SHORT STUDY

Smart charging

Financial savings and electricity market revenues through flexible and bidirectional charging of electric cars

This is a machine-translated version of a study originally published in German. The original is available at www.neon.energy/intelligentes-laden

February 25, 2025

On behalf of Rabot Energy, a brand of RABOT Charge GmbH

Authors:
Clemens Lohr (lohr@neon.energy)
Anselm Eicke(eicke@neon.energy)
Lion Hirth (hirth@neon.energy)

Smart charging

Financial savings and electricity market revenues through flexible and bidirectional charging of electric cars

The original study is available at www.neon.energy/intelligentes-laden

The machine-translated version of this study is available at www.neon.energy/en/intelligentes-laden

Neon Neue Energieökonomik is an energy industry consultancy based in Berlin. As a boutique, we have specialized in sophisticated quantitative and economic-theoretical analyses of the electricity market since 2014. With consulting projects, studies and training courses, we support decision-makers with the current challenges and future issues of the energy transition. Our clients include governments, regulatory authorities, grid operators, energy suppliers and electricity traders from Germany and Europe.

Contact:

Neon Neue Energieökonomik GmbH
Schönleinstraße 31
10967 Berlin

Prof. Dr. Lion Hirth
hirth@neon.energy
+49 157-55 199 715

Table of contents

Summary....................................4

1 Introduction....................................5

2 Methodology....................................6

2.1 Assumptions about the electric car....................................6

2.2 Charging strategies....................................7

2.3 Electricity tariffs and price components....................................8

3 Savings potential....................................11

3.1 Savings potential through intelligent charging....................................11

3.1.1 Existing savings potential....................................12

3.1.2 Conceivable savings potential in the future....................................13

3.2 Savings potential with bidirectional charging....................................15

3.3 Classification....................................17

3.3.1 Other costs and income....................................17

3.3.2 Comparison....................................17

4 Robustness of the results....................................19

4.1 No restrictions on flexibility....................................19

4.2 Other distribution grid....................................20

4.3 Different driving profile....................................21

5 Conclusion....................................23

6 Bibliography....................................24

Summary

Smart charging. On average, electric vehicles only need half an hour a day to recharge their batteries. If this time is chosen intelligently, you can benefit from low electricity prices, for example late at night or at midday. This is already possible today with a dynamic electricity tariff. In addition, time-variable grid charges will be introduced on 1 April this year, further increasing the potential for optimization. In the long term, bidirectional charging, i.e. feeding previously stored electricity back into the grid at very high electricity prices or under extreme grid load, offers further revenue opportunities. Smart charging is not only worthwhile for consumers, but also benefits the electricity system, as it avoids expensive electricity generation, uses more wind and solar power and relieves pressure on the grids.

This study. This short study examines the savings potential of smart charging of electric cars in various constellations. Our analysis is based on a quarter-hourly optimization of charging behavior. This is done by shifting charging times in such a way that the already existing flexibility of the battery is optimally utilized - without sacrificing driving or additional investments. We examine the savings that can be achieved with the current legal framework, as well as the additional benefits that will be made possible by future regulatory adjustments such as bidirectional charging. We calculate the savings from smart charging itself; in addition, dynamic electricity tariffs are generally cheaper compared to fixed-price tariffs (the savings for not having a price guarantee), which we have not taken into account here. We have also neglected synergy effects from local solar power generation and other flexible consumption in the household.

Results. Our modeling results show great savings potential. Smart charging based on a simple dynamic electricity tariff already reduces the electricity bill by around 50%. If time-variable grid charges and other electricity price components are added, costs fall by more than 80%. With bidirectional charging, you can even earn net money, i.e. realize a negative electricity bill. Comparable results can be found for different types of cars, driving profiles and distribution grids. Dynamic electricity tariffs also allow households without their own PV system to benefit from favorable electricity prices, making electromobility more attractive to a broader target group.

Recommendations. In order to realize the high savings potential, a nationwide supply of affordable smart meters is needed. In order for decentralized flexibility to systematically benefit the grid, time-variable grid charges should also be made less bureaucratic and developed further. In the medium term, policy and regulation should enable bidirectional charging.

1 Introduction

Electrification. With the electrification of mobility and the heating sector, new electricity consumers such as electric cars and heat pumps are increasingly finding their way into private households. The high simultaneity of their operation can generate consumption peaks that pose a considerable challenge for the generation side and grid operation. At the same time, the additional storage that these technologies bring to the energy system offers enormous flexibility potential. By shifting the timing of electricity consumption in a targeted manner, operating costs can be significantly reduced without restricting user comfort.

Smart charging. On average, electric vehicles are driven for less than an hour a day and only need a fraction of the remaining time to recharge their batteries. It is therefore relatively easy to postpone charging and benefit from cheaper electricity prices. For example, shifting the charging process from the evening hours to later at night, especially in winter, can result in considerable cost savings. The same applies to a shift to the early afternoon hours, especially in the summer months. Furthermore, bidirectional charging - i.e. feeding previously stored electricity back into the grid - offers additional revenue opportunities. This could become relevant in the event of very high electricity prices or extreme grid loads, for example.

Dynamic electricity tariffs. The basic prerequisite for such savings are time-variable electricity tariffs, which - in contrast to fixed-price tariffs - pass on real scarcity signals from electricity generation and grid capacity to consumers. End customers can already benefit from hourly updated wholesale prices. From April, distribution system operators will also be obliged to offer time-variable grid charges. The prerequisite for this, however, is a time-resolved measurement of electricity consumption, which requires the use of new meters such as smart meters in most households.

This study. In this brief study, we analyze the savings potential of smart charging in conjunction with various time-variable electricity tariffs. We determine this with the help of an optimization model, from which a quarter-hourly charging profile emerges. The aim of the optimization is to minimize the electricity bill from the consumer's perspective. In doing so, we highlight both the savings that are possible with the electricity tariffs provided for in the current legal framework and the additional benefits of future regulatory adjustments. These include, for example, the introduction of stepless, time-variable grid charges or time-variable taxes, levies and surcharges. We are also investigating the added value that bidirectional charging offers in order to further reduce costs and increase flexibility in the electricity system.

2 Methodology

Basic procedure. We estimate the savings potential of flexible charging of a battery electric car. We define the savings potential as the reduction in the electricity bill that can be achieved by postponing charging compared to immediate charging. The load shifting only takes place using the existing battery, i.e. without additional investment. We limit ourselves to the supply of grid electricity and neglect local generation (e.g. PV systems) and other household consumption.

Optimization. For the calculation, we use a quarter-hourly optimization of the charging behavior based on historical time series for the year 2023. The basic assumption of the optimization is that the driving profile can be implemented without restriction. Accordingly, the electric car must be sufficiently charged before each journey. The aim is to exploit the flexibility of the battery and to shift the charging times in such a way that the electricity procurement costs are minimized. The optimal charging strategy depends on the electricity tariff.

2.1 Assumptions about the electric car

Driving profile. Table1 summarizes the technical data of the electric car. The consumption profile corresponds to that of a female commuter with a VW ID 3 Pure from Gaete-Morales et al. (2021). According to the KIT mobility panel (Ecke et al., 2023), the mileage of around 10,442 km is slightly below the national average of 11,676 km. Around 72% of the electrical energy required for this is provided by the vehicle's own wallbox, which results in a significant potential for shifting charging times.

Table1 . Overview of the technical data of the electric car (standard case)

	Standard case
Memory size	45 kWh
Maximum charging power	11 kW
Annual electricity consumption EV	2180 kWh
Annual mileage	10442 km
Charging availability	75%
Charging share outside the household	28%
Charging losses of the battery	5% each for loading & unloading
Battery degradation costs	5 ct/kWh

Technical limitations. The optimization model takes into account the physical limits of the battery. Charging is only possible when the electric car is at home and is also limited by the available maximum charging power of the wallbox and the storage capacity of the battery. Charging and discharging the battery is also subject to losses. For reasons of consistency, we specify charging processes outside the home (e.g. at public charging points) as model-exogenous charging processes. The resulting costs are not included in the electricity bill we analyze, as they are incurred regardless of the charging strategy.

Flexibility restrictions. To avoid over-optimization and to allow for the possibility of spontaneous journeys, we further restrict the optimization of the battery. For example, the battery charge level must be at least 60% every morning at 6 am. In particular, this prevents the battery of the electric car from being regularly charged only to the extent that a journey can just be completed. We also limit the depth of discharge for bidirectional charging to at least 20% of the battery storage capacity. We analyze the influence of these flexibility restrictions in section .4.1

2.2 CHARGING STRATEGIES

Smart charging. To determine the added value of smart charging, we compare the electricity costs of optimized charging with a conventional (non-intelligent) charging strategy. With this "immediate charging", the charging process begins immediately after a journey when the electric car is connected to the wallbox. The charging process runs at maximum connected load until the battery is fully charged. We call smart charging the optimal charging strategy for a given electricity tariff, which makes use of the often long downtimes between two journeys. This involves waiting for a favorable electricity price before charging and thus shifting the load to a later period.

Bidirectional charging. In addition to postponing the charging time, which is already possible today, the framework conditions should also be created in future so that the feeding of electricity back into the grid, i.e. bidirectional charging, can be remunerated. Additional revenue in the amount of the wholesale price can be achieved for the electricity fed into the grid. When discharging, we also take into account the additional energy stored and the associated lower number of cycles for possible journeys in the form of degradation costs at a flat rate of 5 ct/kWh (Sagaria et al., 2025). Degradation specific to the degree of charging and self-discharge are not shown in the model.

2.3 ELECTRICITY TARIFFS AND PRICE COMPONENTS

Electricity tariffs and price components. The cost of a household's electricity consumption is determined by the charging profile and the selected electricity tariff. This is made up of three price components:

- Wholesale price for electricity generation (excl. other procurement costs)
- Grid charges
- Taxes, duties and levies

There are different design options for the three price components (Table2). Their combination enables a variety of different electricity tariffs. All time series for the components are based on historical data from 2023. The level of individual components was selected so that the electricity bill is identical for immediate charging.

Table2 . Design options for the price components of electricity tariffs

Price component	Design options
Electricity price (generation)	• Time invariant • Day-ahead • Intraday
Grid charges (grid)	• Time invariant • Time-variable with 3 levels (§14a, Module 3) • Time-variable grid charge with 8760 steps (according to the Neon method)
Taxes, duties and levies	• Time invariant • Time-variable (scaled with day-ahead price)

Electricity generation costs. It is already possible to make the charging process more flexible on the basis of wholesale electricity prices. Optimized charging shifts the charging process to the hours with the lowest wholesale prices, as far as this is technically possible and without any restrictions on use. The day-ahead electricity prices are known after the day-ahead auction at 12 noon on the previous day. Further optimization on the continuous intraday market enables charging processes to be shifted to particularly favorable quarter hours, which is even more worthwhile due to the higher price volatility on the intraday market compared to the day-ahead market. We depict this aspect in the model in the form of ID1 prices.

Real option. With the start of intraday trading, it is possible to buy and sell electricity continuously and thus generate additional revenue. Continuous trading makes it possible to profit from price fluctuations over the period of intraday trading. The following example illustrates this. At 16:00 is the quarter of an hour with the lowest intraday prices in the following night from 3:00 - 3:15. Loading the car would be scheduled for this time and electricity would be purchased accordingly. If at a later time the intraday price for the quarter hour from 4:15 - 4:30 is the cheapest quarter hour, the previously procured electricity would be sold again and purchased more cheaply for the new quarter hour. The battery therefore has an option value.

As we do not take this real option into account in the modeling, we underestimate the total possible savings potential on the intraday market.

Time-variable grid fees. From April 2025, all distribution system operators must offer a time-variable grid fee in accordance with Section 14a of the Energy Industry Act (EnWG) as part of Module 3 of the corresponding BNetzA specification. The BNetzA has set out a number of requirements for this: several time windows with three price levels of the locally applicable grid fees are envisaged. The time windows and price levels are determined on a calendar year basis and apply to the entire grid area. Using historical feed-in and consumption load profiles for the low-voltage level of various distribution grid operators, we also estimate a quarter-hourly time series of grid costs as continuously variable grid charges (Neon, 2024). In grid areas with high generation surpluses, these can also be negative in individual hours, so that there can also be incentives for additional, grid-friendly consumption. We determine the level of both the time-invariant and the continuous time-variable grid charges according to the resulting grid charges that are incurred for instantaneous charging with time-variable grid charges with three levels. We first use the three price levels of Stromnetz Berlin as a consumption-dominated distribution grid as an example. In section4.2 , we also analyze the savings potential in the LEW distribution grid, which has a high level of PV generation.

Taxes, levies and surcharges. With the exception of VAT, taxes, levies and surcharges on electricity consumption are currently volumetric and time-invariant and amounted to around 5.1 ct/kWh in 2023 (BDEW, 2024). We determine additional savings potential resulting from the introduction of time-variable taxes, levies and surcharges. To this end, we examine the politically discussed case of these payments scaling proportionally to the day-ahead electricity price ("ad valorem" taxes). We exclude payments to consumers when electricity prices are negative. The level of payments for positive electricity prices corresponds to the previous time-invariant payments for immediate charging as for the other price components. At a day-ahead price of 10 ct/kWh, this results in an amount of around 4.6 ct/kWh. If the day-ahead price is 0 ct/kWh or lower, no taxes, levies and surcharges are incurred.

Electricity tariff scenarios. We compare the savings potential of the charging strategies depending on different electricity tariffs. In addition to the time-invariant fixed price tariff of 30 ct/kWh (incl. VAT), we consider (sequentially) the following design options for the price components, which mean increasing variability of the electricity tariff:

1. Optimization based on the day-ahead electricity price
2. Optimization based on the intraday price (ID1)
3. In addition: time-variable grid charges in accordance with Section 14a of EnWG Module 3 (with three charge levels)
4. In addition: optimum time-variable grid charges (infinitely variable)
5. In addition: Introduction of time-variable levies, taxes and surcharges

The price trend for electricity tariff scenarios 1) and 5) compared to the fixed price is shown Figure1 for May 31, 2023 as an example. As a sunny day, electricity prices were mostly below average here.

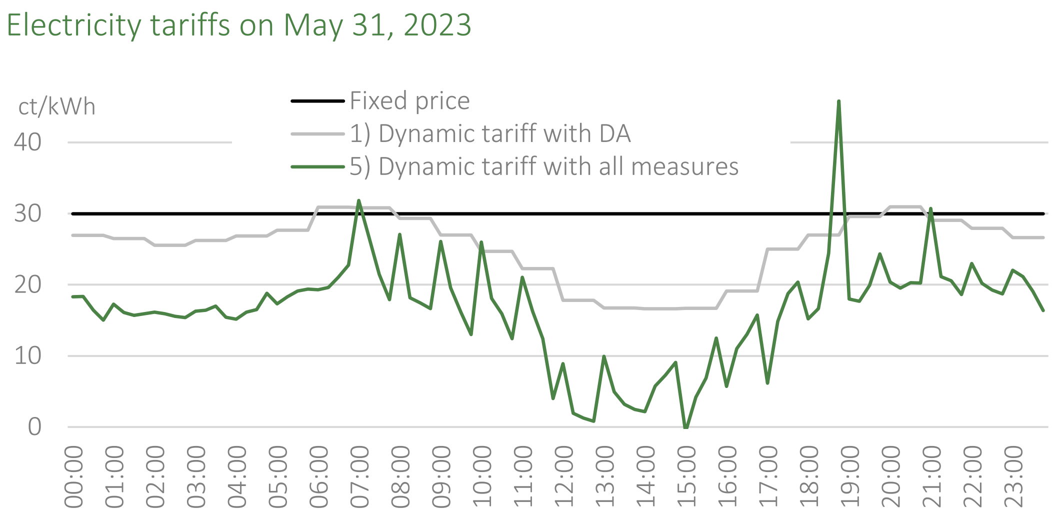

Figure1 : Electricity purchase prices (incl. VAT) for three exemplary electricity tariffs for May 31, 2023. The dynamic electricity tariffs offer the option of choosing a charging period with particularly favorable prices compared to the fixed-price tariff.

The electricity tariffs in this study are lower overall than the usual retail tariffs, as we do not take into account procurement and distribution costs above and beyond wholesale prices, such as risk hedging, marketing and administration costs. Furthermore, we do not include the usual basic prices in tariffs, as these must be paid by consumers even without an electric car. However, all unconsidered components are flat-rate, therefore do not provide any incentives for flexibilization and accordingly have no influence on the savings potential of smart charging.

3 Savings potential

In this chapter, we analyze the quantitative savings potential that can be tapped into through flexible charging of electric cars. We differentiate between savings that can be achieved with the current legal framework and the additional benefits that will be made possible by future regulatory adjustments such as stepless, time-variable grid charges or bidirectional charging.

3.1 Savings potential through smart charging

Reference electricity bill. The electricity bill for immediate charging (reference) amounts to € 475 per year (Figure2). This is calculated from the amount of electricity charged at home (1584 kWh) and the fixed price of 30 ct/kWh. The fixed price is made up of 11.1 ct/kWh for electricity generation, 9.0 ct/kWh for grid charges, 5.1 ct/kWh for electricity tax, levies and surcharges and an additional 19% VAT. If all taxes, levies and surcharges are added together, the three components contribute similarly to the electricity bill. These costs remain independent of the selected electricity tariff for instant charging, as the price components have been adjusted accordingly to ensure a uniform basis. In the fixed-price tariff, there are no incentives to make charging behavior more flexible, which means that there is no leverage for smart charging and the electricity bill remains unchanged at € 475. However, depending on the design of the (time-based) dynamic electricity tariffs, flexibilization can achieve significant cost savings compared to the reference electricity bill.

Electricity bill in the reference case

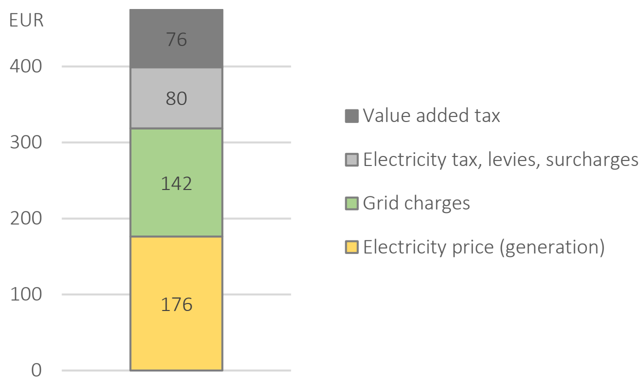

Figure2 : Electricity bill broken down by price components for the fixed-price tariff or when applying the reference charging strategy (without flexibilization) in Stromnetz Berlin's distribution grid.

3.1.1 Existing savings potential

Smart charging at day-ahead prices. If households are equipped with hourly meters, they can already be supplied with dynamic electricity tariffs. For example, electricity suppliers can pass on the day-ahead wholesale prices to their end customers, while the other tariff components remain time-invariant. Such an electricity tariff allows charging times to be shifted to hours with favorable exchange electricity prices. Figure3 shows how smart charging in dynamic electricity tariffs shifts charging to the early afternoon hours in summer and to the night in winter instead of charging immediately in the evening. The afternoon charging period in summer may come as a surprise given the commuter mobility profile. However, as the daily commute only uses part of the battery capacity, it is often possible to wait until weekends or other days off before charging the electric car (charging is not carried out at all on over 200 days).

Average charging power: summer (left), winter (right)

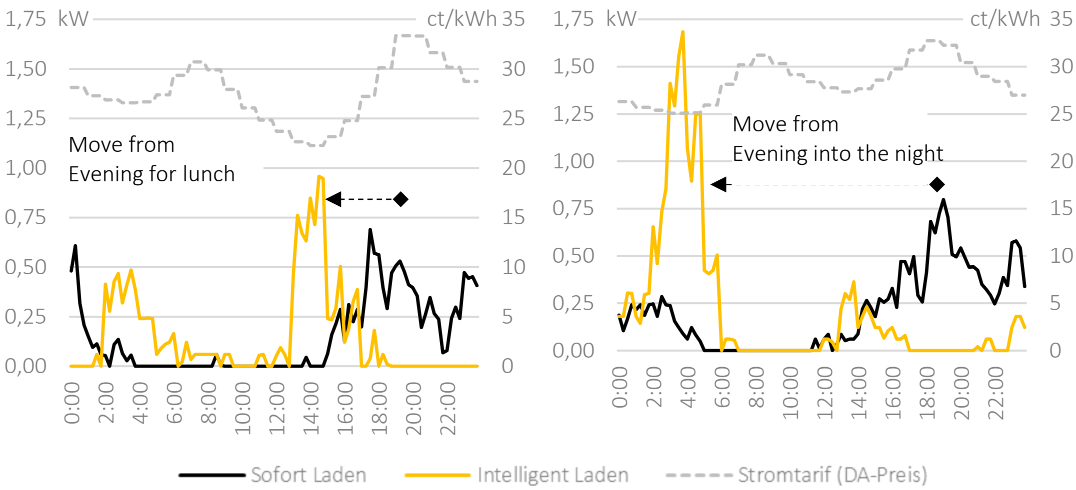

Figure3 : Average charging power (in kW) and electricity tariff (in ct/kWh) over the course of the day, averaged over the summer months (Apr. - Sep.) and winter months (Oct. - Mar.). With smart charging, the evening is largely avoided as a charging period due to the high price of electricity. Instead, charging takes place preferably in the early afternoon in summer and at night in winter.

Savings potential. The savings potential from making charging behavior more flexible increases with increasingly variable electricity tariffs (Figure4). Passing on day-ahead prices alone enables savings of 33% (€ 156 gross p.a.) to be achieved with smart charging. Optimization based on intraday prices (ID1) already generates revenue on the electricity market and thus further reduces the electricity bill by around half. With the time-variable grid fees with three levels offered from April 2025 in accordance with EnWG §14a Module 3, the grid fee costs on the electricity bill can also be significantly reduced (without significantly increasing the generation costs). Smart charging therefore already allows savings of 68% compared to immediate charging within the existing legal framework.

Savings potential (Stromnetz Berlin)

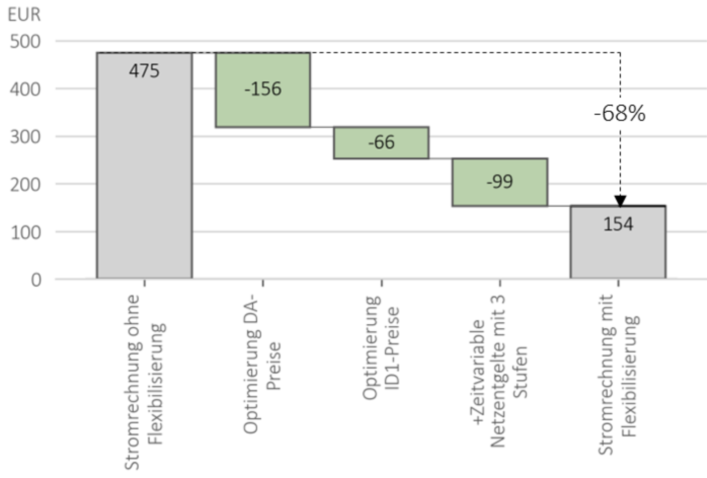

Figure4 : Savings potential (incl. VAT) in the adopted legal framework for smart charging based on the grid charges of Stromnetz Berlin.

3.1.2 Conceivable savings potential in the future

Future measures. In addition to the existing legal framework, further measures are conceivable that could create additional incentives for smart charging. Dynamic grid charges based on the current grid situation could promote more targeted and grid-relieving behavior. In addition, the reduction of time-constant taxes, levies and surcharges would enable an undistorted response to market signals. If these changes are taken into account in the electricity tariff, households could benefit from further savings potential.

Average charging power in summer

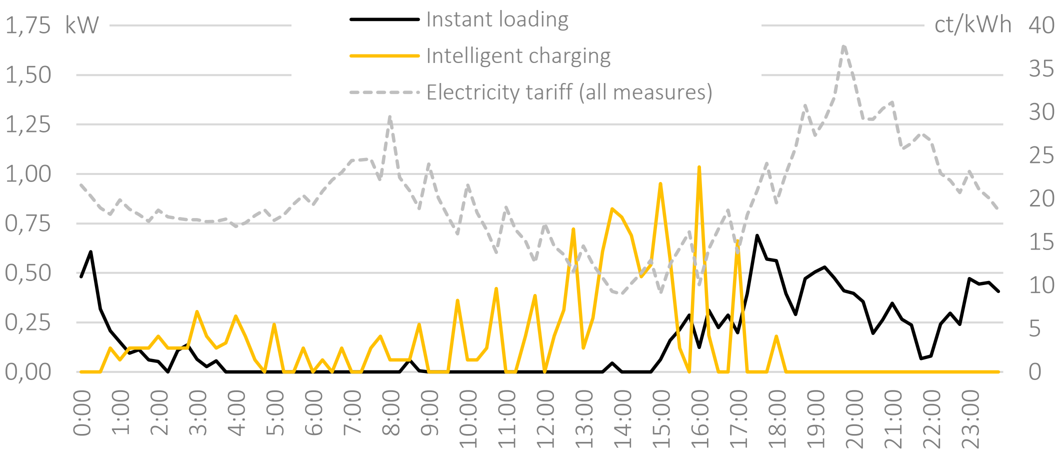

Figure5 : Average charging capacity (in kW) over the course of the day for an electricity tariff (in ct/kWh) with maximum time variability.

Smart charging with strong incentives. Figure5 shows the dynamic electricity tariff with intraday prices, time-variable continuous grid charges and time-variable taxes, levies and surcharges in the summer months. In addition to daily cyclical lows at midday and highs in the evening, this also shows significant intra-hourly fluctuations on average, which result from the intraday prices. This high price variability can be exploited by the generally flexible charging times. Accordingly, an optimized charging profile also exhibits strong and regular fluctuations.

Savings potential (Stromnetz Berlin)

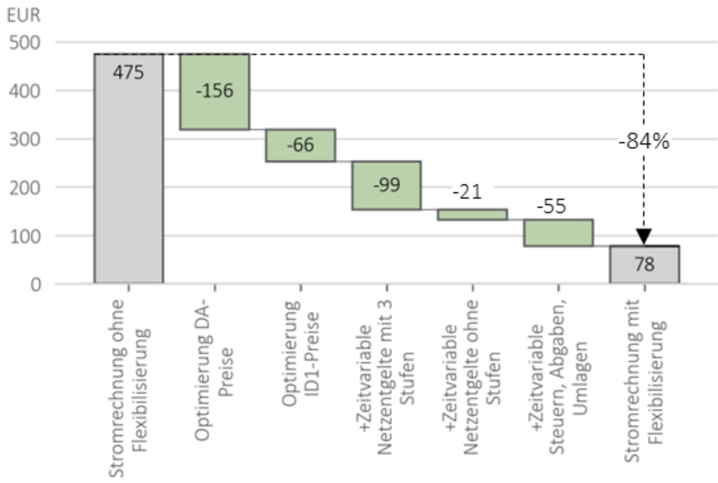

Figure6 : Savings potential for smart charging with future adjustments to the regulatory framework.

Savings potential. With the introduction of further measures, the electricity bill can be further reduced (Figure6). For the Berlin electricity grid, however, the step-free grid fees can only bring further savings of around € 21 compared to those with three steps. Time-variable taxes, levies and surcharges continue to reduce the electricity bill by € 55. The reductions are somewhat lower, however, as this item is also smaller than, for example, the generation costs. However, the overall savings potential of smart charging is so high that "free charging" is conceivable in principle.

3.2 SAVINGS POTENTIAL WITH BIDIRECTIONAL CHARGING

Bidirectional charging. Bidirectional charging enables electricity to be fed back into the grid from the electric car's battery, which is currently not yet possible from a legal and regulatory perspective, but should become possible in the future. In the following results, we examine the added value of bidirectional charging. The household receives compensation at the wholesale price of the respective electricity tariff (excluding VAT). We take into account the additional losses incurred during discharging, the faster battery degradation and the restriction that the battery may only be discharged to a charge level of 20% by feeding energy back into the grid.

Comparison with smart charging. It can be seen fromFigure7 that, compared to smart charging, electricity can not only be bought when prices are low, but also resold when prices are high. The charging periods in summer, preferably in the afternoon and partly at night, correspond to those of smart charging. However, higher charging capacities are achieved, as some of the stored electricity is fed back into the grid in the morning and evening. This behavior not only reduces costs for consumers, but also relieves the distribution grid and the electricity system. In total, 4461 kWh are charged from the grid into the battery over the year under review, of which 2489 kWh are fed back into the grid.

Average charging power in summer

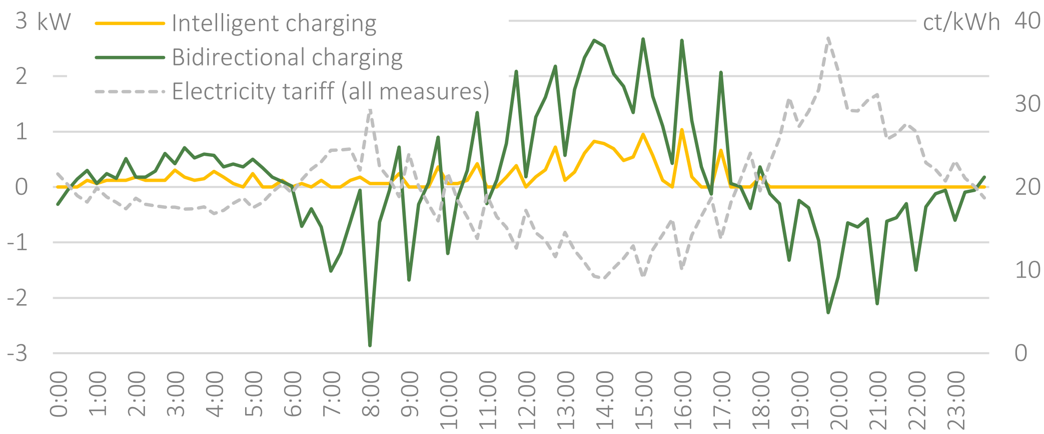

Figure7 : Comparison of the average charging power (in kW) over the course of the day in summer between intelligent and bidirectional charging for an electricity tariff (in ct/kWh) with maximum time variability. The charging periods are identical to those for smart charging. However, the volumes are higher so that the additional energy stored can be sold again when electricity prices are high.

Savings potential. Bidirectional charging can leverage the advantages of high price volatility even more compared to smart charging alone (Figure8). While the forwarding of day-ahead prices does not yet provide any relevant added value compared to smart charging, intraday optimization provides four times the added value. The savings potential from time-variable grid charges also doubles and already enables a "negative electricity bill". Under these conditions, time-variable taxes, levies and surcharges are also an even more effective measure, with savings also tripling. Instead of an electricity bill of 475 € , this amounts to -355 € with full flexibilization. It is therefore plausible that money can be earned through bidirectional charging.

Degradation costs. Bidirectional charging results in additional cycles due to the increased energy stored, which causes the battery to age more quickly. However, the resulting degradation costs are not shown on the electricity bill, but were taken into account in the optimization. These add up to around € 125 with full flexibilization and should be set against the savings on the electricity bill.

Savings potential (Stromnetz Berlin)

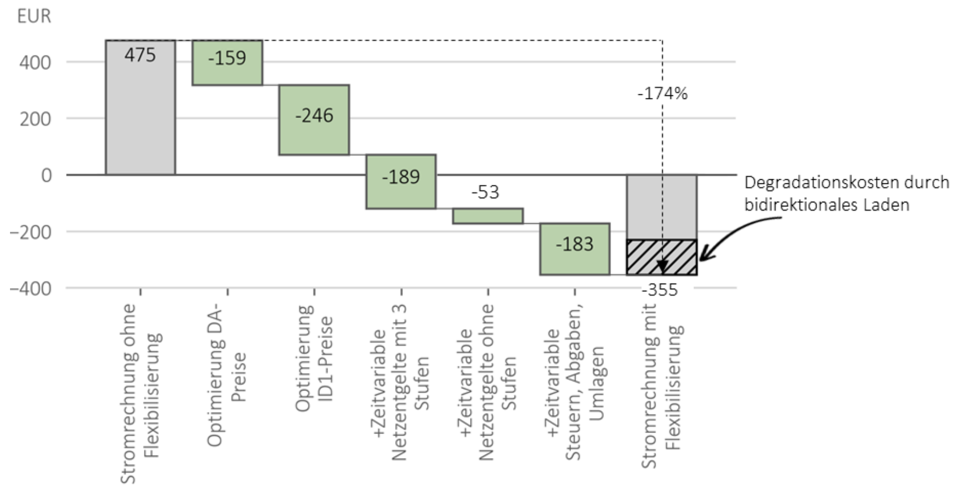

Figure8 : Savings potential for bidirectional charging with conceivable future adjustments to the regulatory framework. The electricity bill can be reduced to such an extent that it is negative and repayments are possible. However, the additional use of the battery leads to accelerated ageing, which results in imputed degradation costs that are not shown on the electricity bill.

3.3 CLASSIFICATION

In this section, we first classify the results of the study in qualitative terms and identify relevant limitations in the form of costs and revenues that were not considered. This is followed by a comparison with the findings of other existing analyses.

3.3.1 Other costs and income

Other costs. The savings potential identified in this study cannot be fully realized directly for households, as additional costs are incurred when optimizing charging behavior. For example, manufacturers charge suppliers a fee for controlling the charging process. The suppliers in turn retain a portion as a margin for the optimization. Further costs are incurred for hardware such as smart metering systems or additional costs for bidirectional charging, which are not absolutely necessary without an optimized charging strategy.

Other revenues. The use of intraday trading as a real option is not taken into account in this study. Significant additional revenue can be generated through the multiple buying and selling of electricity in continuous intraday trading. Further synergy effects with local generation, e.g. through PV systems or other flexible consumers such as home battery storage systems and heat pumps, were not considered and offer opportunities for optimization.

Future development. We have determined the value of smart charging by utilizing existing flexibility of the charging period based on current electricity market data. We therefore do not reflect the future development of the electricity system. On the one hand, this includes the ongoing expansion of new generation capacities, but also the flexibilization of consumers such as increasing storage usage. On the other hand, changes due to regulatory adjustments beyond the varied electricity tariffs, such as the switch from hourly to quarter-hourly products in the day-ahead auction, are not taken into account in this study. These changes can significantly shift the added value of smart and bidirectional charging.

3.3.2 Comparison

Further analyses. The added value of intelligent and bidirectional charging has already been investigated and quantified in numerous other studies. In this section, we set our assumptions and results in relation to the findings of selected analyses, which are followed by a concluding classification.

Fraunhofer ISE & Fraunhofer ISI (2024). In their study, the authors examine the cost benefits of smart and bidirectional charging for different households with and without a PV system. The analysis also takes into account degradation and infrastructure costs ex-post. For optimization on the German day-ahead market without an additional PV system, the authors determine a savings potential - depending on the household size - of between € 138 and € 380. In comparison, our study shows savings of € 156 in the standard profile and € 304 in the frequent driver profile. Resale on the market through bidirectional charging is not considered in the study. However, self-consumption can be increased through targeted discharging (vehicle-to-home), from which the authors derive a savings potential of up to € 451.

E.ON (2024). The E.ON project "Bi-clEVer" examines the potential cost savings through bidirectional charging of an electric car in a household with a PV system and dynamic electricity tariff. The analysis shows a cost saving of € 420 through optimized grid electricity procurement and maximization of solar power self-consumption (vehicle-to-home). In addition, the authors estimate the added value of feeding electricity back into the grid (vehicle-to-grid) at a further € 500, not taking degradation costs into account. These results are of a similar order of magnitude to the savings potential calculated in our study for smart charging (€ 400) and bidirectional charging (an additional € 430). However, our values are based exclusively on market-oriented action with time-variable electricity tariffs, without including self-consumption optimization.

The Mobility House (2023). The Mobility House is aggressively promoting the vision of free charging. In a field test, the company optimized the batteries of a vehicle fleet in regular driving mode on the European power exchange EPEX Spot with the help of intelligent and bidirectional charging. Taking battery degradation and grid connection into account, the company puts the effective savings for end customers at €650 per vehicle per year. This figure is slightly higher than the potential savings we calculated, but also includes the use of the real option in continuous intraday trading, which we did not consider in our model.

Classification. The savings potential we have identified is comparable with that of the other analyses. However, valuable additional insights can be gained from the different assumptions. While in other studies the added value of smart charging results from increased self-consumption of one's own PV electricity, we show that households without their own PV system can also benefit from smart charging. This requires electricity tariffs with high time-variable components that pass on the scarcity signals of electricity generation (and consumption) and grid bottlenecks and have a higher system benefit compared to maximizing self-consumption.

4 Robustness of the results

To test the robustness of our results, we examine three main changes in this section. We investigate how the optimization results change without blanket flexibility constraints, with a rural (instead of urban) distribution network, and with a frequent driver with a larger car.

4.1 No restrictions on flexibility

Flexible battery use. To prevent an unrealistically high flexibility potential, we specify in the charging strategy that the battery must be charged to at least 60% every morning around 6 a.m. and must not be discharged below 20% in the case of bidirectional charging (see section2.1). These rules also apply, for example, during periods when the electric car is not in use and in some cases unnecessarily restrict flexible use. In the following, we therefore look at the additional savings potential that would result from fully flexible battery use, whereby all journeys can still be made unchanged.

Savings potential with full flexibility (Stromnetz Berlin)

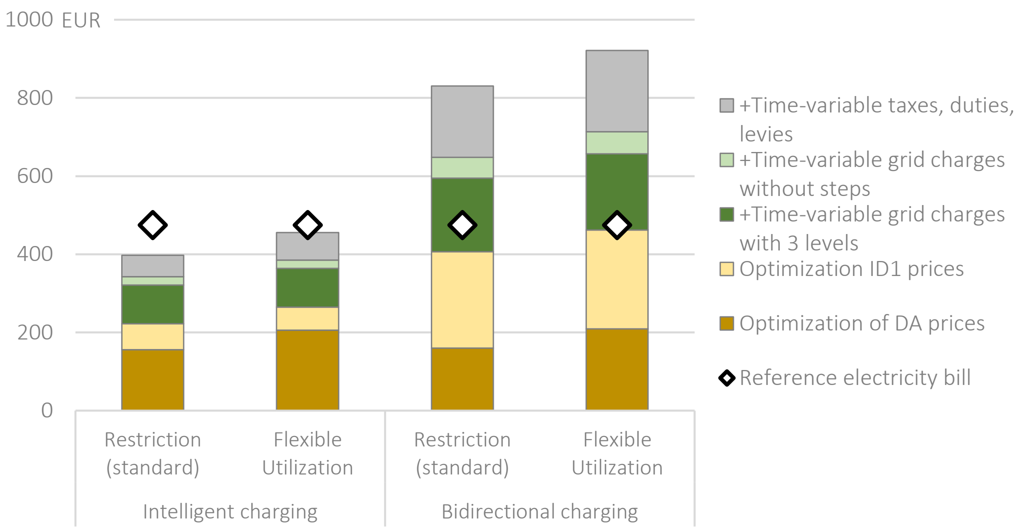

Figure9 : Comparison of the savings potential with limited and fully flexible use of the battery for smart and bidirectional charging based on the grid charges of Stromnetz Berlin.

Savings potential. The very strong assumed restriction on the use of flexibility means surprisingly low financial losses. The majority of the savings can also be realized with the assumed guard rails and restrictionsFigure9 shows that additional savings of around €60 can be achieved with smart charging (€90 with bidirectional charging). These are mainly the result of optimized times of day, which are already reflected in the day-ahead price. While charging is preferably carried out at night (before 6 a.m.) in winter, unrestricted charging offers particular advantage in the summer, allowing the low prices at midday to be fully exploited. Time-variable taxes, levies and surcharges that are linked to day-ahead prices can further increase the optimization potential.

4.2 OTHER DISTRIBUTION GRID

LEW distribution grid. For the previous analysis, the costs and tariffs for the urban distribution grid in Berlin, which consistently has higher local consumption than local generation, were used to determine the grid charges. In the following, we repeat the optimization for a very differently structured distribution grid in rural areas, namely the LEW distribution grid. This has a large proportion of rural areas and, in contrast to the Berlin electricity grid, has a generation surplus in 15% of all quarter hours due to high solar power generation. These generation surpluses are greater than those of the consumers due to the high simultaneity at peak times and are therefore decisive for the grid expansion requirement.

Grid fee tariffs. This is reflected in the three-stage time-variable grid charges illustrated inFigure10 : While Stromnetz Berlin uses the high-price window in the evening hours as an incentive to avoid consumption in these hours, in the LEW distribution grid it is worthwhile to purchase electricity in the low-price window at midday. The stepless grid fee, which was created using a neon methodology, takes into account that the most critical moments in the LEW distribution grid are caused by surplus generation and that negative grid fees should therefore also stimulate higher consumption in individual quarter hours. Flexibly chargeable electric cars can react to this and benefit according to the configuration in the respective grid area.

Time-variable grid charges in accordance with Section 14a EnWG (3 levels) & infinitely variable

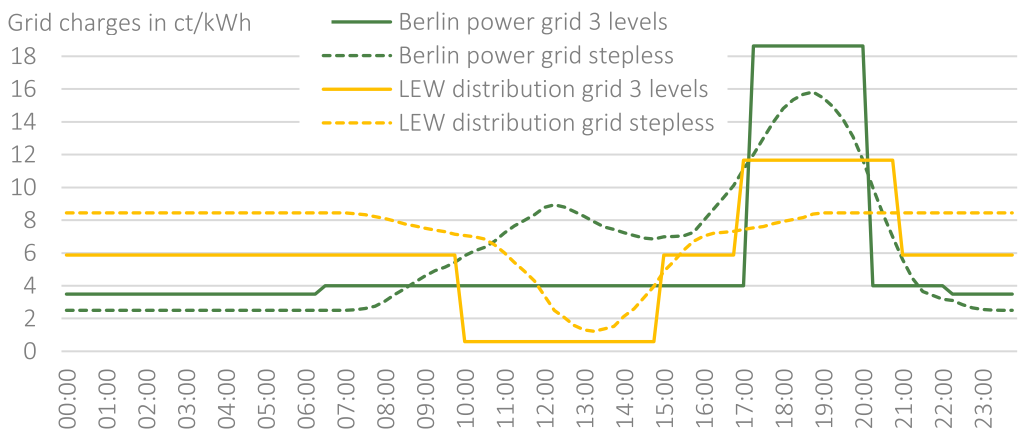

Figure10 : Comparison of grid fees for Stromnetz Berlin and LEW Verteilnetz. The grid charges with three levels apply identically every day. The grid fees without steps are only shown as average values over a year. For LEW Verteilnetz, individual quarter-hourly values can also assume negative values in the event of very high generation surpluses.

Savings potential. The optimization passing on exchange prices with constant grid charges reveals no differences between the two grid areas, or negligible differences in the case of bidirectional charging (Figure11). Preventing charging in the evening hours in the Berlin electricity grid initially enables a relatively greater cost reduction with a three-stage grid charge than in the LEW distribution grid. However, targeted grid relief in the event of heavy oversupply with time-variable grid charges without stages, including the utilization of negative grid charges, enables a considerable reduction in the electricity bill in the LEW distribution grid. However, the savings potential and thus the added value of flexible charging are very close to each other in both distribution grid areas despite different price signals.

Savings potential in various distribution grids

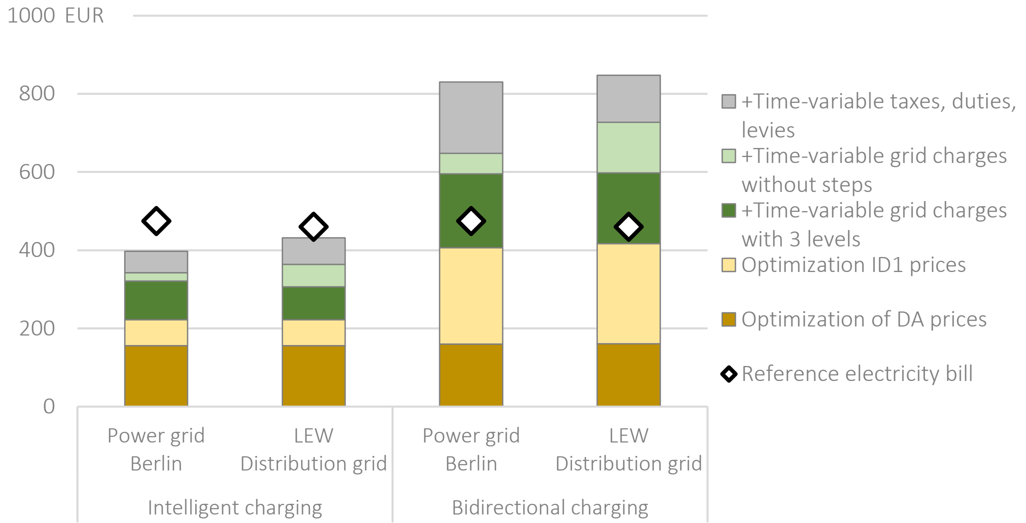

Figure11 : Comparison of the savings potential in the grid areas of Stromnetz Berlin and LEW Verteilnetz for smart and bidirectional charging. Due to regional differences in grid charges, the reference electricity bill of € 460 in the LEW distribution grid is slightly lower by € 15 than in Stromnetz Berlin.

4.3 DIFFERENT DRIVING PROFILE

Frequent driver profile. The added value of smart charging is characterized by the flexibility of the charging periods. The standard case considered so far, with a mileage slightly below the German average, has a much greater scope for battery use than the frequent driver profile examined below. The frequent driver profile is based on the profile of a Tesla Model 3 with a mileage that is 5 times higher and therefore lower charging availability (Table3). On the other hand, the higher power consumption required offers greater savings potential in absolute terms, which can be tapped with slightly greater battery capacity and charging power. The proportion of charging processes that do not take place at the wallbox at home - e.g. at public charging stations - is comparable for both profiles.

Table3 . Overview of the technical data of the electric car for the standard case and frequent driver driving profiles.

	Standard case	Frequent driver
Memory size	45 kWh	57 kWh
Maximum charging power	11 kW	15.5 kW
Annual electricity consumption EV	2180 kWh	8349 kWh
Annual mileage	10442 km	53960 km
Charging availability	75%	62%
Charging share outside the household	28%	29%
Charging losses of the battery	5% each for loading & unloading	
Battery degradation costs	5 ct/kWh	

Savings potential. The potential savings are shown inFigure12 and are higher in absolute terms for the frequent driver profile than in the standard case (€830 for smart charging and €1255 for bidirectional charging). However, this is also due to the approximately three times higher reference electricity bill (€ 1473). The relative savings are significantly lower. With smart charging, the electricity bill can only be slightly more than halved (57%) for all measures. With bidirectional charging, free charging is conceivable at best for the frequent driver profile (85% savings). The contributions of the individual measures are similar for both driving profiles. Taking day-ahead prices and time-variable grid charges into account enables major savings.

Savings potential according to driving profile (Stromnetz Berlin)

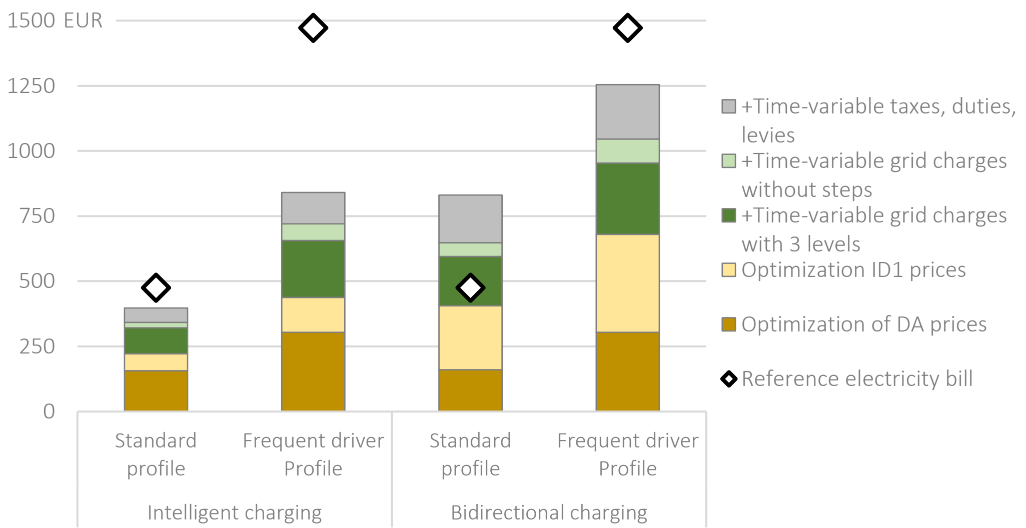

Figure12 : Comparison of the savings potential of the standard and frequent driver profiles for smart and bidirectional charging based on the grid charges of Stromnetz Berlin.

5 Conclusion

Smart charging. Smart charging of electric cars offers significant savings potential for households. Even a dynamic electricity tariff based on wholesale prices can reduce the electricity bill of average car users who react flexibly to prices by half (-47% in this study). Electricity tariffs with even more time-variable price components make it possible to reduce the electricity bill to almost zero (-84%).

Bidirectional charging. Bidirectional charging could make it possible to achieve negative electricity bills in the future. In addition to the high savings potential for consumers, this also means considerable added value for the electricity system: the electric car is charged in the afternoon at low prices and part of it is fed back into the grid in the evening. Bidirectional charging enables electromobility to relieve the electricity system instead of placing a greater burden on it.

Recommendations. The high savings potential justifies consumers and suppliers to engage in smart charging management for their electric vehicles in order to significantly reduce their electricity bills. All that is needed is a dynamic electricity tariff based on wholesale prices. As smart charging can also reduce the burden on the electricity system, decision-makers should seize the opportunity to implement dynamic electricity tariffs across the board. The introduction of further reforms such as time-variable grid charges, which adapt to the current grid situation in real time, or time-variable taxes, levies and surcharges can also reduce the electricity price level, prevent unnecessary grid expansion and make electromobility attractive for households without their own PV system.

6 Bibliography

Gaete-Morales et al. (2021). An open tool for creating battery-electric vehicle time series from empirical data, emobpy. Sci Data 8, 152. https://doi.org/10.1038/s41597-021-00932-9.

Ecke et al. (2023). Deutsches Mobilitätspanel (MOP) – Wissenschaftliche Begleitung und Auswertungen Bericht 2022/2023: Alltagsmobilität und Fahrleistung. https://doi.org/10.5445/IR/1000164704.

Sagaria et al. (2025). Vehicle-to-grid impact on battery degradation and estimation of V2G economic compensation. Applied Energy. https://doi.org/10.1016/j.apenergy.2024.124546.

Neon (2024). Mehrwert dezentraler Flexibilität. Oder: Was kostet die verschleppte Flexibilisierung von Wärmepumpen, Elektroautos und Heimspeichern? https://neon.energy/mehrwert-flex/.

BDEW (2024). BDEW-Strompreisanalyse Dezember 2024 – Haushalte und Industrie. https://www.bdew.de/media/documents/BDEW-Strompreisanalyse_12-2024_Q796OxD.pdf.

Fraunhofer ISE, Fraunhofer ISI (2024). Potential of a full EV-power-system-integration in Europe & how to realise it. https://www.transportenvironment.org/uploads/files/2024_10_Study_V2G_EU-Potential_Final.pdf