-in tariffs for self-generation plants will lead to an increase in the importance of self-consumption. For the application aiming at peak load smoothing, the consideration of further companies of different branches is necessary to make a generally valid statement. The investigation of the present application has shown that the full potential of V2F requires a combination with energy-flexible production processes, to enable a shift of the load peaks in the times of available vehicle storage. By introducing a globally optimizing controller, it is also advisable to tap remaining optimization potential and integrate a forecasting capability. In addition, it may be the subject of further work to compare the V2F model with the purchase of a stationary battery. In particular, the investment costs, which were excluded in ths work, should be taken into account. As the results show, the seasonal fluctuations in storage utilization as a result of the seasonal dependency of solar power generation must be taken into consideration. In order to check the feasibility with regard to employee acceptance, a remuneration concept should also be developed.

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