Peak Shaving – a cost-benefit analysis for different industries

Timo Kern, Basil Bukhari

FfE, Am Blütenanger 71, 80995 München, Adresse, tkern@ffe.de, ffe.de

Abstract:

The rising population of electric vehicles (EVs) and the high cost of grid fees mean that there is a huge potential for reducing electricity costs through peak shaving in Germany. To calculate potential revenues via bidirectional charging (Vehicle-to-Business) of EVs, the cost of electricity for industries is linearly minimized. Electrical load profiles of companies, driving behavior of employees, and charging and discharging constraints of EVs to minimize the cost of electricity were considered. The economic feasibility of bidirectional charging is analyzed by comparing it to smart charging approaches. The real companies' load profiles are categorized into four peak load categories, "< 500 kW", "500-1000 kW", "1000-5000 kW", and "> 5000 kW" for analysis. The payback periods and net income associated with bidirectional charging compared to smart charging are generally found to be under 5 years based on medium-term CAPEX of charging infrastructure. It is also observed that the effect on equivalent full cycles (EFC) due to bidirectional charging is minimal. This paper highlights the economic potential of peak shaving by EVs and thus, incentivizes industries to integrate bidirectional EVs.

Keywords: bidirectional charging of EVs, peak shaving, grid fees

1 Introduction

Bidirectional charging of electric vehicles (EVs) may constitute a significant resource for providing flexibility to the energy system. The energy transition demands the decarbonization of all sectors, including the mobility sector. To achieve this a transition from fossil-fueled vehicles to electric mobility is inevitable. Potentially millions of EVs in Germany alone could not only draw power from the grid but could be additionally used to discharge back to the grid and thus provide flexibility to the energy system. One possible application of this flexibility is using EVs for peak shaving for industrial sites, i.e. reducing maximum power consumption of a site by charging during a time of submaximal power demand and discharging during a time of maximum power consumption. A reduction in peak consumption could significantly bring down total electricity costs of industrial consumers while simultaneously reducing the peak demands placed on the electricity grid.

Grid fee makes up a significant part of the electricity price for industrial consumers /BDEW-01 20/. It is partly dependent on energy consumption but also highly dependent on maximum power consumption of the company. As shown in Figure 1, the power prices for the four distribution system operators (DSO) Bayernwerk AG, Netze BW, WW Netz and EWE Netz have risen sharply over the last 10 years. For this reason, there is an increasing incentive to reduce the peak load in order to save costs through the power price. Other components of total electricity costs are only dependent on total consumption. Since peak shaving does not reduce consumption but only shifts loads total electricity consumption is increased due to charging/discharging losses of the EVs' batteries.

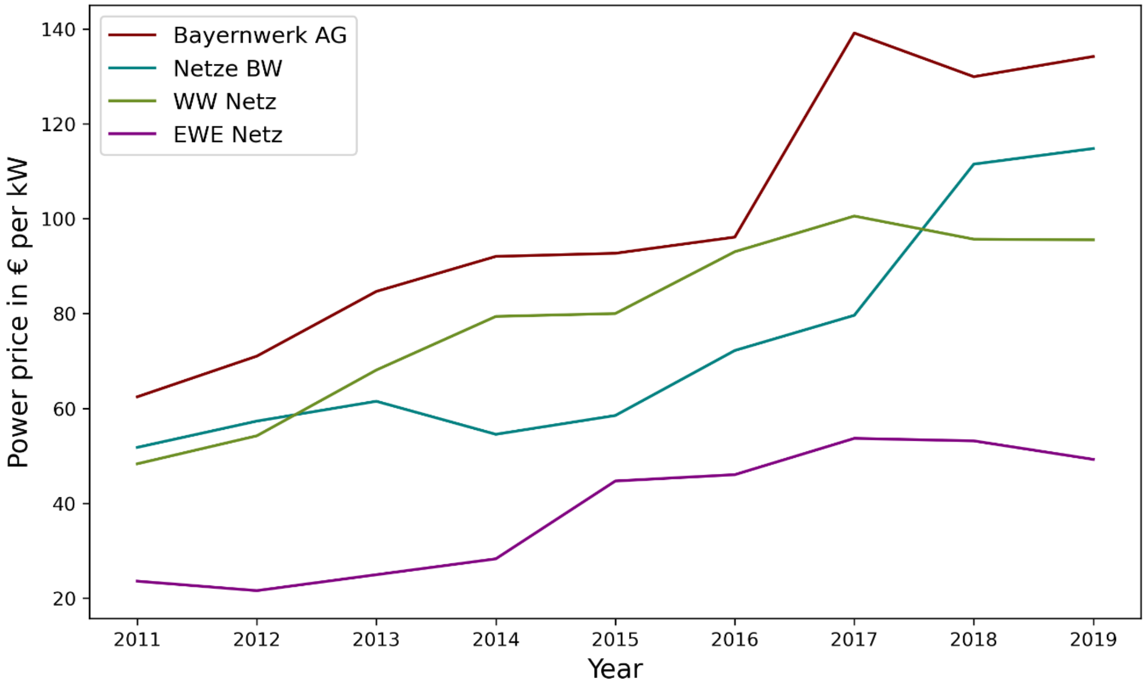

Figure 1: development of the power price of the distribution system operators Bayernwerk, Netze BW, WW Netz and EWE Netz.

As opposed to this study, most previous studies related to peak shaving focus mainly on increasing electric grid stability [/KEPCO-01 17/, /UBR-02 19/], increase flexibility of power systems /HULU-01 19/ and benefits to power grid companies [/SUOE-01 19/, /UOCO-01 15/]. In this paper, we will present a preliminary estimation of the cost reduction possible for various industrial sites. To this aim we simulated bidirectional charging behavior of EVs optimized for a maximum reduction in total electricity costs using real industrial load profiles.

Section 2 will discuss the methodology used for simulating the potential costs reductions through bidirectional charging, while section 3 will present the simulation results and discuss potential sensitivities. We conclude in section 4 by summarizing our findings and presenting an outlook for future research.[1]

2 Methodology

Simulating potential cost reductions through bidirectional charging was implemented through a constrained linear optimization. In this section cost function, and optimization constraints are discussed, whereas input parameters of the optimization are presented in subsection 3.1.

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[1] This paper presents the results generated in Basils master project /UBK-141121/. Parts of his thesis are reused in the corresponding sections, especially in section 3.

2.1 Cost function

Total electricity costs for an industrial site utilizing bidirectional charging were determined by linear optimization using discrete-time *t*. The cost function f_{cost}, i.e. total electricity costs for one year consists of grid fee *g* and other price components *o:*

$$f_{cost} = g + o \tag{1}$$

Both grid fee g and other price components o are dependent on energy consumption

$$E^{tot} = \sum E_t \tag{2}$$

(where E_t is the energy consumption at time *t)* and grid fee is also dependent on peak power P^{max}, the maximum power drawn from the grid over all time steps

$$P^{max} \geq P_t^{from,grid}. \tag{3}$$

Thus the cost function is

$$f_{costs} = p_e^{gf}.E^{tot} + p_p^{gf}.P^{max} + p_e^{opc}.E^{tot} \tag{4}$$

with the grid fee $g = p_e^{gf}.E^{tot} + p_p^{gf}.P^{max}$ and the other price components $o = p_e^{opc}.E^{tot}$,

where p_e^{gf} is the energy price, p_p^{gf} is the power price and p_e^{opc} is the multiplication factor for the energy dependent price components of the electricity price.

Grid free varies depending on grid level, and full load hours $FLH = \frac{E^{tot}}{P^{max}}$ of the load profile. Grid fee can be discounted through 1) atypical grid usage and 2) intensive grid usage. Load profiles with FLH > 7000 are viable for intensive grid usage and can get considerable discounts on grid fee (≥ 80 %). Peak load hours *plh* are defined by the DSO. If a maximum power consumption during peak load hours $P^{plh,max}$ is smaller or equal to threshold grid fee can be according to StromNEV (Section 19(2) S. 1) calculated using $P^{plh,max}$ instead of P^{max}. Both atypical, as well as intensive grid usage, were not considered for the analysis. Since peak load hours are defined by the DSO and can thus vary greatly atypical grid usage was excluded from the analysis to make the results more robust to regional variation.

Input parameters for the optimization can be categorized into EV characteristics (battery capacity, maximum charging power, ...), driving behavior, electricity prices, and the load profile and are described in subsection 3.1.

2.2 Constraints

For minimizing the electricity costs of a company, in each time step the energy drawn must be equal to the energy consumed. Therefore, we integrate the power flows at the company's grid connection point according to Equation 5. The drawn power from the grid $P_t^{from,grid}$ must be equal to the load of the company P_t^{load} added with the EV charging power $\sum_{cEV} P_t^{EV,Charging}$ and subtracted with the EV discharging power $\sum_{cEV} P_t^{EV,Discharging}$ over all EVs *cEV:*

$$P_t^{from,grid} = P_t^{load} + \sum_{cEV} P_t^{EV,Charging} - \sum_{cEV} P_t^{EV,Discharging} \tag{5}$$

To minimize electricity costs of a company energy consumption (i.e. the energy $E_{charging,EV}$charged by the vehicles + the industrial load E_{load}) must be equal to the energy drawn from the grid:

The stored energy of every EV is constrained by conservation law:

$$E_t^{EV} = E_{t-1}^{EV} + P_t^{EV,charging}.\eta^{EV,charging}.\Delta t - \frac{P_t^{EV,discharging}}{\eta^{EV,discharging}}.\Delta t - P_t^{EV,driving}.\Delta t \tag{6}$$

Where E_t^{EV} is the energy stored in the EV at time *t*, Δt is the time step used in the simulation, and $\eta^{EV,charging}$ and $\eta^{EV,discharging}$ are the charging/discharging efficiencies of the EV.

For the start of the simulation, i.e. $t = 0$

$$E_{t=0}^{EV} = E^{EV,initial} \tag{7}$$

holds. Further E_t^{EV}, $P_t^{EV,charging}$, and $P_t^{EV,discharging}$are constrained by maximum values as given in:

$$0 \leq E_t^{EV} \leq E^{EV,cap} \tag{8}$$

$$0 \leq P_t^{EV,charging} \leq P^{EV,charging,max} \tag{9}$$

$$0 \leq P_t^{EV,discharging} \leq P^{EV,discharging,max} \tag{10}$$

for all *t*. To model user behavior, we introduce the constraints 12 and 13 to limit the state of charge (SoC) of the EVs. The stored energy in the EV battery is limited by the maximum battery capacity $E^{EV,cap}$

$$SoC_{safety}^{EV} \cdot E^{EV,cap} \leq E_t^{EV} \leq \ E^{EV,cap} \tag{11}$$

and a SoC_{safety}^{EV} is implemented in order to make unplanned trips, e.g. in case of emergencies possible. Upon departure the SoC has to be at least equal to the safety SoC, so that:

$$E_{t,departue}^{EV} \geq \ SoC_{departure}^{EV} \cdot E^{EV,cap} \tag{12}$$

Smart charging (used as a reference point to gauge the profitability of bidirectional charging) was implemented by adding a constraint:

$$P_t^{EV,discharging} = 0. \tag{13}$$

3 Results and Evaluation

In this section, the results of the simulation are presented.

3.1 Definition of base scenario

The parameter definitions and conditions for this use-case are provided in Table 1. All evaluations include simulations of 1, 5, 10, 20, and 30 EVs. We compare bidirectional charging EVs to smart charging EVs. Unmanaged charging would add further peaks to the load profile which may increase the power-dependent part of the grid fee significantly and is therefore not suitable as a reference point. EVs using a smart charging strategy will try to avoid increasing peak load so that increased electricity costs are only due to an increase in electricity consumption and not due to a greater peak load.

Table 1: parameters for the base scenario

EV And EVSE Characteristics	
Number of EVs	1, 5, 10, 20, and 30
Battery capacity	40 kWh
Maximum charging/discharging power	11 kW
Minimum safety SOC	0.3
Minimum SOC at departure	0.7
EV Driving Behavior	
On-site availability of EV	Three-shift system
Driving consumption	Average German employee (37 km one-way commute at 37 km/hs)
Electricity prices	
Annual price of DSO and grid fee	Average annual prices of Bayernwerk Power price: 100.2 €/kW Energy price: 0.54 ct/kWh
Grid operator	Bayernwerk AG

A total of 103 real industrial load profiles from the years 2011 to 2019 were used for the analysis. The load profiles were from various industries, i.e. chemical industry (9 load profiles), mechanical industry (46 load profiles), metallurgy (10 load profiles), food and nutrition (19 load profiles), and rubber and plastics (19 load profiles). All considered load profiles have > 2500 FLH so that the higher power and lower consumption price uniformly apply to them.

Since maximum power consumption is an important characteristic of the load profile the profiles have been binned into ≤ 500 kW (14 load profiles), 500 to 1000 kW (28 load profiles), 1000 – 5000 kW (43 load profiles), and ≥ 5000 kW (18 load profiles).

EV behavior was modeled by logbooks based on 1) assumptions about the shift system on the industrial sites and 2) average behavior of commuters in Germany.

Since near-peak (≥ 90% of maximum power consumption) loads could be observed during evening and night time a three-shift system (Mo – Fr: early shift (6:00 am – 2 pm), late shift (2 pm to 10 pm, night shift (10 pm to 6 am); Sa-Su: day shift (6 am – 6 pm), night shift (6 pm – 6 am)) was assumed for the employees on-site. EVs are considered to commute 32 km (one way) at 37 km/h which corresponds to the average driving behavior of an employee in Germany /DESTATIS-115 17/. Additional energy consumption through non-work-related driving behavior was assumed to be covered by charging at home or public charging stations and thus neglected for the analysis.

3.2 Revenues of peak shaving by bidirectional charging EVs

The revenues associated with bidirectional charging for each peak type depend strongly upon the number of EVs. The median revenue differences between bidirectional charging and smart charging are given in Figure 2. The first EV is always the most profitable and saved costs per EV decrease with an increasing number of EVs. also provides some indication when adding further EVs leads to a drastic reduction in revenue per EV. For the peak types “< 500 kW”, “500-1000 kW”, “1000-5000 kW”, and “> 5000 kW”, the appropriate number is 1, 5,10, 30 EVs.

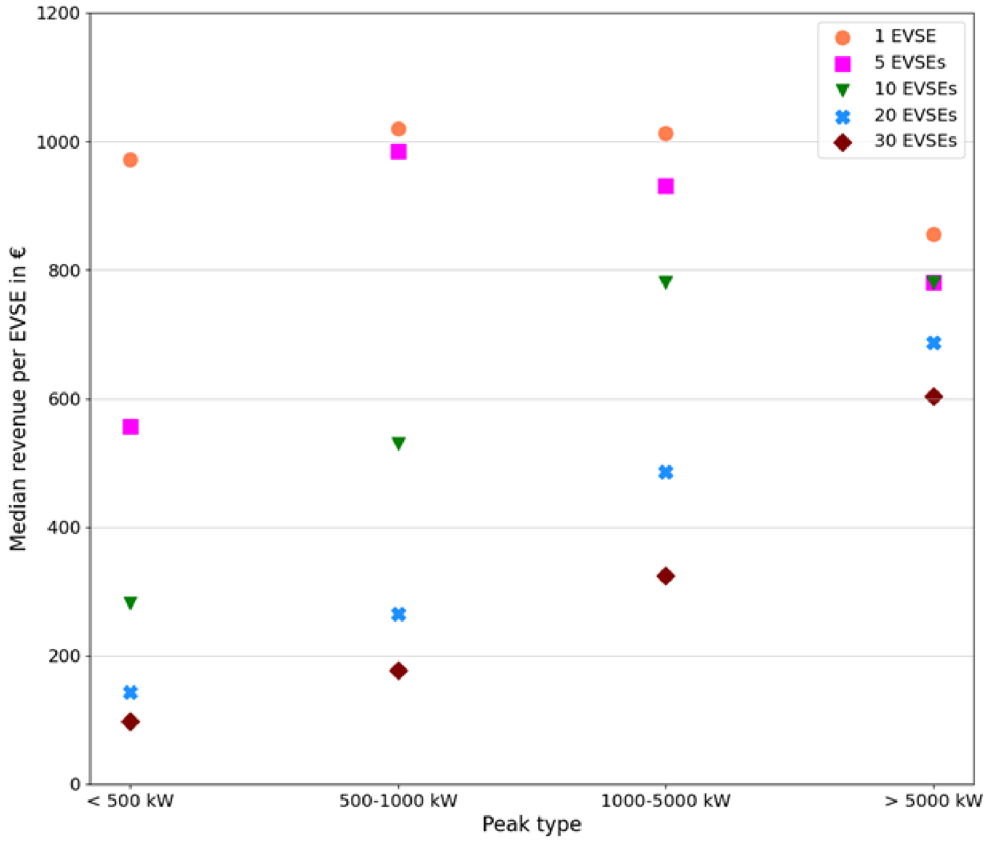

Figure 2: revenue difference between bidirectional charging and smart charging per EV plotted against binned peak load and number of EVs.

Figure 3 compares the revenue difference between bidirectional charging and smart charging per EVSE for companies with FLH greater than 5,000 hours and companies with FLH less than 5,000 hours. Neither the companies with high full load hours nor the companies with low FLH can systematically generate higher revenues per EVSE, so the FLH of a company cannot provide any information on the revenue potential.

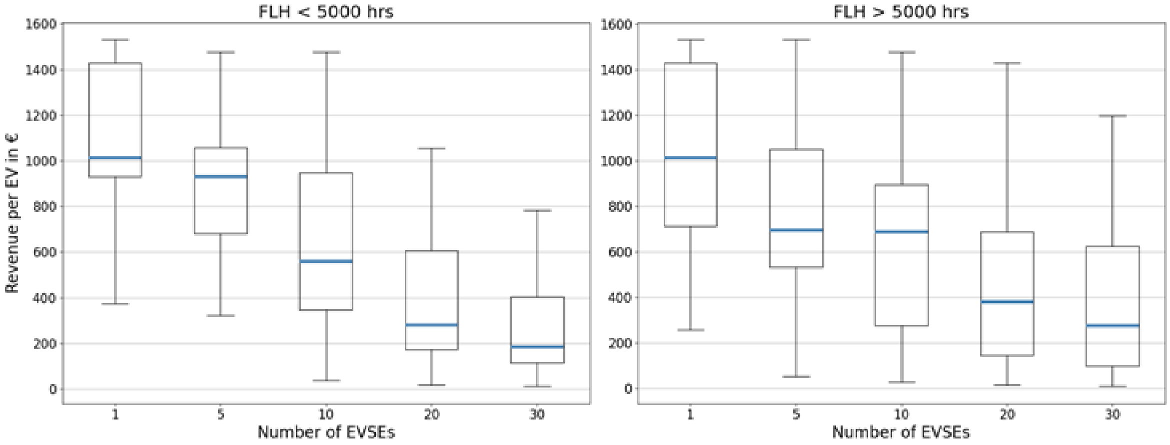

Figure 3: Boxplot with median values, comparing the revenue difference between bidirectional charging vs smart charging per EVSE with annual FLH less than 5000 hours (left) and annual FLH greater than 5000 hours (right).

3.3 Effect of distribution system operator on revenues

The revenues associated with peak shaving are highly sensitive to the DSO or to be precise, on the price of grid fee. Table 2 shows the prices of four different DSOs in Germany. Bayernwerk AG has the highest average power price, followed by WW Netz, Netze BW, and EWE Netz.

Table 2: Average grid prices for DSOs from the year 2011-2019 for annual FLH above 2500 hours.

		Annual FLH ≥ 2500 h	
DSO	Network-level	Average power price €/kW	Average energy price €/kWh
Bayernwerk AG	MV	100.2	0.0054
EWE Netz	MV	38.4	0.0144
Netze BW	MV	73.5	0.0083
WW Netz	MV	79.4	0.0108

The change in power price, energy price, and the resulting change in the average revenues of the DSOs are compared to Bayernwerk AG as shown in Figure 4. All other DSOs have lower average power prices and higher average energy prices compared to Bayernwerk AG. As a result, for all other DSOs, bidirectional charging EVs have lower revenues compared to Bayernwerk AG. The change in revenue closely resembles the change in the average power price of the grid fee. For EWE Netz, Netze BW, and EWE Netz, a change price of -61.7%, -26.6%, and -20.8% in average power results in a change of -63.1%, -23.6%, and -21.2% in revenue respectively.

Energy prices have minimal effect on revenue change. The high average energy prices of EWE Netz and WW Netz cause the change in revenue to be slightly higher than the average change in power price, which is not the case for Netze BW due to the lower average energy price.

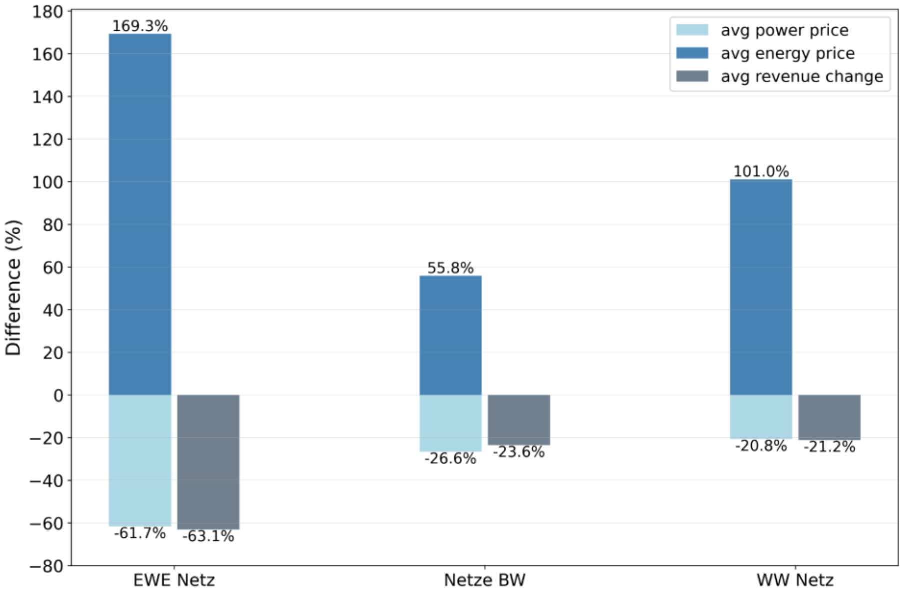

Figure 4: Percentage difference between average prices of grid fee components and associated revenue change of DSOs compared to Bayernwerk AG.

3.4 Effect of use case peak shaving on EFCs of EV

Equivalent full cycles (EFC) are an important parameter influencing the lifetime of a battery. Due to peak shaving, the EV battery charges and discharges more than normal, which increases the EFC of an EV battery. However, the mean increase in EFC for bidirectional charging compared to smart charging is between 0.11 to 0.32 EFCs/a, whereas the maximum increase in EFC is 4.2 EFCs/a for 30 EVs.

This increase in EFCs is extremely low. Since the number of peaks shaved throughout the year is relatively low the effect of peak shaving on EFC/a is negligible compared to the charging needs caused by commuting. This suggests that peak shaving does not have a notable effect on battery lifetime.

3.5 Payback period and net income

Payback period $t_{payback}$ can be used as a rough estimate for the profitability of projects. Calculation of payback period and net profit is derived from the calculated revenues per EV per year R_{ev} subtracted by the additional costs for peak shaving by bidirectional charging EVs. We assume a medium-term additional CAPEX C_0 of 1,300 to 2,200 € for bidirectional EVSE and additional measuring equipment compared to smart charging EVSE and measuring equipment /FFE-95 19/. For calculating yearly costs and resulting payback periods, we assume an EVSE lifetime of 15 years, a rate of interest $i = 3.5\ \%$, and a yearly maintenance costs $c = 2\% \times C_0$. The payback period based on medium-term CAPEX can be calculated using the following equation:

$$\frac{C_0}{\sum_{1}^{t_{payback}} \frac{R_{ev} - c}{(1+i)^{t_{payback}}}} = 1 \tag{14}$$

Figure 5 shows the payback period based on the medium-term CAPEX. The payback periods are calculated for each peak type and a varying number of EVs. The red line is marked at 15 years to indicate the end of life (EOL) of the charging infrastructure.

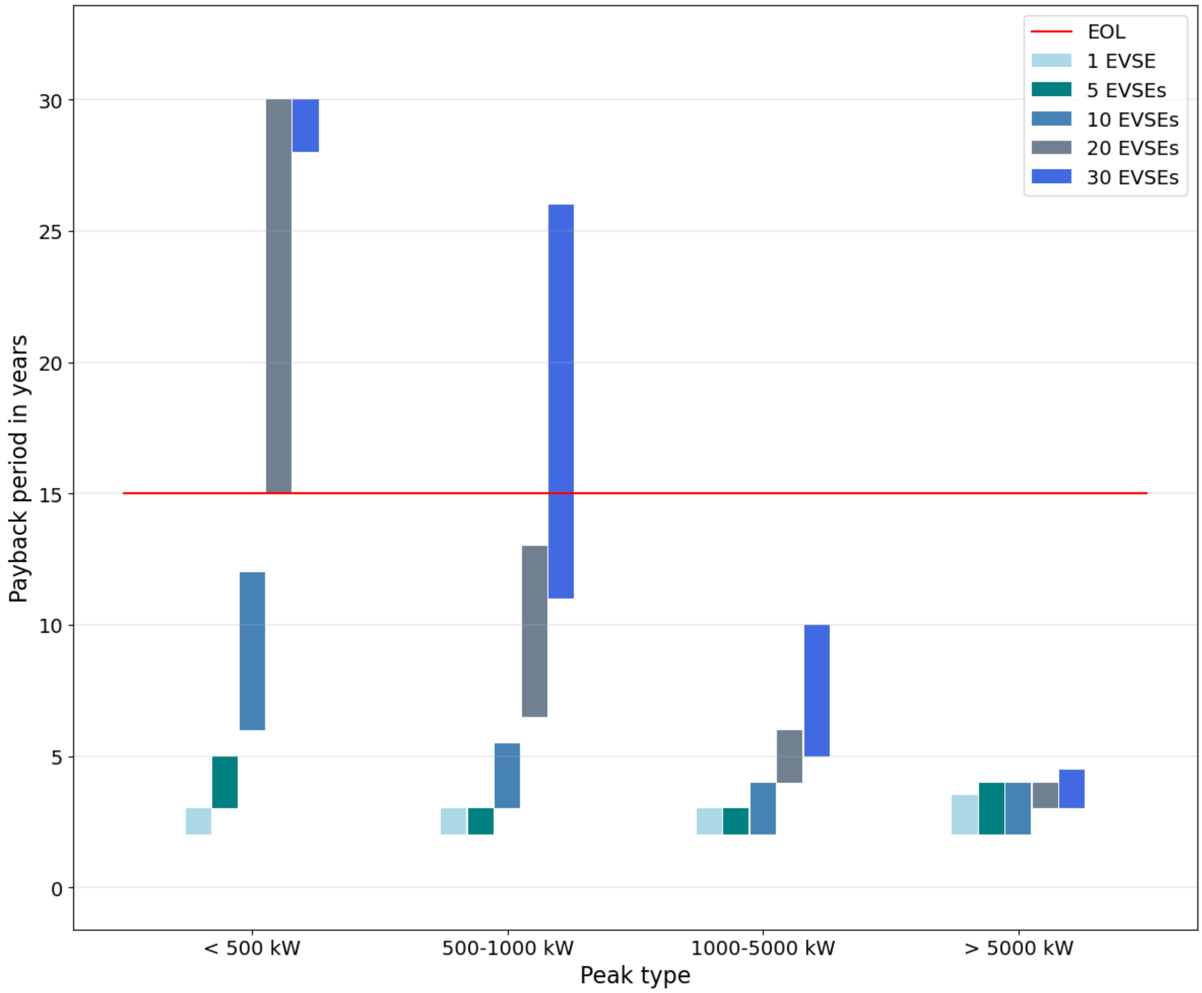

Figure 5: Bar graph showing the range of discounted payback periods based on medium-term CAPEX for realistic driving profiles use case. The plot covers all peak types and the number of EVs ranges from 1 to 30. The EOL of charging infrastructure is represented by the red line. Payback periods greater than 30 years are excluded from the visualization.

The payback periods for medium-term CAPEX range from 1 year to more than 30 years. With an increasing number of EVs, the payback period tends to increase. It is mainly due to the additional CAPEX and reducing revenues with an increasing number of EVs.

For the peak type “< 500 kW” only 1 to 10 EVs show lower average payback periods of up to 5 years. For peak types “500-1000 kW”, “1000-5000 kW” and “> 5000 kW”, the number of EVs increases to up to 10, 20, and 30 EVs respectively. This trend indicates that for higher peak loads, more EVs can be included for peak shaving.

The payback periods indicate the feasibility of a project by providing information about the timeline to break even with the investment. However, it still does not provide an estimate of total revenues or net income at the EOL of the charging infrastructure. The ranges of net income at the EOL of the charging infrastructure are shown in Figure 6. The red line marks the break-even point.

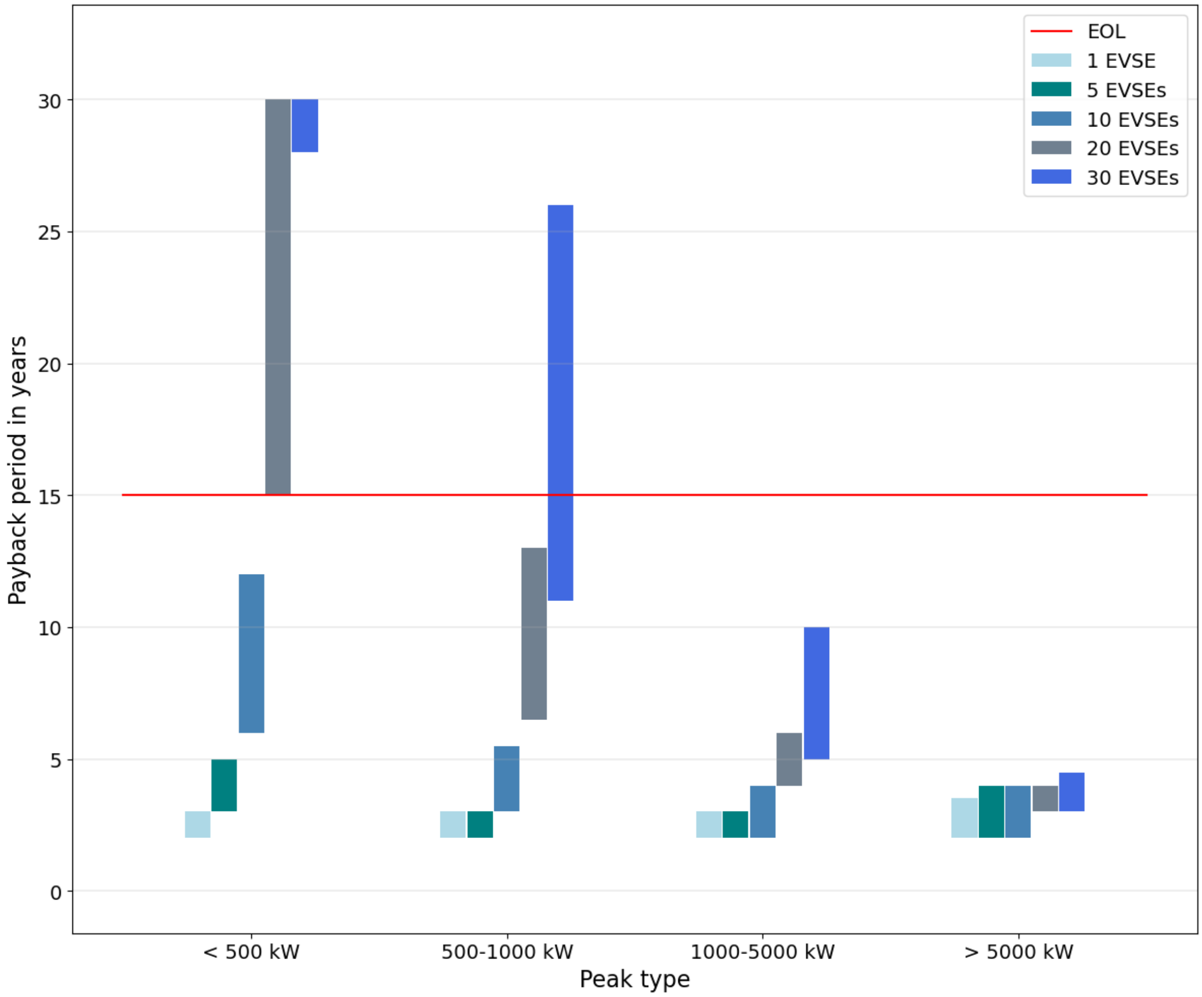

Figure 6: Bar graph illustrating the range of net income based on medium-term CAPEX realistic driving profiles use case. The plot covers all peak types and the number of EVs ranges from 1 to 30. The red line marks the break-even point at the EOL of the charging infrastructure.

4 Discussion and Outlook

Peak shaving with bidirectional EVs could be an interesting opportunity to reduce companies' electricity costs in Germany. Using a linear optimization model, we modeled peak shaving with EVs to estimate cost reduction potentials. For the load profiles considered potential median revenues of bidirectional EVs go up to 1,000 €/EV/a. The integration of multiple bidirectional electric vehicles into a company's load management is more worthwhile the higher the company's peak load is. Further, we showed that the potential revenues of bidirectional EVs are highly dependent on the electricity tariffs of the companies’ distribution system operators. Calculated revenues indicate that payback periods for bidirectional charging equipment using medium-term investment costs are below 5 years on average. The savings potential for companies can be so high that the incentive of bidirectional electric vehicles for employees can be worthwhile from the company's point of view.

To classify our results, it is important to discuss the limitations of the modeling. Firstly, the profitability of peak shaving is highly dependent on the grid fees set by the grid operators.

Therefore, future price changes, as well as regional variation, may greatly affect profitability. Secondly, assuming a 3-shift system for every company, a bidirectional EV was set on-site at all times. Even in larger industrial plants, this may not be given due to individual working schedules, vacation times, sick leave, etc. Thirdly, the feasibility of peak shaving is dependent on the respective industrial load profiles. The sample of load profiles used for simulation is not representative of the German industry so that a greater sampling size and variety are needed to gauge how widespread peak shaving could be implemented.

Nevertheless, our analysis presents a first assessment that peak shaving is a promising use case for bidirectional charging at industrial sites.

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