unIT-e²: The Future of Smart and Bidirectional Charging - Use Case Prospects from the User's Perspective in Germany

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Abstract

Electric vehicles (EVs) are a key component to decarbonise the transportation sector. Hence, the adoption of EVs must be attractive to end users, which is why this paper examines smart and bidirectional charging use cases focusing on benefits and prospects from the user's perspective for 2024 until 2030 in Germany. Use cases like photovoltaic (PV) self-consumption optimization, peak shaving, variable tariffs, and direct market trading are evaluated. The multi-criteria assessment includes the technical readiness of respective technical systems, use case profitability, and a realistic number of potential EV users per use case. Our findings show that today none of investigated use case appears to be ready for large-scale implementation. For smart charging, the first use cases to become technically scalable and profitable from the user's perspective are PV self-consumption optimization and peak shaving. Bidirectional charging is found to become technically mature later in time. Large-scale implementation of the first bidirectional charging cases could start around the end of 2025. All of the investigated use cases are projected to become profitable around 2030 at the latest with profits ranging from less than 100 € up to more than 2,000 € per EV and year.

1 Introduction

Electric vehicles (EVs) are a key component to decarbonise the transport sector. In the conflicting area of economic concerns and systemic constraints, use cases of smart charging and bidirectional charging offer an attractive solution to raise the total number of EVs while not being detrimental to the energy system and electric grid [1,2].

In this regard, we define a use case as optimising an EV's charging strategy to achieve an objective, typically to minimize electricity costs or create additional revenue. Such optimization of an EV's charging strategy is referred to as smart charging, taking user behaviour, EV restrictions, and other limitations into account. If the EV and the surrounding setting also allow for discharging the EV's battery, we use the term bidirectional charging.

If a use case only influences the electricity supply within the balance zone of a property, i.e., behind the grid connection point, we speak of "behind-the-meter use cases". For bidirectional charging, *vehicle-to-home* (V2H) is used for private households, and *vehicle-to-business* (V2B) is used for business and industry. If a use case involves the feed-in of electricity into the public grid, i.e., beyond the grid connection point of a property, it is referred to as an "in-front-of-the-meter" use case. As this only occurs for bidirectional charging, it is synonymous with *vehicle-to-grid* (V2G). [3,4]

In Germany, the ramp-up of electric mobility is in full swing, even if it was slightly sluggish in the first half of 2024 [5]. However, the implementation rate for smart charging use cases in Germany is very slow at best, and it is virtually non-existent for bidirectional charging use cases. A major reason for this is that users of EVs are often unaware of the benefits of use cases, or the general use case implementation is still too complex [6]. In addition, there are currently few or no well-developed and standardized technical solutions [7].

As highlighting benefits for EV users is the gateway for large-scale implementation of EV use cases, this work aims to evaluate the prospects of smart charging and bidirectional charging from the perspective of EV users in Germany. We apply a multi-criteria assessment, where different, independent analyses of previous publications are combined and interpreted. This paper constitutes an extension of the work of [8] and is part of the research conducted in the *unIT-e² project* (funding code 01MV21UN01), where more than 30 partners of the energy and automotive industry investigate and test the integration of smart electric mobility in the German energy system [9].

2 Methodology

We summarized the methodology applied in this paper in Figure 1. Two methodological steps are taken. First, three separate analyses, each investigating a different aspect of relevant smart charging and bidirectional charging use cases in Germany, are selected from the literature and interpreted in terms of their implications for the implementation prospects of use cases from the user's perspective. Second, the aspects considered in the three analyses are processed jointly for a set of use cases to depict the future prospects of these use cases from 2024 to 2030.

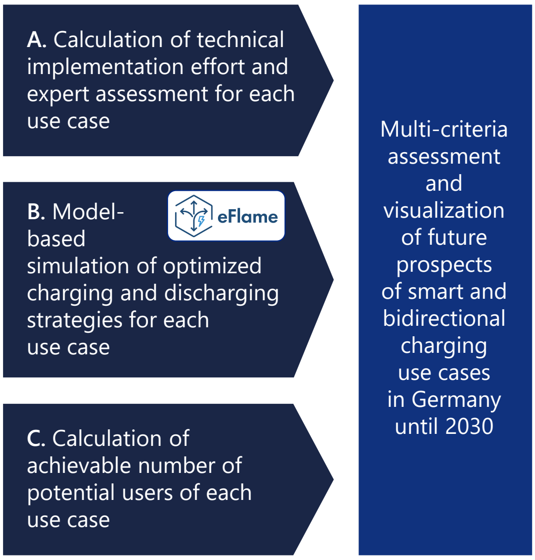

Figure 1 Simplified overview of the applied methodology

2.1 Three Separate Analyses from Previous Works

The three analyses to be interpreted in the first methodological step are labelled with A, B, and C in Figure 1.

A. This analysis aims to characterise the technical readiness of smart charging and bidirectional charging use cases. It involves two separate assessments. First, calculations of the effort associated with implementing use cases, as presented in [10], are considered. The technical implementation effort of each use case is determined as a numerical value based on the involved parties, the required technical components, and respective interfaces necessary to implement a fully functional technical system at home or work. In this regard, [11] is used to determine the necessary parties, technical components, and interfaces. The exact methodology to obtain an unbiased and comparable effort value for each use case is described in [10]. Second, an expert survey concerning the predicted large-scale implementation of each relevant use case is conducted among experts from the research institute FfE working on the project unIT-e^2 and in the general field of electric mobility research. For both smart charging and bidirectional charging, we asked separately about the expected point in time for large-scale implementation of the respective use case in Germany.

B. This analysis aims to predict potential profits from the user's perspective generated via smart charging and bidirectional charging. We define financial profits as the savings in electricity costs resulting from an optimized charging (and discharging) strategy minus additional technology costs. In each case we compare smart charging and bidirectional charging with simple direct charging without charging management.

A model-based approach is pursued to obtain potential cost savings today and in the future. The model framework *eFlame* (electric Flexibility assessment modelling environment) is used to optimize the charging strategy for smart charging and bidirectional charging under various boundary conditions and limitations for each relevant use case and year [12]. Per simulation set, multiple independent simulations are run with different user and driving profiles [13]. The resulting charging and discharging profiles are used to calculate overall charging costs, which are then compared to the charging costs of direct charging.

For the additional technology costs, four cost components are defined: purchase costs of the charging station, installation costs of the charging station and other necessary equipment, installation, operation, and maintenance of metering equipment, and additionally needed hardware for charging management. The costs for each component are derived for smart charging and bidirectional charging in contrast to direct charging for today and 2030.

Simulation results and additional technology costs from [4] and [13] are taken. Potential reductions in greenhouse gas emissions are not considered in the present paper.

C. This analysis aims to estimate the potential number of EV users who can participate in a use case. It is not the number of existing EVs or charging stations that is relevant in this regard, but use case limitations such as market volumes or available locations. The number of potential users of each use case is calculated in [14], where the number is called the “achievable user potential”. For each use case, the calculation varies depending on the specific aspects and limitations of the use case. Among other aspects, the EV availability is taken into account.

2.2 Multi-criteria Assessment

In the second methodological step, selected results of the three analyses, A, B, and C, are combined in a multi-criteria assessment with the aim to visualise and discuss the future use case prospects from the user’s perspective.

We derived the methodology for the multi-criteria assessment from [8], where a similar assessment is conducted. The methodology yields a graphical chart that includes the results of all three analyses. The chart is a timeline from 2024 to 2030 that reflects on the prospects of each use case for smart charging and bidirectional charging.

First, a set of use cases for which the three analyses have been conducted is chosen for smart charging and bidirectional charging.

Second, the results of the two assessments regarding the technical readiness of each case are translated into a projected date at which large-scale implementation is likely. The effort value of the respective use case from [10] is converted into a point in time at which implementation would be feasible. The greater the effort value, the later the date. The date is compared with the result of the expert survey. The latter of the two points in time is selected as the projected date of large-scale implementation. This date is set as the starting point of the respective timeline bar of the use case.

Third, average profits from [4] and [13] are used for each use case. Between the respective base year and 2030, the results are linearly interpolated to display a time course of profits from 2024 to 2030 (see [8], where profits are called net cost savings). The respective average profits from 2024 to 2030 are then transferred into a colour rating, where negative values are displayed in red and highly positive values in dark green. The colour rating is used to colour the timeline bar of each use case.

Fourth, the numbers of EV users who can participate in a respective use case are linearly interpolated between 2021 (base year) and 2030, where only the results between 2024 and 2030 are considered. We then translate the EV user numbers into numeric values that represent the width of the timeline bar of each use case, such that the bar width represents the number of potential EV users.

The final chart, which incorporates all three aspects of the use case assessment, represents the concluding result of the methodology. We present and discuss the chart in terms of future use case prospects from a user's perspective in the subsequent chapter.

3 Results

In Section 3.1, we first describe this work's scope and selected use cases. In section 3.2, we then present the visualisation of use case prospects in Germany resulting from the multi-criteria assessment (see Section 2.2) and discuss essential implications for EV users and the energy system.

3.1 Scope and Use Cases

Table 1 summarises the use cases of smart charging and bidirectional charging, which we selected for the multi-criteria assessment. These use cases represent the intersecting set of cases from the previous separate analyses of the three different use case aspects (technical readiness, profitability, and number of potential users). Except for the use case balancing service (FCR), all use cases are considered for both smart charging and bidirectional charging. It is important to highlight that the use cases sequential spot market trading and PV self-consumption + spot market trading represent so-called multi-use cases, where single use cases are combined to maximise EV battery usage and thus profits [13]. For a more detailed description of the use cases, see [8].

Table 1 Short overview of investigated use cases

Use case title	Short description	Specifics/ scope
PV* self-consumption optimization	Maximising the usage of self-generated PV electricity to best meet local electricity demand	Only considered for location "at home"
Peak shaving	Reducing the local peak load over a time period, if capacity charge applies	Only considered for location "at work"
Dynamic tariff	Using electricity prices that change dynamically over time to purchase at times of low and sell at times of high prices	Electricity prices based on day-ahead market
Sequential spot market trading	Direct trading on spot markets thereby buying electricity at times of low prices and selling electricity at times of high prices	Sequential trading on all three spot markets (day-ahead, intraday auction, continuous intraday)
PV self-consumption optimization + spot market trading	Maximising the local usage of self-generated PV electricity and parallel trading on spot market	Trading on continuous intraday market
Balancing service (FCR**)	Direct trading on a balancing market thereby providing balancing power for grid frequency restoration	Trading on FCR market

* PV: Photovoltaic
** FCR: Frequency Containment Reserve

3.2 Use Case Prospects in Germany unit 2030

Figure 2 shows the final visualisation of the multi-criteria assessment. As described in Section 2.2, a coloured bar represents the profitability of the respective use case over time. The darker the green colour, the more profitable is the use case from the user's perspective. The bar width over time indicates the number of EV users who could potentially operate the use case depending on market and location limitations (not depending on the actual number of EVs). The bar segment over time for which the entire technical system - including backend-to-backend communication, standardised interfaces, and respective hardware - is not considered as sufficiently mature for large-scale implementation is illustrated by less bright colours. From the point at which the system is considered technically ready, the bar is shown in full, bright colour.

A key finding from Figure 2 is that the prospects of most use cases for both smart and bidirectional charging in Germany are positive in terms of profitability until 2030, indicated by the green colour of the timeline bars. In the early years of the timeline (2024 to 2026), bidirectional charging use cases are, in most cases, still less profitable than smart charging use cases due to higher additional technology costs, particularly for the bidirectional charging station. Over time, bidirectional charging use cases become more economically attractive, partly because of decreased technology costs, and, in most cases, offer significantly higher profit opportunities in 2030 than smart charging.

The two behind-the-meter use cases, PV self-consumption optimization (at home) and peak shaving (at work), display comparably low to moderate profits over time. For PV self-consumption optimization, smart charging yields slightly higher profits than bidirectional charging. In this case, additional cost savings from bidirectional charging cannot compensate for the additional technology costs compared to smart charging, even up to 2030. Still, the indicated profits are robust and most likely sufficiently attractive for the use case to be implemented on a large scale. For peak shaving (at work), bidirectional charging yields higher profits than smart charging. This is because the peak load to be reduced at the site can be reduced to a greater extent by bidirectional charging, and a greater reduction in the peak load leads to significantly higher cost savings [4]. Hence, peak shaving via bidirectional charging will likely be financially attractive to EV users or business owners. Whether the expected profits of peak shaving via smart charging are sufficiently high for large-scale implementation dependents on the location, EV

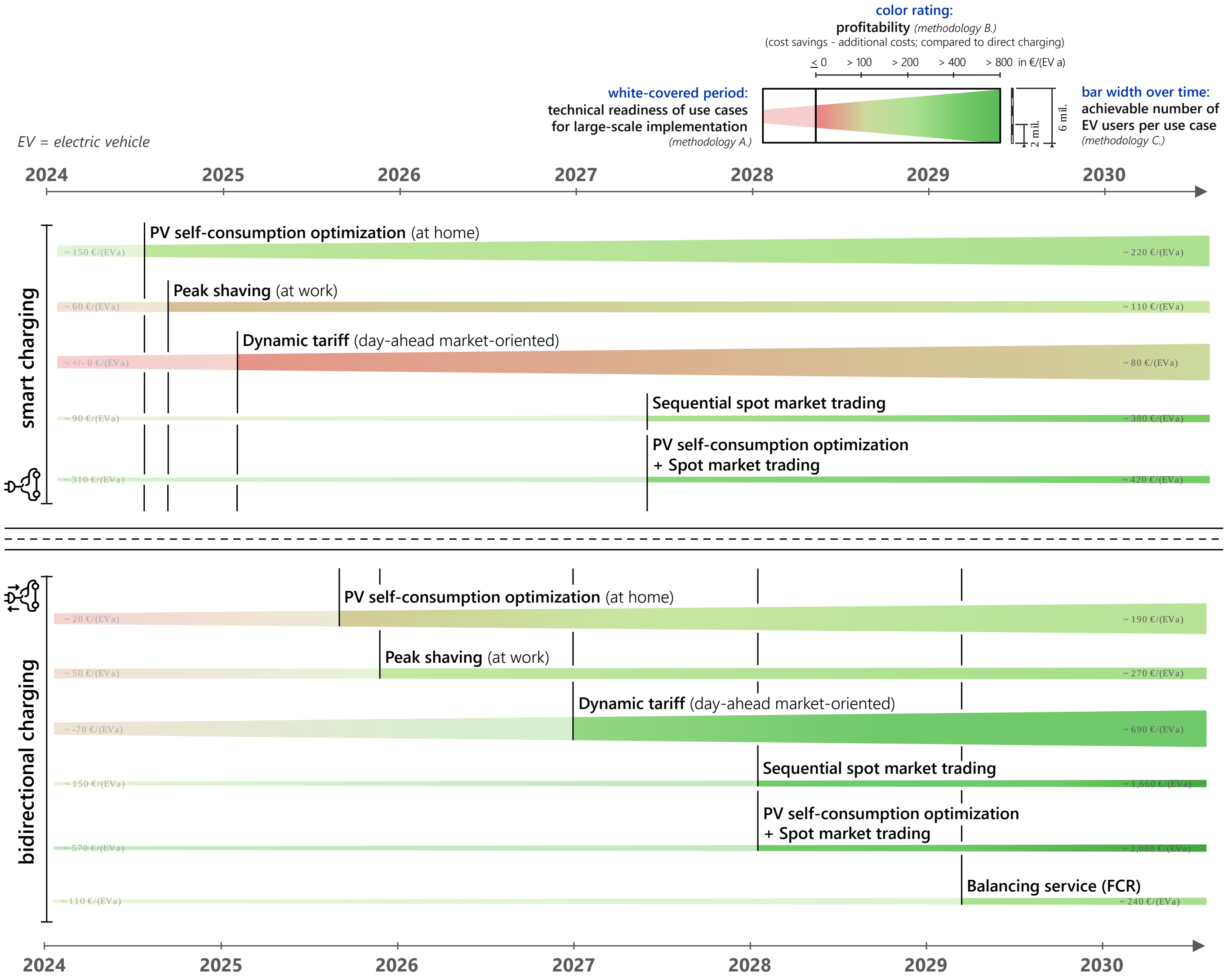

Figure 2 Use case implementation roadmap for Germany: use case profitability (bar colour), number of potential users (bar width), and technical readiness (beginning of stronger coloured bar) over time for smart charging (top) and bidirectional charging (bottom)

availability, and the number of available charging stations for the use case.

The smart charging use case dynamic tariff shows the lowest profits until 2030, as the savings in electricity costs for charging, which can be achieved on the day-ahead market, are only moderately higher than the additional costs of smart charging, even by 2030. This is in particular because we assume that the volatility on the day-ahead market in 2030 is similar to today [13]. Higher profits can be expected for a dynamic tariff based on intraday market prices.. Even in 2030, with profits of around 80 € per EV per year for the day-ahead market-based tariff, it is questionable whether these prospects for users would trigger a large-scale implementation of smart charging. Concerning bidirectional charging, expected profits are significantly higher than for smart charging for all years, as the charging strategy is optimized and additional revenues are generated via discharging electricity into the public grid. Hence, large-scale implementation of variable tariffs using bidirectional charging is rather likely.

For the multi-use cases sequential spot market trading and PV self-consumption optimization + spot market trading, expected profits are very high, such that it would be most definitely attractive to implement the use cases from the user's perspective. Profits of at least 1,000 € per EV and per year are conceivable as early as 2028, and by 2030 profits will rise to exceptionally high levels. For the two multi-use cases, these profits are accompanied by a high energy throughput through the EV battery, which can increase cyclical battery ageing. Whether advancements in battery technology will mitigate the effects of cyclical battery ageing in the future remains the subject of discussion [13].

For balancing service (FCR), moderate to sufficiently high profits are displayed in Figure 2. A benefit of this use case is that reserving power for FCR is remunerated. A drawback might be that stationary battery storages already dominate the FCR market, which makes the future FCR market highly competitive. Still, balancing service (FCR) can be an attractive use case from the user’s perspective based on the presented results.

In terms of user potentials, some of the most economically attractive use cases show a limited number of potential EV users who could implement the use case, whereas others display a substantial number (timeline bar width in Figure 2). For PV self-consumption optimization and peak shaving, a moderate to comparably high number of potential users is identified. We see a considerable increase over time, especially for PV self-consumption, with 5.3 million potential users for PV self-consumption optimization and 1.7 million potential users for peak shaving in 2030.

The use case dynamic tariff (day-ahead market-oriented) shows the largest number of potential users, as the day-ahead market in Germany represents the largest spot market, where substantial shares of the total electricity are traded. As the increase of the bar width in Figure 2 shows, the market size is expected to increase further over time, resulting in up to 5.2 million potential users of the use case.

The numbers of potential users of the two multi-use cases are limited by the volume of the German intraday market, which translates into just under 1 million potential use case users. For the use case balancing service (FCR), a number of only around 200 thousand potential use case users is calculated [14]. Thus, even though most market-based use cases are expected to yield high profits by 2030 or earlier, their limited market volume restricts the number of users that can benefit from the respective use case. There is also a risk of cannibalization effects for these relatively small markets. A large number of EV users participating in the corresponding market would reduce the market’s price spreads, which would, in turn, lead to reduced profits.

Comparing these numbers of potential use case users with the projected number of 8.2 million EVs in Germany by 2030 [15], it can be said that use case limitation will not restrict the application of smart and bidirectional charging until 2030, but most likely the number of available and technical suitable EVs will.

Regarding technical readiness, scalable, interoperable systems for smart charging are not yet available but are likely to become available soon in Germany [7]. Figure 2 depicts that we expect the first smart charging use cases to become implemented on a larger scale within the next years. In other countries than Germany, large-scale implementation is already happening or might happen sooner. Regarding the two multi-use cases, we predict that the technical complexity of these cases will delay large-scale implementation, which is why the brightly coloured bars of these cases for smart charging start in mid 2027 in Figure 2.

Concerning bidirectional charging, all use cases are expected to be implemented on a large scale later than for smart charging. We assume the first scalable, competitive bidirectional charging use cases will be available in Germany by mid to late 2025. The order of technical readiness is identical for bidirectional charging to that for smart charging. The use case balancing service (FCR), which is only displayed for bidirectional charging, is judged as the most complex case and will thus be implemented on a large scale at the latest.

In general, the prediction of when the respective use cases will be implemented on a large scale is subject to high uncertainty. However, we consider the order of use case implementations as plausible and the dates of large-scale implementation in Figure 2 as general indicator of when to expect the respective use cases. The indicated date could be used in energy system analysis, for example, to assess the impact of smart charging and bidirectional charging on the energy system.

4 Conclusion

The multi-criteria assessment presented in this work demonstrates a methodological approach of evaluating future prospects of use cases in a multi-faceted and scientifically grounded manner.

Key findings of the evaluation of prospects of use cases of smart and bidirectional charging in Germany until 2030 are the following:

- Smart charging use cases will likely be implemented in Germany on a larger scale in the coming years (especially behind-the-meter use cases).
- Most smart charging use cases are already profitable today and will be reliably profitable in the future; only the use case dynamic tariffs might yield insufficient profits due to only moderate price spreads in the day-ahead market.
- The large-scale implementation of bidirectional charging use cases will still take some time, especially as adequate technical standards must be implemented and a sufficient number of technology providers must be reached.
- When bidirectional charging use cases start to be implemented on a larger scale, high individual profits are expected for all cases; for multi-use cases, exceptionally high profits can be reached.
- The achievable number of EV users for the investigated use cases – even for 2030 – is limited due to market and user constraints (not necessarily due to the availability of EVs or charging infrastructure).
- The limited number of EV users in some cases could have the effect that the profits per use case will not be as high as shown here, as a large number of market participants might cannibalize market prices (not taken into account).

To sum up, we expect both smart charging and bidirectional charging to play an important role in the future of the German individual transportation sector. Based on the findings of this work, smart charging might become an established technology before bidirectional charging can be implemented on a larger scale. It remains to be seen how big the share of EV users applying bidirectional charging use cases will be in Germany in 2030.

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