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Prospects of use cases and multi-use of smart electric vehicle charging and discharging from the user's perspective

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Vollständiger Abdruck der von der TUM School of Engineering and Design der Technischen Universität München zur Erlangung eines

Doktors der Ingenieurwissenschaften (Dr.-Ing.)

genehmigten Dissertation.

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Prüfende der Dissertation:

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Die Dissertation wurde am 15.05.2024 bei der Technischen Universität München eingereicht und durch die TUM School of Engineering and Design am 14.10.2024 angenommen.

Abstract

To mitigate the climate crisis and limit greenhouse gas (GHG) emissions, all energy consumption sectors must adopt a climate-neutral energy supply. A key strategy for this decarbonization process in the transportation sector is the shift from fuel-based to electric vehicles (EVs). The incipient spread of EVs increases the coupling of the transportation and energy supply sectors, which raises the challenge of effectively integrating EVs into the energy system. At the same time, EV usage must be attractive, i.e. beneficial, for potential users to ensure an EV ramp-up and not stifle it.

This cumulative dissertation examines use cases of smart charging and bidirectional charging. As user benefits arising from respective use cases are essential for a persistent EV adoption, the user's perspective is assumed and the prospects for large-scale implementation of use cases today and in the future are assessed based on various analyses. The examined single-use cases comprise local optimization, such as self-consumption optimization or peak shaving, market-oriented optimization based on spot or balancing markets, and grid- and system-serving optimization, e.g. ancillary services. Particular emphasis is placed on assessing selected multi-use cases, i.e. combinations of single-use cases. The assessment of use case prospects involves the analysis of the effort required for the technical implementation of use case and synergies resulting from implementing multi-use cases. Using the optimization model eFlame, realistic ranges of net cost savings and GHG emission reductions from the user's perspective are determined and discussed. The maximum and achievable numbers of EV users per use case are calculated to assess the user potential for each use case regardless of the actual number of registered EVs.
To reconcile the two objectives of user attractiveness and systemically effective EV integration, systemic benefits are discussed for each relevant use case and contrasted with the previously assessed user benefits. So-called cornerstones of action are derived, which entail concrete levers to facilitate the systemically beneficial use case integration.

The results of the various analyses from the user's perspective are ambivalent. Today, none of the single- or multi-use cases displays user benefits in all investigated aspects. Especially for bidirectional charging, most use cases are assessed as technically complex and potential user benefits are not high enough to justify an implementation in the short term (until 2026). Concerning future prospects, some use cases, such as self-consumption optimization and spot market trading, are likely to be conclusively beneficial from the user's perspective in the medium term (from 2026 until 2029). In the long term (from 2029), all investigated use cases, with one exception, are likely to be conclusively beneficial for EV users. However, depending on the actual EV ramp-up, the number of potential EV users can be a limiting factor for some use cases by 2030.
Considering the system's perspective, four cornerstones of action are derived. First, to reduce initial thresholds, use cases should be easily accessible for EV users and user benefits must be simple to understand. Second, implementing market-oriented use cases should be accelerated through different actions, as these cases are well suited to combine user benefits, especially high cost savings, with systemic benefits from the medium term onwards. Third, grid-serving use cases should be reliably implemented to ensure that local electricity grids are not affected. Fourth, providers and other responsible parties should be encouraged and enabled to implement more complex use cases, particularly multi-use cases, as these use cases best combine user and systemic benefits.

Kurzfassung

Um die Klimakrise zu bewältigen und Treibhausgasemissionen zu reduzieren, müssen die Endenergiesektoren klimaneutral gestaltet werden. Eine Schlüsselstrategie zur Dekarbonisierung des Verkehrssektors ist der Wechsel von Verbrennern zu Elektrofahrzeugen (EVs). Durch die zunehmende Verbreitung von EVs entsteht eine verstärkte Kopplung zwischen dem Verkehrs- und dem Bereitstellungssektor. Dies bringt die Herausforderung mit sich, EVs sinnvoll in das Energiesystem zu integrieren. Gleichzeitig muss die EV Nutzung attraktiv sein, d. h. einen Mehrwert für potenzielle Nutzer bieten, um den Hochlauf der Elektromobilität zu fördern.

Diese kumulative Dissertation untersucht Anwendungsfälle (Use Cases) von intelligentem und bidirektionalem Laden. Da Nutzer-Mehrwerte entscheidend für einen stetigen EV-Hochlauf sind, wird die Nutzerperspektive eingenommen, um heutige und zukünftige Aussichten für eine großflächige Umsetzung der Use Cases zu bewerten. Die untersuchten Single-Use Cases umfassen lokale Optimierung, wie Eigenverbrauchsoptimierung und Peak-Shaving, marktbasierte Optimierung anhand von Spot- oder Regelmärkten und netz- und systemdienliche Optimierung, z. B. Systemdienstleistungen. Ein Fokus liegt auf der Bewertung ausgewählter Multi-Use Cases, also Kombinationen von Single-Use Cases. Die Bewertung aus Nutzerperspektive umfasst die Analyse des Aufwands für die technische Umsetzung und entsprechende Synergien bei Multi-Use Cases. Mit dem Optimierungsmodell eFlame werden realistische Spannweiten der Kosteneinsparungen und Treibhausgasemissionsreduktionen aus Nutzerperspektive für die Jahre 2020 bis 2022 und 2030 ermittelt. Die maximale und erreichbare Anzahl an EV-Nutzern pro Use Case wird für 2021 und 2030 berechnet, um Nutzerpotenziale unabhängig von der tatsächlichen Anzahl registrierter EVs zu bewerten.
Um die beiden Ziele der Nutzer-Mehrwerte und der systemisch sinnvollen EV-Integration in Einklang zu bringen, werden für jeden relevanten Use Case die entstehenden systemischen Vorteile diskutiert und den zuvor ermittelten Nutzer-Mehrwerten gegenübergestellt. Darauf basierend werden sogenannte Handlungseckpfeiler abgeleitet, die konkrete Hebel beinhalten, um die systemisch vorteilhafte Integration von Use Cases zu befähigen.

Die Ergebnisse der Analysen aus Nutzerperspektive sind ambivalent. Gegenwärtig weist kein Single- oder Multi-Use Cases Nutzer-Mehrwerte in allen untersuchten Dimensionen auf. Besonders beim bidirektionalen Laden werden die meisten Use Cases als technisch zu komplex eingeschätzt, um heute schon massenfähig umgesetzt zu werden. Zukünftig können einige Use Cases, wie Eigenverbrauchsoptimierung und Spotmarkt-Handel, mittelfristigen (2026 bis 2029) eindeutig vorteilhaft für Nutzer werden. Alle untersuchten Use Cases, mit einer Ausnahme, werden langfristig (ab 2029) eindeutige Nutzer-Mehrwerte aufweisen. Je nach tatsächlichem EV-Hochlauf kann die Anzahl potenzieller EV-Nutzer bis 2030 jedoch ein begrenzender Faktor sein.
Aus systemischer Perspektive ergeben sich vier Handlungseckpfeiler. Erstens sollte der Use Case Zugang für Nutzer erleichtert und Nutzer-Mehrwerte leicht verständlich aufbereitet werden. Zweitens sollten marktbasierte Use Cases durch Maßnahmen beschleunigt werden, da diese Fälle mittelfristig hohe Kosteneinsparungen und systemische Vorteile in Einklang bringen. Drittens sollten netzdienliche Use Cases implementiert werden, um sicherzustellen, dass Stromnetze nicht lokal überlastet werden. Viertens sollten Anbieter befähigt werden, komplex Use Cases, insbesondere Multi-Use Cases, umzusetzen, da diese Nutzer-Mehrwerte und systemische Vorteile bestmöglich vereinen.

Contents

Abbreviations

Please note that the following list is based on the main body of this dissertation and does not completely cover the abbreviations used in the publications.

AC	Alternating Current
aFRR	automatic Frequency Restoration Reserve
c	costs/ prices
CH	Charging Hours
DC	Direct Current
E	Energy
EFC	Equivalent Full Cycles
eFlame	electric Flexibility assessment modeling environment
EMS	Energy Management System
EU-ETS	European Union Emissions Trading System
EV	Electric Vehicle
EVSE	Electric Vehicle Supply Equipment
FCR	Frequency Containment Reserve
GHG	GreenHouse Gas
ICEV	Internal Combustion Engine Vehicle
LP	Linear Programming
mFRR	manual Frequency Restoration Reserve
MILP	Mixed Integer Linear Programming
P	Power
PHEV	Plug-in Hybrid Electric Vehicle
pLCA	prospective Life Cycle Assessment
PV	PhotoVoltaic
RES	Renewable Energy Sources
RQ	Research Question
SBS	Stationary Battery Storage
SMGW	Smart Meter GateWay
SOC	State Of Charge
t	time step
TIE	Technical Implementation Effort
TLGF	Taxes, Levies, Grid Fees
UC	Use Case
V2B	Vehicle-to-Business
V2G	Vehicle-to-Grid
V2H	Vehicle-to-Home

List of publications

This cumulative dissertation aims to evaluate the future prospects of single-use cases and multi-use cases of smart charging and bidirectional charging from the user's perspective. The following four publications mainly constitute this work:

[Pub1] **P. Vollmuth** (formerly Dossow) and M. Hampel, "Synergies of Electric Vehicle Multi-Use: Analyzing the Implementation Effort for Use Case Combinations in Smart E-Mobility," *Energies*, vol. 16, no. 5, p. 2424, 2023. DOI: 10.3390/en16052424.

[Pub2] **P. Vollmuth** (formerly Dossow) and T. Kern, "Profitability of V2X under uncertainty: Relevant influencing factors and implications for future business models," *Energy Reports*, vol. 8, no. 16, pp. 449-455, 2022. DOI: 10.1016/j.egyr.2022.10.324.

[Pub3] **P. Vollmuth**, D. Wohlschlager, L. Wasmeier and T. Kern, "Prospects of Electric Vehicle V2G Multi-Use: Profitability and GHG Emissions for Use Case Combinations of Smart and Bidirectional Charging Today and 2030," *Applied Energy*, 371, 123679, 2024. DOI: 10.1016/j.apenergy.2024.123679.

[Pub4] **P. Vollmuth**, K. Ganz and T. Kern, "Smart e-mobility: user potential in Germany today and in the future," in *NEIS 2023 Proceedings - Conference on Sustainable Energy Supply and Energy Storage Systems*, Hamburg, VDE Verlag GmbH, 2023, pp. 273-280.

In this dissertation, the contents and the methodical interaction of the four publications are presented and discussed. All persons involved in the work of a respective publication are listed as authors. Nevertheless, in all four listed publications the first author developed the concept, the methodological approach to answer the respective research questions, and was responsible for interpreting and discussion the results.
The citation keys [Pub1] to [Pub4] refer to the publications. The four publications are attached in the Appendix.

1 Introduction

The climate crisis is in full progress and its consequences are becoming more and more apparent, both globally and locally. Governments around the world have set ambitious climate targets to keep global warming well below 2 °C. To meet these targets, each sector of energy consumption needs a rapid, efficient transition strategy. For the transportation sector, electric mobility is a key component of decarbonization. By shifting from the internal combustion engine vehicle (ICEV) to the electric vehicle (EV), operational greenhouse gas (GHG) emissions caused while driving are gradually reduced. This effect is enabled by the simultaneous transition of the energy supply sector, i.e. electricity generation, towards renewable energy sources (RES).

As displayed in Figure 1, the technology shift regarding passenger cars in Germany has been slow at best. Even though EV registrations have increased in recent years, a self-contained ramp-up of electric mobility in Germany is not yet in sight. The projection of the German Environmental Ministry shows a significant and constant increase in EVs in the future [1]. Nonetheless, the target of having 15 million EVs on the roads by 2030, as stated by the German government, will most probably be missed by a wide margin [2].

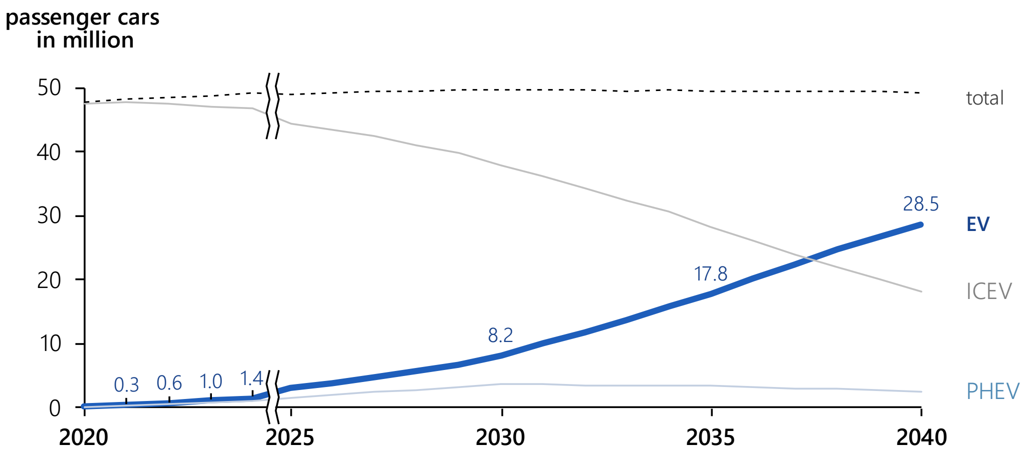

Figure 1: *Number of registered passenger cars in Germany; EV: Electric Vehicle, ICEV: Internal Combustion Engine Vehicle, PHEV: Plug-in Hybrid Electric Vehicles; until 2024: registration numbers [3, 4, 5]; from 2025: projection by the German Environmental Ministry [1].*

The future electrification of the transportation sector via EVs and the ongoing energy transition must proceed harmoniously. Unmanaged charging of EVs as soon as connected to the electric vehicle supply equipment (EVSE), hereafter referred to as direct charging, poses the risk of high charging simultaneity, which could, in turn, lead to local grid congestion [6]. The EV's battery storage could not only serve to fulfil the user's mobility needs but also be used as an integral part of the energy system to provide flexibility and system stability [7]. With the increasing adoption of EVs, large flexible storage potentials become available. In contrast to other flexibility technologies, which must be purchased and installed additionally, EVs are a much more resource-efficient alternative if purchased by users in any case.

Using appropriate technology, the EV's charging strategy can be smartly managed for the period when EV and EVSE are connected. This is referred to as smart charging. Further technological development enables not only charging but also discharging electricity from the EV's battery. This option is named bidirectional charging. Both smart charging and bidirectional charging can be used to apply a range of EV use cases that typically aim to minimize electricity costs or create additional revenues. A use case is defined as a set of actions a system performs to achieve an explicit objective that is typically of value to one or more parties involved in the system [8]. In the context of electric mobility, a use case translates into a specific adjustment of the EV's charging strategy for a designated objective.

Since the total costs of ownership for EVs are at present not necessarily lower than for ICEVs [9] and EVs are still subject to concerns about range and shortage of charging locations [10], effective mechanisms to lower costs for EV users are needed. In this conflicting area of economic and systemic concerns, EV use cases of smart charging and bidirectional discharging offer an attractive solution.

If use cases are designed intelligently and purposefully, further benefits for the local grid and energy system can be achieved. At present, direct charging of EVs is the standard. Only a few reliable smart charging solutions are in operation. Bidirectional charging is still undergoing technical and regulatory development and is not yet fully available for users [11, 12].

This cumulative dissertation analyzes the benefits of smart charging and bidirectional charging from the user's perspective. User benefits, which are the gateway for large-scale implementation of use cases, comprise predominantly financial benefits (cost savings), environmental sustainability, and, in some cases, local self-sufficiency. Users are those who benefit directly from a use case by paying for the associated electricity costs and, in many cases, also owning the EV. Other involved parties, which must also benefit from a use case for it to be implemented, are not the primary focus group. Hence, concrete aspects of actual implementation, such as real technical implementation, specific tariff structures, or actual business models, are not discussed in depth.

Not only use cases with a single designated objective are considered (single-use cases), but also so-called multi-use cases, which combine several objectives in one charging strategy. The scope of this work is limited to fully electric passenger cars, henceforth referred to as EVs, in Germany. Other vehicle technologies, such as plug-in hybrid electric vehicles (PHEVs), are excluded due to lack of relevance (see Figure 1). In terms of charging locations, the focus lies on private households (hereafter: at home) and workplaces (hereafter: at work), as these locations are better suited for smart charging and bidirectional charging than public charging locations.

In Section 1.1, the current state of technology and research is presented based on recent literature and aspects of smart and bidirectional charging that are relevant to this work are introduced. On this basis, research gaps are derived, which represent the motivation for this dissertation. Section 1.2 then explains the research objectives and research questions and introduces the structure of this dissertation. Section 1.3 provides a comprehensive description of the applied methodology utilized to generate the content in Chapters 2 and 3.

1.1 State of research and research gaps

In the field of electric mobility, different research areas exist to assess use cases of smart charging and bidirectional charging. These research areas can be divided into user research, technical research, and charging strategy research.

User research, which examines the behavior of potential EV users under various influences, is not within the scope of this dissertation. Although user behavior is inherently relevant for use case assessments, assuming that users are monetarily motivated and exhibit average reproducible behavior [13], the relevant aspects of this work are covered without going into details of user research.

Technical research primarily focuses on the electronics of EVs and EVSEs as well as on the interplay of the overall technical system in the field of technical components and electronics. While the actual technical research is not the focus of this work, the design of the technical systems necessary to implement smart charging or bidirectional charging use cases is, however, relevant to understand certain aspects of the analyses presented in Chapters 2 and 3.

In general, smart charging has been a research topic for some time and is already a reality today in simple forms of technical implementation [14]. Alternating current (AC) EVSEs with low to medium charging powers (up to 22 kW) are most commonly used for smart charging, as fast charging is not required. Direct current (DC) EVSEs are only used for high-power charging, when fast charging becomes necessary [11]. Smart charging requires a particular set of input data that enables the smart control of the charging process. The most important data are the state of charge (SOC) of the EV battery when plugging into the EVSE, the desired SOC on departure, the planned departure time, and the forecast data according to which the charging process is optimized. Data accuracy is key to ensure that the charging process can be postponed in a genuinely sensible way without affecting the user's mobility. Limiting factors set by the user that restrict the flexibility of smart charging are, in addition to the regular need for mobility, the connection rate with which the EV is connected to the EVSE and the safety surcharges that the user adds to the necessary SOC on departure. On the technical side, a limiting factor is the durability of EV electronics. As the EV should be connected to the EVSE for as long as it is available at a respective charging location and the corresponding electronic control units must be active during this time, operating hours of the EV electronics are much higher for smart charging than for conventional direct charging [14]. At present, the durability of EV electronics is not necessarily designed for such high operating hours over the lifespan of the EV [15].

More recently, bidirectional charging has become the subject of research projects [16, 17, 14, 18, 19, 20]. In terms of actual technical implementations, bidirectional charging is not yet feasible in Germany except for pilot applications. Digital interfaces still need to be standardized and the system's complexity is challenging in some cases [21]. In Germany, DC charging is expected to be the standard for bidirectional charging [16]. For this technical setup, a bidirectional EVSE, which contains an inverter for discharging in addition to the conventional rectifier for charging, is required. The bidirectional chargeable EV does not need any additional hardware. In other countries, AC EVSEs could become standard for bidirectional charging. Bidirectional chargeable EVs then need bidirectional on-board chargers. Such bidirectional on-board chargers must be compatible with the respective country's regulatory grid connection requirements (so-called grid codes) [11]. Besides the data needed for smart charging, bidirectional charging requires a minimum SOC (also called safety SOC), below which discharging is not permitted. A potential additional technical limitation is the number of equivalent full cycles (EFCs) of the EV battery. One EFC describes the energy needed to fully discharge and recharge the battery once. EFC is thus a measure of cyclical battery aging caused by a high energy flow through the battery [22]. Cyclical battery aging depends on various factors, but above all on cell technology [23]. As much additional energy might flow through the EV battery depending on the bidirectional charging use case, cyclical battery aging is more critical than for smart charging. At present, it is not conclusively established whether manufacturers or providers will limit the number of EFCs for their business models for bidirectional use cases or indirectly price the resulting costs of battery cell degradation [14].

Different approaches to describe the corresponding technical systems necessary to implement smart charging and bidirectional charging are used in the literature. Kirpes et al. [24] apply the widely known Smart Grid Architecture Model (SGAM) to represent different layers of the often complex use case systems, whereas Dreyer et al. [25] present self-defined stages of system configuration. In [26], no layer or stage-based architecture is proposed, but an interactive representation is chosen. Depending on which use case is considered, the required technical components and connections are displayed and described. None of the research approaches includes an assessment of how complex the technical implementation of individual use cases is from the user's perspective. The evaluation of the technical implementation effort constitutes a **research gap** to be closed in this dissertation.

Charging strategy research, which uses computational optimization models to simulate and evaluate time-related changes and effects of use case specific charging strategies, is most relevant to this work.

At this point, an introduction of the use cases of smart charging and bidirectional charging that are relevant to this work is appropriate. These use cases are summarized in Table 1. In [Pub1] and [27], more detailed descriptions of the respective use cases are provided. The cases are assigned to different categories. For the category local, only local parameters and no remote, time-variable signals are relevant for optimization. For bidirectional charging, strictly no electricity is fed from the EV back into the public grid (only V2H and V2B use cases). For market-oriented cases, market-based price signals are used for either local or remote optimization via a cloud-based backend. Depending on contract design and implementation, electricity can be fed back into the public grid for bidirectional charging (V2G use cases). Grid-serving cases share the objective of supporting the electric grid (either distribution or transmission grid) through price signals or signals defined by the grid operators. Behind-the-meter refers to the principle of optimizing on-site, i.e. behind the grid connection point. Time-variable price signals or similar can be transmitted externally for this purpose. The local EMS, however, has the authority to determine how the signals are used. In contrast, for the category in-front-of-the-meter, flexibility is pooled, orchestrated, and optimized remotely in front of the grid connection point by the technical aggregator. On-site, a consumption schedule is passed to the flexible assets (in this work, the EV). The primary location is introduced to indicate which charging location is most sensible for the implementation of a respective use case. For some cases, no explicit preference can be stated.

Concerning multi-use cases, the categories and user benefits of the corresponding single-use cases are superimposed. When at least one single-use case is applied in front of the meter, the multi-use case is categorized as in-front-of-the-meter. In terms of technical implementation, a parallel operation of the use cases is implied. All single-use case objectives are considered simultaneously in the optimization process. For each time step, a decision is made as to which charging strategy best contributes to these objectives.

***Table 1**: Definition of relevant single-use cases including short description*

Use case title	Category	Short description	Primary location(s)	User benefit(s)
PV self-consumption optimization	local behind-the-meter optimization	Maximization of usage of self-generated PV electricity to best meet local electricity demand	at home	Electricity procurement cost savings and increased self-sufficiency
Peak shaving	local behind-the-meter optimization	Reduction of local peak load over a time period, if capacity charge (grid fee price component) applies	at work	Grid fee cost savings and optimal use of grid connection capacity
Emergency power supply	local behind-the-meter optimization	Assuring that local electricity supply will be maintained in the event of a power system failure (blackout)	at home and at work	Increased security of electricity supply
Market-oriented price signal (based on day-ahead or intraday market prices)	market-oriented behind-the-meter optimization	Utilization of time-variable electricity prices based on spot market prices to consume electricity at times of low prices and feed electricity back into the grid at times of high prices	all/ no explicit preference	Electricity procurement cost savings and additional revenues through V2G
Spot market trading (day-ahead or intraday markets)	market-oriented in-front-of-the-meter optimization	Direct trading on a spot market by buying electricity at times of low prices and selling electricity at times of high prices	all/ no explicit preference	Electricity procurement cost savings and additional revenues through V2G
Balancing services (FCR, aFRR)	market-oriented and grid-serving in-front-of-the-meter optimization	Direct trading on a balancing market thereby reserving and providing balancing power and energy for grid frequency restoration	all/ no explicit preference	Additional revenues
Redispatch provision	market-oriented and grid-serving in-front-of-the-meter optimization	Direct trading on a potential future redispatch market thereby adjusting power consumption and feed-in to reduce load on transmission grid	all/ no explicit preference	Additional revenues
Grid-serving power range dimming (§ 14a)	grid-serving in-front-of-the-meter optimization	Regulatory-obligatory reduction of local power consumption in cases of local grid congestion to reduce load on distribution grid	at home and at work	Grid fee cost savings
Dynamic grid fees	grid-serving behind-the-meter optimization	Utilization of time-variable, dynamic grid fees to consume electricity at times of low prices and potentially feed electricity back into the grid at times of high prices	all/ no explicit preference	Grid fee cost savings
Reactive power provision	grid-serving in-front-of-the-meter optimization	Provision of reactive power for grid support (voltage stability) through DC-EVSE if needed	all/ no explicit preference	Additional revenues

The charging strategy of a use case is modeled using an optimization model to minimize charging costs for smart charging or to minimize charging costs and maximize discharging revenues for bidirectional charging. Thus, benefits for the EV user are quantified. A different approach is to model the charging strategy from a system's perspective. Here, the optimization objective is also to minimize costs. Not the individual charging costs are considered, but the overall relevant systemic costs. Such energy system analysis thus assesses which charging strategy is most cost-effective for the overall energy system. From both the user's and the system's perspective, the different use cases presented in Table 1 can be considered, with boundary conditions and model parameters being defined individually for each case. Most use cases can be applied for smart charging or bidirectional charging.

Starting with **use cases operated locally**, behind the grid connection point, optimizing the local usage of self-generated photovoltaic (PV) electricity via smart or bidirectional charging is a promising and often investigated use case. For bidirectional charging, PV self-consumption optimization is often referred to as vehicle-to-home (V2H), as it is considered beneficial primarily when charging at home. In [28], V2H is investigated from the user's perspective via power dispatching algorithms. PV tariff, weather conditions, and driving behavior are found to be key influencing factors in cost savings. In [29], an optimization model based on mixed-integer linear programming (MILP) is used to analyze household electricity cost savings. Substantial cost savings are determined for different installed heating systems. Similarly, Kern et al. [15] present a MILP optimization model to determine cost savings for private users. Applying PV self-consumption optimization via smart charging and bidirectional charging for private households with one EV, annual cost savings of up to 300 € are calculated for today's conditions. The model presented in [15] constitutes the basis for the model applied in this dissertation (see Section 2.2).

Some of the more recent studies analyze complex systems involving an energy management system (EMS) and EVs to perform PV self-consumption optimization with the objective of demonstrating how robust or efficient an EMS can work [30, 31, 32]. These publications do not, however, indicate any potential cost savings or other user benefits explicitly. Nor does any of the researched literature provide information on potential changes in operational GHG emissions caused by the respective charging strategy, i.e. the emissions allocated to operating the EV from the user's perspective. The general reduction in emissions through a PV system compared to a location without PV is analyzed in some publications for the balancing scope of the local site, such as in [33]. The evaluation of PV self-consumption optimization from a system's perspective is also found to some extent in the literature. Ganz et al. [34] assess the impact of PV self-consumption optimization on the energy system by aggregating individual EV charging profiles and integrating those into an energy system model. The results indicate that PV self-consumption reduces overall systemic costs and lowers the need to curtail RES and install stationary battery storages (SBS). Discussions in [35] suggest that the positive effect of the use case in summer turns into a negative effect in winter, yet no energy system model simulations are used to conclusively validate this reasoning. Apart from this, effects on the distribution grid level are examined in the literature. Gemassmer et al. [36] show that PV self-consumption optimization significantly influences distribution grid loads. Findings in [37] and [38] demonstrate that PV self-consumption can reduce the stress on the distribution grid at times of peak load.

The use case peak shaving also constitutes a local optimization behind the grid connection point. Peak shaving describes the strategy to reduce charging power or even discharge the EV at times of a peak in the local electricity demand. For bidirectional charging, this use case falls in the category of vehicle-to-business (V2B), as it is usually suitable at work, where a capacity charge must be paid and therefore overall grid fee costs can be reduced. From the user's perspective, peak shaving can generate significant cost savings depending on the local electricity consumption profile, EV availability, and local capacity charge [39, 40]. Peak shaving simulation results are highly susceptible. As demonstrated in [41], for up to six EVs performing smart charging, high cost savings per EV are possible. For every additional EV, cost savings per EV decrease. Kang et al. [42] investigate peak shaving while simultaneously incorporating the reduction of GHG emissions for the balancing scope of the local site into the charging strategy. They show that local emission reduction is compatible with peak shaving. However, at a certain point, either a higher peak load becomes imperative to further reduce local emissions, or less emissions reduction is inevitable to decrease the peak load. No literature is available that uses energy system modeling to analyze peak shaving from a system's perspective. Some publications assess peak shaving effects on the distribution grid [6, 37, 43], where peak shaving generally reduces local grid loads and thus mitigates the risk of grid congestion.

To sum up the research on local behind-the-grid use cases, most publications evaluate the respective use cases from a user's perspective with the primary objective of cost minimization. Systemic benefits are assessed in fewer publications and rarely by means of energy system modeling. A relevant **research gap** is thus the comprehensive assessment of systemic benefits of local behind-the-meter use cases in contrast to prevailing user benefits.

Optimizing the charging strategy based on **market-oriented price signals** is widely researched. In contrast to local behind-the-meter use cases, these cases are less dependent on the charging location and can be applied wherever a corresponding technical system is available [44]. Use cases related to the electricity spot markets are most common in this regard, where either variable electricity prices oriented to the dynamic spot market prices are considered or spot market prices are applied directly. For bidirectional charging, the term vehicle-to-grid (V2G) is usually used, as electricity is discharged from the EV into the public grid. From the user's perspective, spot market-oriented smart charging or bidirectional charging has the potential to reduce the user's electricity costs substantially.

At present, a relatively small number of electricity providers offer variable electricity tariffs to apply the use cases market-oriented price signal in Germany. The providers tibber, 1KOMMA5° and aWATTar each offer dynamic prices based on the German day-ahead spot market [45, 46, 47]. Other providers, such as The Mobility House or octopus energy, offer less dynamic tariffs, which are also based on market-oriented electricity procurement but are designed not to overload EV users with information [48, 49]. Actual spot market trading via smart or bidirectional charging is not yet offered by any player in Germany.

For lack of experience due to the small number of providers today, model-based approaches are used in research to identify respective user benefits. As shown in [50] via a strategic approach and in [44] via linear programming (LP) optimization modeling, participating in the day-ahead spot market via EVs can yield substantial cost savings of around 200 € per EV and year already today. Participation in the shorter-term markets (in Germany, the intraday auction and the continuous intraday market) opens up the prospect of even greater cost savings, as these markets are more dynamic and price spreads are higher than for the day-ahead market [51]. In [44], cost savings from 350 €/(EV·a) up to more than 1,000 €/(EV·a) are obtained for these markets. Naharudinsyah and Limmer [52] apply a MILP optimization model for trading in the intraday market via EVs and found that electricity charging costs can be reduced by around 8 % compared to direct charging. Schmidt et al. [53] demonstrate that continuous intraday trading via EVs can be more cost-effective than via SBS if investment costs are considered.

Tepe et al. [54] focus on commercial EV fleets and determine cost savings of around 200 €/(EV·a) for an optimum pool size of EVs participating in the continuous intraday market via a MILP modeling approach. Potential cost savings via spot market-oriented use cases are found to be influenced by many different factors. Technical parameters, such as EV battery capacity, charging and discharging losses, and price characteristics, represent an important category of influence [55, 44, 56]. Behavioral factors, such as driving patterns and the probability of connecting EV and EVSE, have at least as much influence on resulting user benefits, according to [57, 15].

The focus of the majority of published literature is on the objective of minimizing electricity costs. From a system's perspective, most publications use energy system modeling to examine spot market-oriented use cases, as energy system models often include a spot market model. Kern and Kigle [7] aggregate profiles of bidirectionally chargeable EVs as input for their energy system model. They show that bidirectionally chargeable EVs reduce the installed capacity of power plants fueled by fossil energy sources and facilitate the integration of RES, especially PV power. At the same time, spot market electricity prices are decreasing [7]. Similarly, Hongqian et al. [58] found that V2G has a generally positive effect on market prices and system emissions in urban areas, although EVs are modeled in a simplified, stochastic way. In [59], the reduced need for other storage technologies and fossil-based electricity generation when applying V2G is also confirmed for the example of Finland. On the distribution grid level, systemic effects are not expected to be entirely positive. Uniform price signals resulting from spot market-oriented use cases can lead to high charging simultaneity and potentially to grid congestion, as multiple studies show [6, 36, 60].

Another field of market-oriented use cases is ancillary services, which are generally utilized to maintain system stability. Most prominently in the literature, the balancing service frequency containment reserve (FCR) is examined as a potential smart charging or bidirectional charging use case, as batteries are generally well suited to participate in this market due to their fast response times and cost-effectiveness [61]. Among the first publications, Dallinger et al. [62] simulated bidirectional chargeable EVs participating in the German FCR market. Results show annual cost savings of around 160 € per EV, but their modeling does not include the actual FCR dispatch. Model-based simulations by Figgener et al. [63] of large-scale EV fleets, again without accounting for FCR dispatch, result in higher cost savings of 250 €/(EV·a) to 400 €/(EV·a) for the German FCR market. Tepe et al. [54] present cost savings of a similar magnitude (380 €/(EV·a)) and determined that cost savings from FCR market participation often exceed cost savings of spot market participation when using bidirectionally chargeable EVs. Besides FCR market participation in Germany, several studies have been conducted for the American [64, 65], French [66], and Danish [67, 68] FCR markets. Only in [69] and [70] are results presented from model-based simulations that indicate that reduced operational GHG emissions can accompany balancing service use cases if compared to other feasible technical options. It is noteworthy that this does not automatically imply globally reduced GHG emissions, as at a systemic level other effects, such as emission certificate trading via the European Union emissions trading system (EU-ETS), influence emissions.

Participating in the secondary balancing market (automatic frequency restoration reserve (aFRR)) via smart charging or bidirectional charging is less researched, as FCR appears, at present, to be more financially attractive and feasible from the user's perspective. Still, the first research papers that include aFRR as a potential use case are being published [71, 72]. Another potential ancillary service that could become applicable to smart and bidirectional charging in the future is the provision of redispatch. However, since at the moment no redispatch market suited for EVs exists in Germany, no user-centered research can be conducted in this regard so far. On the distribution grid level, apart from mitigating strategies to reduce high grid loads caused by increased charging simultaneity, the concept of variable or dynamic grid fees could become a relevant use case in the future. Even though, at present, no dynamic grid fees are applicable in Germany due to regulations, in the future such dynamic grid fees might become a means to mitigate the risk of local grid congestion [73]. As Blume et al. [74] show, dynamic grid fees designed for specific distribution grids can reduce transformer overloads by 82 % on average if charging processes are smartly managed in the future.

Concerning market-oriented and grid-serving use cases, the first identified **research gap** is the inclusion of operational GHG emissions into the assessment. Most publications focus their final assessment only on financial benefits or implications for the electric grid. GHG emissions are rarely mentioned at all. If operational GHG emissions are mentioned, they are often only described qualitatively or as a side benefit. As reducing operational GHG emissions could potentially be a relevant user benefit to actively participate in the decarbonization process, research should focus more on this aspect. Secondly, none of the mentioned literature focuses on comparing realistic results on user benefits for today with future years. Either realistic base cases are drawn for the status quo but not compared with realistic scenarios for the future, or future years are analyzed but without a coherent comparison with the current situation. The development and evaluation of realistic scenarios for today and coherent scenarios for the future can close this research gap.

An additional approach to increase the benefits of smart charging and bidirectional charging is to combine multiple single-use cases into **multi-use cases**, thereby stacking individual use case benefits. The single-use case included in a multi-use case could either be implemented in parallel, such that multiple objectives are pursued simultaneously, sequentially, meaning that one single-use case is operated at a time, or the implementation could switch dynamically between parallel and sequential mode depending on circumstances and boundary conditions [75].

Even though multi-use cases are generally complex and not yet relevant for actual implementation [14], charging strategy research is beginning to be conducted in this area. Most commonly, consecutive trading on the different spot markets is investigated in multiple publications. Focusing on smart charging, findings in [76] for the multi-use case of day-ahead market trading and intraday auction trading via a rolling horizon approach indicate only a slight reduction in EV charging costs. Simulations for the same multi-use case in [77], however, result in more than 50 % cost savings on average compared to fixed prices. In [44], the continuous intraday market is introduced as a third market for combined spot market trading. Bidirectional charging is also investigated. Results show that cost savings of bidirectional charging can be up to 500 €/(EV·a) for today and might reach 1,300 €/(EV·a) if EV battery size and efficiencies increase. Demir et al. [78] propose an actor-critic algorithm with deep reinforcement learning agents to model the multi-use case of combined spot market trading and balancing services for the Dutch markets. They found that the algorithm increases modeling accuracy and results in higher cost savings. In [15], Kern et al. present a MILP model using rolling horizon optimization to combine PV self-consumption optimization and spot market trading, implying a sequential operation. Findings indicate that, especially during winter time, spot market trading can complement PV self-consumption optimization, resulting in an increase in annual cost savings of 70 % on average in comparison to single-use PV self-consumption optimization. Englberger et al. [75] propose a MILP multi-use case modeling approach for EV fleets, where single-use cases are virtually stacked by reserving partitions of the EV's battery for specific use cases, and a battery degradation sub-model is included. PV self-consumption optimization and spot market trading are considered, as well as peak shaving and balancing services (FCR). Very high cost savings of more than 2,000 €/(EV·a) are obtained if all four single-use cases are combined. In [40], where Biedenbach and Strunz model the multi-use operation of heavy-duty electric trucks, self-consumption optimization, spot market trading, and peak shaving are implemented in parallel. By assigning individual costs to each single-use case, the objectives of the single-use cases can be optimized in parallel using one objective function. Various sensitivities are simulated for the depot of heavy-duty electric trucks. Huang et al. [60] investigate a different domain, namely the behind-the-meter optimization of a large building cluster via multi-use cases. On-site, not only EV constraints but also cooling, heating, and power load must be considered. By aggregating EV charging profiles and including variable price tariffs, peak shaving, and active power control in the objective function, a genetic algorithm is presented. Results indicate that stacking the various single-use cases increases EV battery utilization.

In general, modeling and assessing multi-use cases still constitutes a **research gap**, as few researchers address this topic compared to the multitude of studies on single-use cases. One reason is the increased complexity of multi-use cases, which must be integrated into a computational model. Another reason might be that multi-use cases are not yet under development by manufacturers and flexibility providers. In all publications, the amount of electricity flowing through the EV battery increases when applying a bidirectional charging multi-use case. Operating hours are rarely evaluated. Hence, additional technical limitations, such as a restriction of EFCs or operating hours, should be investigated further for multi-use cases, since these limitations can become highly relevant. Based on the presented literature review, no publications have evaluated systemic benefits of multi-use cases. A major reason for this is the immense complexity involved in integrating charging strategies for multi-use cases into an energy system model and generating realistic scenario results. Nonetheless, due to the relevance of multi-use cases in the future, further model development is needed to improve the assessment of the systemic benefits of multi-use cases. Lastly, the examined publications rarely discuss the number of potential EV users who could implement a corresponding use case. Although [44] provides respective market volumes and translates those into a corresponding number of charging locations, further research on the feasible number of users per use case is required.

1.2 Research objective, research questions and structure of dissertation

The main research objective of this dissertation is to assess smart charging and bidirectional charging use cases from the user's perspective. As use cases will only be implemented if benefits are created for users, user benefits are key to the successful integration of smart electric mobility. Multi-use cases constitute an important advancement in this regard, since multiple benefits are combined in one case. Hence, not only single-use cases but also multi-use cases are assessed.

Only when user benefits are clearly understood can decision-makers and innovators focus on levers to promote those use cases, which also create great systemic benefits. To address the main objective, four research questions (RQs) are defined and answered in this dissertation. Below, the RQs are stated and additional background is provided.

RQ 1: What are the differences in the effort required for technical implementation of the use cases, and what synergies result from the implementation of multi-use cases?

The basis for assessing the benefits of smart charging and bidirectional charging use cases is a clear understanding of how the use cases are implemented. The focus lies on the technical implementation effort required to enable the operation of a use case at a user location rather than on the effort to develop the necessary technical components. It includes an assessment of the implementation efforts of multi-use cases and the associated synergies.

RQ 2: What is the potential range of user benefits of single-use cases and multi-use cases today and in the future?

Cost savings are the main user benefit, as electricity costs can be reduced when applying smart charging or bidirectional charging compared to direct charging. Reducing operational GHG emissions is another benefit, as is an increase in self-sufficiency. The user benefits are subject to many influencing factors and may thus vary depending on the circumstances. Determining the range of user benefits for varying circumstances and the effect of different influencing factors is crucial to obtaining a conclusive, reliable understanding of the benefits of various use cases. Emphasis is placed on the differences between user benefits today and in the future.

RQ 3: What is the maximum number of users who can carry out the use cases today and in the future?

The maximum number of users per use case is a crucial indicator for evaluating the general potential of the use cases. The number is particularly relevant for those parties whose business model is based on a use case, who offer components for specific use cases, or who provide support during the implementation or operation of a use case. From a user's perspective, the number indicates how many users might operate a certain use case today and in the future and how competitive it might get in terms of market share and prices, which is especially relevant for market-oriented use cases. It is important to note that this number does not take the number of registered EVs into account.

RQ 4: What are the prospects for a user-driven implementation of single-use cases and multi-use cases, and which levers are key for a systemically beneficial integration of EVs?

Since smart charging and bidirectional charging are essential to integrate electric mobility into the energy system, it is vital to determine at which point in time respective use cases are likely to be beneficial for most users under various circumstances. The evaluation of these prospects for a user-driven use case implementation forms the basis for a system-focused assessment. Taking respective systemic benefits of each use case into account, it becomes possible to identify effective levers that would facilitate the integration of those use cases, which are most beneficial from a system's perspective.

Figure 2 visualizes that this dissertation is structured in four parts oriented towards the RQs. Single-use cases and multi-use cases are analyzed separately but consistently. Bases for the first three parts are the four publications that primarily constitute this work:

Publication 1: Synergies of Electric Vehicle Multi-Use: Analyzing the Implementation Effort for Use Case Combinations in Smart E-Mobility, *Energies 2023* **[Pub1]**

Publication 2: Profitability of V2X Under Uncertainty: Relevant Influencing Factors and Implications for Future Business Models, *Energy Reports 2022* **[Pub2]**

Publication 3: Prospects of Electric Vehicle V2G Multi-Use: Profitability and GHG Emissions for Use Case Combinations of Smart and Bidirectional Charging Today and 2030, *Applied Energy 2024* **[Pub3]**

Publication 4: Smart E-Mobility: User Potential in Germany Today and in the Future, *NEIS 2023 Proceedings* **[Pub4]**

The publications are attached in the Appendix.

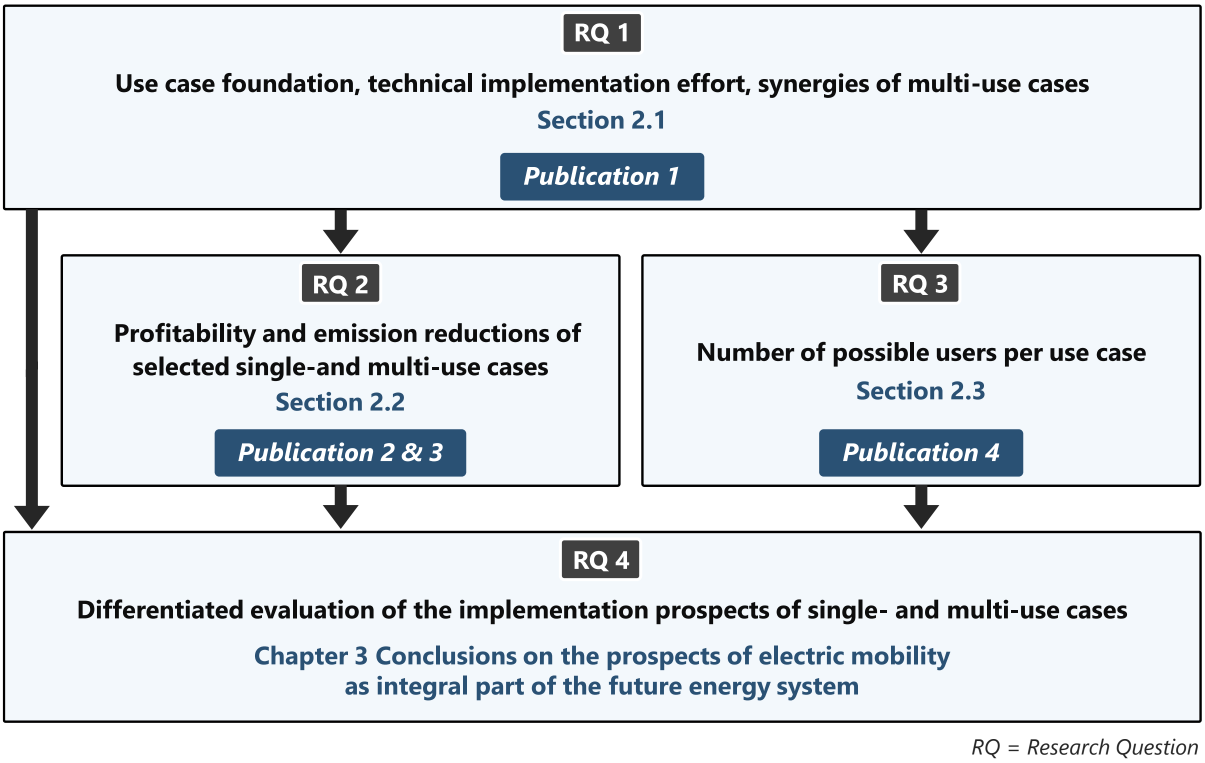

***Figure 2**: Structure of the dissertation divided into four parts with assignment of research questions (RQ), publications and sections/ chapters of this work.*

Each of the first three parts is presented and described in detail in an individual section in Chapter 2. The first part (Section 2.1) constitutes a prerequisite for the second (Section 2.2) and third part (Section 2.3). The fourth part of this dissertation represents the merger of the research conducted in the first three parts. This part, described in Chapter 3, is not based on previous publications but draws conclusions from all aspects analyzed in the preceding parts. A description of the applied methodology is provided in the next section.

1.3 Methodology

Following the same scheme as the illustration of the structure of the dissertation, Figure 3 shows the overall methodology of this work. The four parts of the dissertation are described subsequently. Further details on the individual methods per publication are provided in Chapter 2 and on the methodological consolidation of results in Chapter 3.

The **first part, *Use Case foundation, technical implementation effort, synergies of multi-use cases***, aims to create a general understanding of the relevant use cases and their technical implementation. The second objective is to evaluate the effort necessary for technical implementation and the resulting synergies of multi-use cases.
The starting point is a methodological identification and template-based definition of relevant single-use cases of smart charging and bidirectional charging in discussion workshops with appropriate experts from the energy and automotive industry [27]. Illustrations of the simplified technical systems as part of the definition are used to create detailed visualizations of the technical implementation of the single-use cases. The multi-use cases are defined based on the single-use case definitions. All suitable combinations of up to three single-use cases are taken into account. The visualization of the multi-use cases results from the superimposition of the respective single-use case visualizations.
Both for single- and multi-use cases, the visualizations constitute the basis to calculate the technical implementation effort for each relevant case. After listing the elements (involved parties, technical components, interfaces) that are necessary for a use case, effort values are assigned to each element by methodologically assessing effort value estimates of distinguished experts in the field of smart and bidirectional charging use cases. The sum of effort values for all elements necessary for a corresponding use case yields the technical implementation effort per use case. The calculation method for single-use cases is the same as for multi-use cases. The technical implementation effort is assumed to remain unchanged over time, such that no differentiation is made between different years in the calculations. To analyze the synergies of multi-use, the difference between the technical implementation effort of the multi-use case and the effort of the sum of the corresponding single-use cases is calculated. The resulting savings in the implementation effort represent the measure for synergies and a means to prioritize the multi-use cases in terms of high savings in the implementation effort. [Pub1]

The main objective of the **second part, *Profitability and emission reductions of single-use cases and selected multi-use cases***, is to determine the user benefits of single- and multi-use cases for today and the future.
Input for this part are the detailed definitions of the use cases from the first part. The main user benefit to be assessed is the potential reduction in electricity costs resulting from a changed charging strategy. Additionally, operational GHG emissions are shaped by the charging strategy, such that operational GHG emission reductions

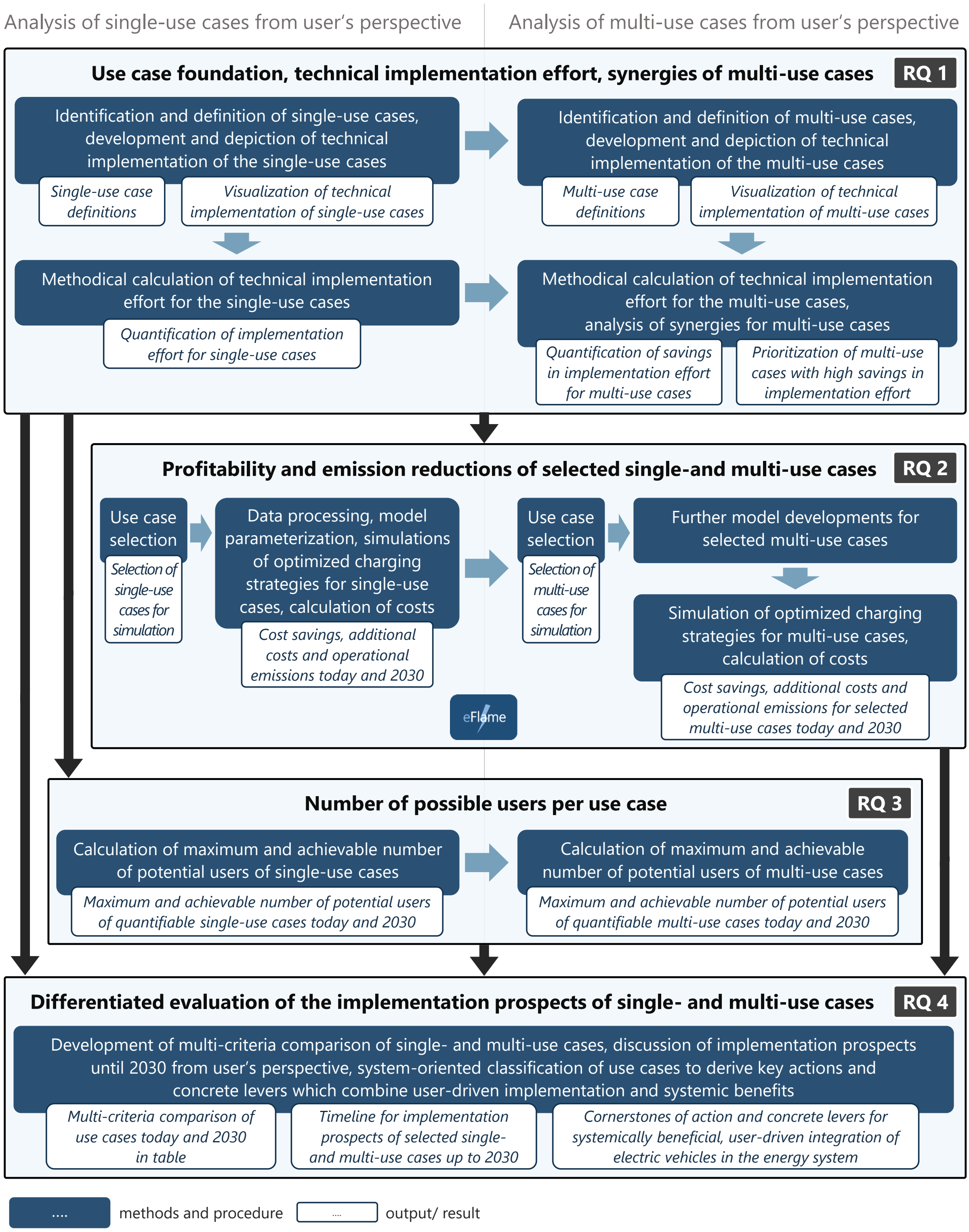

Figure 3: *Detailed methodology of the dissertation divided into four parts including brief description of methods, results and connections within each part and between the parts.*

constitute a second potential user benefit. Other benefits, which are only attainable for some of the use cases, are not assessed. As a starting point, the single-use cases that have already been defined to the extent that they can be modeled are selected. For certain use cases, for example, no market has yet been defined, or the regulations are too unspecific, so these cases cannot be considered.

To determine the cost savings and reductions of operational GHG emissions from the user's perspective, a model-based approach is pursued using the MATLAB optimization model eFlame (electric Flexibility assessment modeling environment). For all cases, the optimization objective is to minimize electricity costs through smart charging or bidirectional charging in comparison to direct charging. Depending on the use case, LP or MILP is applied. Multiple boundary conditions are defined to design the modeling as realistically as possible. To run simulations, extensive input data are required. The data are acquired from a variety of sources, including experts from the automotive and energy industries within the research projects [14, 16], publicly accessible databases, and actual measurement data from pilot installations [79], to obtain validated sets of input data for the years 2020, 2021, 2022, and 2030. As the cost savings depend on many influencing factors, numerous simulations, including a structured variation of the most influential parameters (sensitivities), are conducted for each selected single-use case. Hence, the simulations result in a range of potential cost savings and emission reductions, which are discussed and evaluated in terms of user benefits and business model implications. Regarding financial user benefits, the resulting savings in electricity costs are countered by additional technology costs. These additional technology costs are calculated separately and arise from additional hardware specifically required for smart charging and for bidirectional charging. [Pub2]

For the multi-use cases, several criteria are utilized for selection. The aim is to select a small number of representative cases consisting of only two single-use cases each, since modeling multi-use cases is complex and effortful regarding computational power. Firstly, if a multi-use case contains at least one single-use case that is not selected for modeling single-use cases, the respective multi-use case is omitted. Secondly, similar to the selection of single-use cases, the criterion as to whether sufficient frameworks (market, regulatory) exist for the multi-use cases is applied. Due to the increase in complexity and novelty of multi-use cases, this criterion rules out several cases. Thirdly, the synergy-based multi-use case prioritization from the first part is used as additional input. By aligning the remaining use cases with the prioritization, two exemplary multi-use cases are selected for eFlame simulations, which demonstrate medium to high synergies and manageable technical implementation efforts.

Developments in eFlame are conducted, as the model implementation for multi-use cases differs from that for single-use cases. A similar variety of simulations is run for the multi-use cases and the years 2021, 2022, and 2030 with some adjustments due to use case specific characteristics. The results are again assessed from the user's perspective in terms of cost savings, including additional costs and GHG emission reductions. [Pub3]

In the **third part, *Number of possible users per use case***, the objective is to provide an indication of the potential of the use cases from a user's perspective. The number of existing EVs is not relevant in this part. Instead, the maximum number of users that could generally apply a use case if sufficient EVs were available. As in the second step, the status today and the year 2030 are assessed.

Relevant inputs are the detailed use case definitions from the first part. Based on the definitions, those single-use cases for which it is possible to quantify the number of potential users are examined. All other cases can either not be considered because they are not yet established or because they are generally applicable and determining the number of users is superfluous. Two different types of potential user numbers are calculated:

the maximum number of potential users as an upper, theoretical estimate of the total possible number of users and the achievable number of potential users as a more realistic assessment of the number of users incorporating specific premises and further limitations. For each quantifiable single-use case, the numbers of potential users are calculated individually for 2021 and 2030 on the basis of available data and use case specifics. For multi-use, the intersection of users of the corresponding single-use cases constitutes the users of the multi-use case. The maximum and achievable number of users is therefore determined by calculating the respective intersection. The resulting maximum and achievable numbers of users allow for an evaluation of the potentials and limitations of the use cases with regard to the expected EV ramp-up and other contextual factors. [Pub4]

The **fourth part, *Differentiated evaluation of the implementation prospects of single-use cases and multi-use cases***, constitutes the consolidation of the three previous parts. The first objective is to evaluate the prospects of which single- and multi-use cases are most likely to be implemented from a user's perspective in a differentiated and conclusive manner. The second objective is to identify key actions and concrete levers that promote the user-driven implementation of those use cases that are notably beneficial from a system's perspective. To this end, systemic benefits of the respective use cases are first established.

Inputs for this part are the quantification of implementation effort for single and multi-use cases from the first part, the cost savings and emission reductions for the selected cases today and 2030 from the second part, and the numbers of potential use cases users today and 2030 from the third part. These inputs are combined in tabular form and color-rated to visualize benefits and downsides of all investigated use cases. For those cases simulated in the second part, a timeline of the potential user-driven implementation of the cases up to 2030 is developed. On these bases, use case prospects of implementation are assessed and the most important influencing factors are identified. The use cases are subsequently discussed and classified in terms of their systemic benefits. So-called cornerstones of action are defined, each comprising a call for action to address a specific aspect of the use case implementation. For each cornerstone, concrete levers that promote systemically beneficial use cases are derived by adjusting most relevant influencing factors that shape the implementation prospects of the respective use cases. The work closes with a critical reflection on the findings and an outlook on potential areas for further research.

2 Comprehensive assessment of use cases

This chapter summarizes the content of the four publications that primarily constitute this work. [Pub1] is described in Section 2.1, [Pub2] and [Pub3] in Section 2.2, and [Pub4] in Section 2.3. Following a summary of the respective publication, a brief outline of the applied methods and selected key results that are important for the understanding of this dissertation are provided in each section. The publications are attached in the Appendix.

2.1 Use case foundation, technical implementation effort, synergies of multi-use cases

Paper Title:	**Synergies of Electric Vehicle Multi-Use: Analyzing the Implementation Effort for Use Case Combinations in Smart E-Mobility**
Authors:	Patrick Vollmuth (formerly Dossow), Maximilian Hampel
Journal:	Energies (2023)
DOI:	10.3390/en16052424
Own contribution	Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – Original Draft Preparation, and Writing – Review & Editing.
Status:	published (see Appendix [Pub1])

Short summary: The detailed evaluation of the technical implementation of the system required for smart charging and bidirectional charging of EVs has been identified as a research gap. In particular, the implementation of multi-use cases has not yet been considered. Thus, this publication assesses the technical implementation effort of single- and multi-use cases. In this respect, the technical implementation effort is a measure for determining the technical effort for the implementation of an operational use case at the user's location. The effort required to develop technical components or similar is not included. The primary focus of the work lies in the assessment of synergies in the technical implementation of multi-use cases, as these cases hold the potential to generate high user benefits through the combination of individual use case benefits.

The presented findings demonstrate that in-front-of-meter use cases, which involve a range of different parties, interfaces, and data, are generally accompanied by a high technical implementation effort from the user's perspective. Multi-use cases that involve in-front-of-meter use cases, such as spot market trading, balancing services, or redispatch provision, show the greatest synergies. These multi-use cases are, however, also the cases with the largest implementation efforts in absolute terms. If behind-the-meter use cases, such as self-consumption optimization or peak shaving, are part of a multi-use case, the absolute implementation effort is usually lower. With the main objective of combining user benefits and systemic benefits through multi-use cases, it is sensible to combine different types of use cases. Technical developments and regulatory definitions that have not yet been finalized are the main hurdles to technical implementation.

2.1.1 Methods and procedure

To evaluate the technical implementation of smart charging and bidirectional charging, relevant single-use cases are identified and defined through a series of workshops with experts from the automotive and energy industry within the unit-e² research project [14]. A methodical procedure, the so-called use case methodology, is applied to define the use cases in a consistent and explicit way [27]. The technical systems necessary to implement each single-use case individually are subsequently established through discussions and iterations. Visualizing each system, consisting of actively involved parties, required technical components, and interfaces for data exchange, enables a unified technical understanding between all experts.

Regarding multi-use cases, suitable multi-use cases resulting from the single-use cases are identified. All cases that are not based on a similar incentive system or that do not follow the same price signal are suitable for multi-use. The order of implementation is irrelevant to the assessment. To ensure that the number of multi-use cases remains manageable, the number of single-use cases per multi-use case is limited to a maximum of three cases. Above this limit, the complexity becomes so high that these cases are considered unrealistic for implementation. As for the single-use cases, the multi-use cases are methodically defined. The visualizations for those single-use cases, which form a corresponding multi-use case, are superimposed to obtain the necessary technical systems of the multi-use cases. The union of involved parties, technical components, and interfaces thus defines the multi-use case system. Through subsequent expert discussions, elements that are additionally required only for a certain multi-use case are added in some instances.

After defining the use cases, the method to calculate the technical implementation effort of each use case is applied. The method first lists all elements (involved parties, required technical components, interfaces) necessary for implementing a respective use case. For each element, an effort value, measured in so-called effort units, is assigned. The sum of effort units required for a specific single-use case or multi-use case (UC) yields the technical implementation effort (TIE) of the use case (Equation 1). To determine the effort values for each element, expert surveys are conducted with the experts from the unIT-e² project. In the survey, the experts specify effort ratings on a scale of 0 to 100 for those use cases with which they are familiar enough. Based on the resulting data set, non-linear curve fitting is used to determine the effort values of the individual elements that are part of the respective use cases. The curve fitting algorithm assigns each element the effort value that provides the best fit with the survey data set when calculating the TIE bottom-up via Equation 1.

The comparison of the TIE of all use cases considered relevant provides an indication of the efforts for the user and, indirectly, of the complexity of the cases. The comparison of the TIE of a specific multi-use case with the sum of TIEs of the single-use cases it contains reveals the savings in effort and, thus, the synergies of the multi-use case (Equation 2).

$$TIE_{UC_i} = \sum_k [effort\ units_k(UC_i)] \qquad \textbf{(Eq. 1)}$$

$$Savings\ in\ TIE_{\boldsymbol{UC_i+UC_j}} = (TIE_{UC_i} + TIE_{UC_j}) - TIE_{\boldsymbol{UC_i+UC_j}} \qquad \textbf{(Eq. 2)}$$

where k is the element index, i and j are the use case indices

The calculations are followed by an assessment of the TIE of the single- and multi-use cases with a focus on synergies of multi-use. For this purpose, discrete rating categories are introduced by assigning a range of TIE and savings in TIE to each rating category. An evaluation of technical and regulatory challenges and development requirements is included in this final methodological step.

2.1.2 Selected key results

All relevant use cases of smart and bidirectional charging are displayed in Table 1 in Section 1.1. To analyze the respective TIE, the technical system necessary to apply the relevant use cases is presented in Figure 4. All use cases can be applied with the illustrated system. Behind the meter, the system is displayed at the component level. In front of the meter, involved parties are shown without technical components for reasons of simplification. A more detailed system illustration is available online [26] with the interactive feature that the technical implementation of individual use cases can be displayed by pressing the corresponding button.

As in Table 1, a distinction is made between implementation at home and at work. Behind the meter, an EMS orchestrates the optimization and transmits the charging schedule to the EVSE. A smart meter gateway (SMGW) is used to transmit measurement data securely in compliance with legal requirements and to receive and forward signals from network operators. In-front-of-the-meter, backend-to-backend communication is carried out between component manufacturers and energy sector parties.

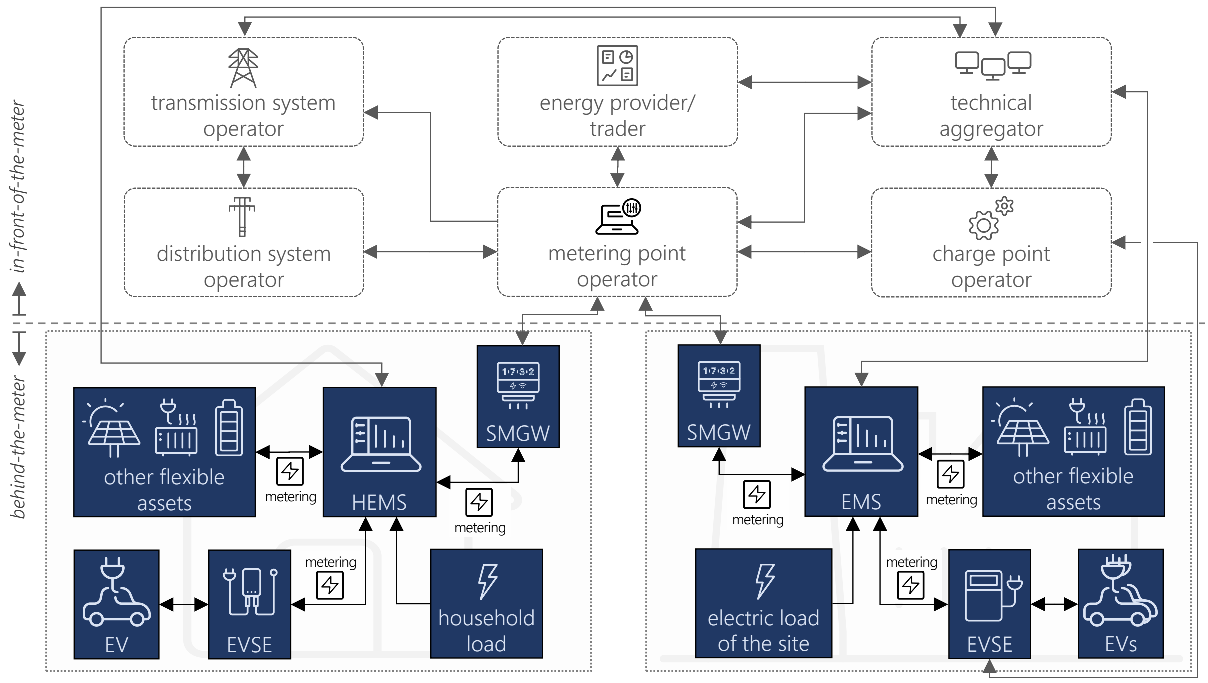

Figure 4: *Schematic layout of the technical implementation of smart charging and bidirectional charging use cases at home and at work; focus on behind-the-meter components (dark blue boxes) and associated data communication/ interfaces (black arrows), simplified display of in-front-of-the-meter parties (white boxes) and their communication channels (grey arrows).*

Concerning the calculated TIEs, Figure 5 displays a selection of results for an implementation at home (left) and for an implementation at work (right), each consisting of two single-use cases. The TIE of each multi-use case (dark blue bars) is compared to the TIE that would result from implementing the two corresponding single-use cases separately (grey bars). A full list of the TIEs of relevant single-use cases is presented in Table 2 in Section 3.1, where increased attention is paid to individual effort values. More data is provided in [Pub1].

In Figure 5, the multi-use cases that show the lowest savings in TIE and the multi-use cases that show the highest savings in TIE when comparing simultaneous multi-use case implementation with the hypothetical separate implementation are displayed. The savings in effort units are a measure of implementation synergies. At home, the multi-use case redispatch provision plus emergency power control has the lowest savings in effort units. At work, reactive power provision plus balancing services (FCR, aFRR) has the lowest savings. It is apparent that those multi-use cases that contain a complex, effort-intensive single-use case and a relatively low-effort single-use case exhibit low synergies. Low synergies often occur for multi-use cases that include a behind-the-meter and an in-front-of-the-meter single-use case. High synergies at home are found for three multi-use cases that include market-oriented price signals, dynamic grid fees, spot market trading, balancing services (FCR, aFRR), or redispatch provision with TIE savings as high as 45 % compared to a separate implementation. At work, similarly high synergies are possible for five multi-use cases. In addition to the single-use cases mentioned above, peak shaving and grid-serving power range dimming (§ 14a) are included in the selection.

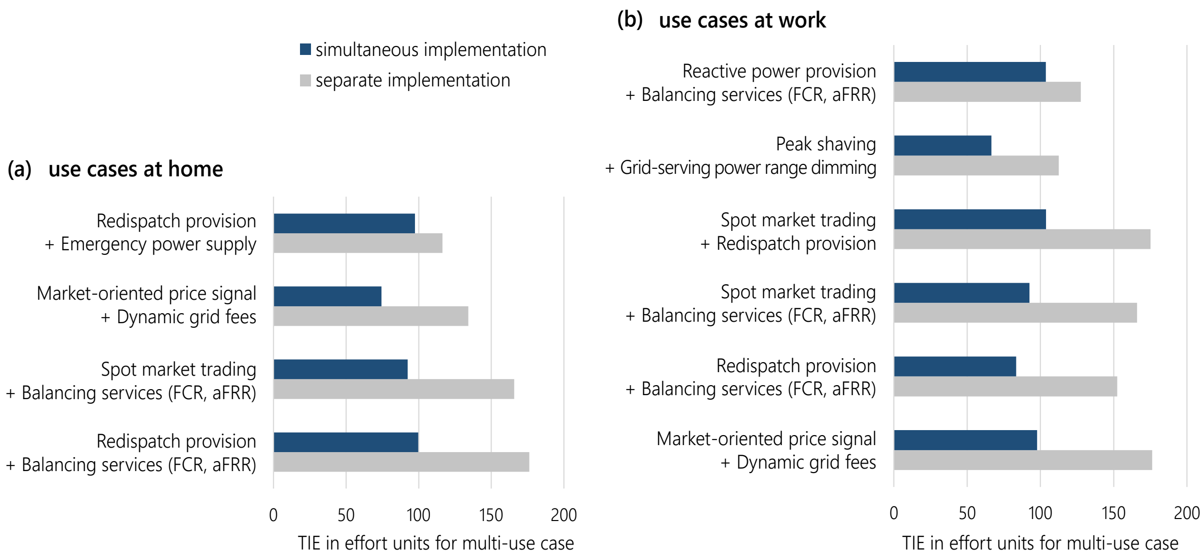

***Figure 5**: Calculated TIE (technical implementation effort) of selected multi-use cases in dark blue compared to the sum of TIEs of the two single-use cases that constitute the respective multi-use case in gray; left: implementation at home, right: implementation at work.*

In conclusion, synergies of implementing multi-use cases are low when substantially different single-use cases, one of which involves comparably complex in-front-of-the-meter processes, are combined. High synergies are found for multi-use cases that mainly include similar in-front-of-the-meter use cases. Especially those multi-use cases that include balancing services (FCR, aFRR), spot market trading, or redispatch provision exhibit high savings in TIE and are thus particularly interesting for further research. These multi-use cases often display a high absolute effort value. Potentially high synergies should thus be distinct from generally low TIEs and vice versa.

2.2 Profitability and emission reductions of single-use cases and selected multi-use cases

Publication assessing single-use cases:

Paper Title:	**Profitability of V2X Under Uncertainty: Relevant Influencing Factors and Implications for Future Business Models**
Authors:	Patrick Vollmuth (formerly Dossow), Timo Kern
Journal:	Energy Reports (2022)
DOI:	10.1016/j.egyr.2022.10.324
Own contribution	Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – Original Draft Preparation, and Writing – Review & Editing.
Status:	published (see Appendix [Pub2])

Short summary: Financial benefits are decisive for vehicle users who choose an EV rather than a conventional ICEV and opt for a use case of smart charging or bidirectional charging. This paper examines the potential profits of electric mobility single-use cases with a focus on bidirectional charging from 2020 to 2040. Cost-optimized charging and discharging strategies are computed using the eFlame optimization model. The resulting cost savings or respective revenues are offset against the additional technology-related costs, which are calculated and assessed in detail. The results are presented as ranges of profits for the different bidirectional charging categories, with the spread of profits providing a measure of uncertainty. Crucial implications for future business models associated with bidirectional charging use cases are derived.

The profit assessment reveals that some cases can most certainly become profitable in the near future. For V2H use cases, for instance, high annual profits are determined in 2040. Some use cases of the other bidirectional charging categories (V2B and V2G) are subject to high uncertainties, with profitability remaining unsure in future years. External circumstances are found to have a great impact on profitability, with user behavior and charging location being most relevant. Conclusions on business model development indicate that the business model design should focus on customer segments, revenue streams, and value propositions to mitigate uncertainties and increase the chances of profitability. These findings and implications are also applicable to smart charging.

Publication assessing multi-use cases in comparison to single-use cases:

Paper Title:	**Prospects of Electric Vehicle V2G Multi-Use: Profitability and GHG Emissions for Use Case Combinations of Smart and Bidirectional Charging Today and 2030**
Authors:	Patrick Vollmuth, Daniela Wohlschlager, Louisa Wasmeier, Timo Kern
Journal:	Applied Energy (2024)
DOI:	10.1016/j.apenergy.2024.123679
Own contribution	Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – Original Draft Preparation, and Writing – Review & Editing.
Status:	published (see Appendix [Pub3])

Short summary: A relevant research gap concerns the benefits that multi-use cases of electric mobility can offer as an enhancement to single-use cases. In addition to profitability, assessing the potential reduction of operational GHG emissions when applying a use case is important. This paper presents and evaluates potential annual profits and reductions in operational GHG emissions for selected single- and multi-use cases of smart charging and bidirectional charging for the years 2021, 2022, and 2030. Findings are discussed from the user's perspective. Profits result from electricity cost savings from detailed simulations with the eFlame optimization model, reduced by additional technology costs. Operational GHG emission reductions are calculated by multiplying the hourly charging power by hourly GHG emission factors, using prospective life cycle assessment (pLCA) for 2030.

Results show that smart charging is profitable in most single- and multi-use cases today (2021, 2022) and in all use cases in 2030 when compared to direct charging. Bidirectional charging is profitable today for the considered multi-use cases, in some of the investigated single-use cases, and becomes consistently profitable in 2030. The most important influencing factors are market price characteristics, user behavior, charging restrictions, and regulations for discharged electricity. Regarding today's emissions, operational GHG emissions are reduced in some cases while increasing in others. The highest reduction is found for the multi-use case PV self-consumption optimization plus spot market trading. Yet, the multi-use case sequential spot market trading reveals an increase in emissions. In 2030, operational GHG emissions are reduced for all cases, as charging is positively influenced by a lower GHG intensity of the German electricity mix and less restrictive constraints are applied due to anticipated technological and regulatory developments.

2.2.1 Methods and procedure

The methodological approaches in both publications are similar but not identical. [Pub2] focuses on the profitability of bidirectional charging single-use cases today and in the future from the user's perspective and implications for potential future business models. Potential cost savings compared to direct charging are calculated and offset against additional technology costs. [Pub3] extends this work by considering smart charging and bidirectional charging and by including representative multi-use cases in the assessment. In addition, not only cost savings but also reductions in operational GHG emissions compared to direct charging are calculated and evaluated in [Pub3].

As a starting point in [Pub2], single-use cases are selected as representatives for the three bidirectional charging categories V2H, V2B, and V2G based on feasibility, data availability, and expected relevance. For the selected single-use cases, different eFlame simulations are run to determine average optimized charging strategies and resulting cost savings for the years 2020 to 2040 at intervals of five years. The input data for the different simulations are carefully selected to cover the broadest possible range of realistic parameters. The determined cost savings are offset against separately calculated additional technology costs for each respective year (net cost savings). For each of the three bidirectional charging categories, four separate profit paths are developed and displayed: a lowest profits path, a highest profits path, a so-called gloomy path, and a so-called optimistic path. The first two paths represent a general profit range, while the latter two reflect more realistic, consistent profit paths. The resulting profit ranges are subsequently analyzed and discussed, focusing on future user-driven implementation. Lastly, the profitability prospects and main influencing factors are linked to potential business models to derive implications for future business model designs.

In [Pub3], different use cases are selected for simulation. The scope is narrowed down to charging locations at home and three representative use cases. Two of these are multi-use cases to evaluate multi-use cases in greater detail for smart charging and bidirectional charging. The model eFlame is developed further to simulate the selected multi-use cases. Input data are determined with the aim of establishing realistic base cases for today and 2030. Furthermore, parameter variations (sensitivities) are defined to account for the most relevant influencing factors. On this basis, various eFlame simulations are run. In addition, hourly lifecycle-based emission factors of the German electricity generation of the respective year are multiplied by the charging and discharging power resulting from the simulations to obtain the operational GHG emissions for today and 2030 from the user's perspective. Both resulting cost savings and emission reductions are methodologically analyzed. Lastly, averaged cost savings are again offset against updated additional technology costs to assess the profitability of the use cases for today and 2030 with a focus on bidirectional charging.

Since the eFlame optimization model is used in both publications to simulate optimized charging strategies according to the respective use case, eFlame is briefly described. Figure 6 shows a simplified illustration of the functionality of eFlame. The model's objective is to optimize charging and discharging strategies of flexibly operable EVs, thereby minimizing overall electricity costs at the respective grid connection point. Several technical components can be included in the optimization (in Figure 6, components that are not used in [Pub2] or [Pub3] are displayed in grey). All included components are modeled by fixed parameters, which constitute limitations for the boundary conditions, and by decision variables, which can be altered to meet the model's objective.

Before the actual optimization step, input data is processed and integrated. Work has been done in this regard, such as adding the option of using hourly emission factors or providing spot market price forecasts for day-ahead and intraday markets for future years.

Regarding the optimization step, objective functions are specified for different use case categories. For behind-the-meter use cases, where no electricity is discharged from the EV into the public grid, Equation 3 applies. For each time step (Δt), purchased electricity ($P_t^{\mathrm{grid,in}}$) at the respective price ($c_t^{\mathrm{el,buy}}$) is minimized. If a local PV system exists, electricity fed into the public grid ($P_t^{\mathrm{grid,out}}$) at the respective PV remuneration fee ($c_t^{\mathrm{el,sell,PV}}$) is simultaneously maximized. By connecting the EV's charging and discharging power ($P_t^{EV,\mathrm{charge}}$, $P_t^{\mathrm{EV,discharge}}$) to the power at the grid connection point ($P_t^{\mathrm{grid,in}}$, $P_t^{\mathrm{grid,out}}$) via a boundary condition, the charging strategy is determined for a set optimization horizon (T).

$$min\left(\sum_{t=1}^{T}\begin{bmatrix} c_t^{\mathrm{el,buy}} \cdot P_t^{\mathrm{grid,in}} \cdot \Delta\mathrm{t} \\ -\, c_t^{\mathrm{el,sell,PV}} \cdot P_t^{\mathrm{grid,out}} \cdot \Delta\mathrm{t} \end{bmatrix}\right) \qquad \textbf{(Eq. 3)}$$

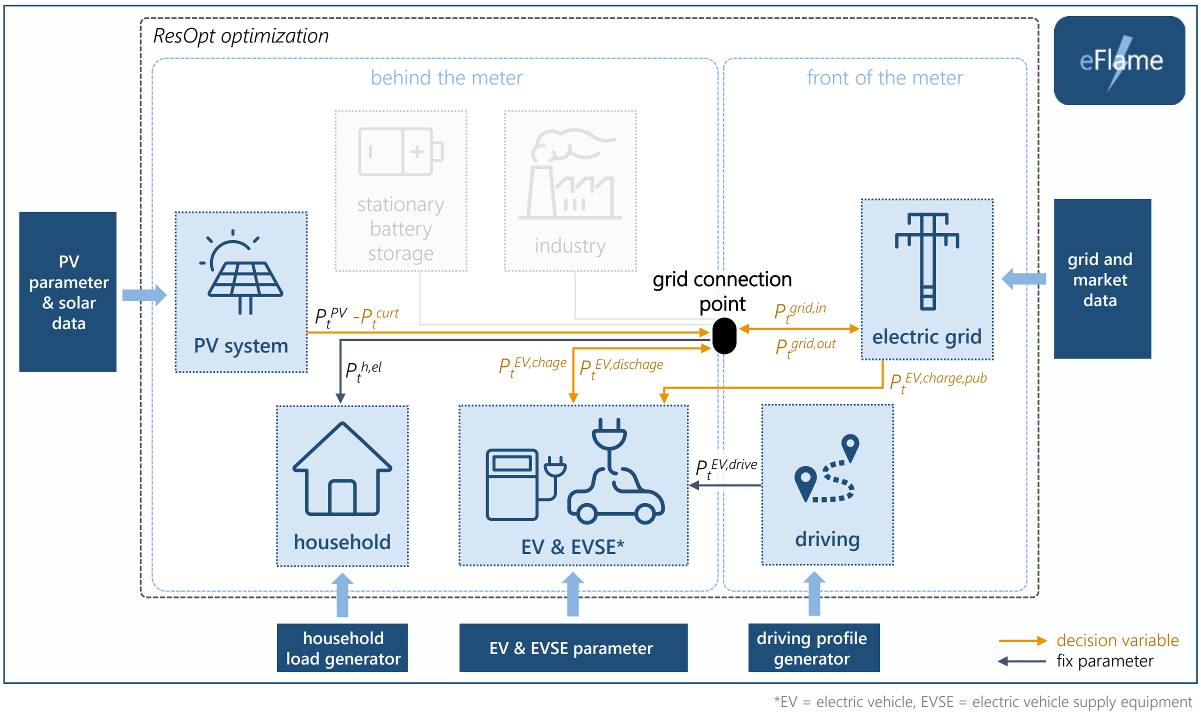

Figure 6: *Simplified illustration of the optimization model eFlame (model components that are not used in any of the publications are grayed out).*

For market-oriented use cases, where electricity from the EV is discharged into the public grid, Equation 4 is implemented. Again, purchased electricity ($P_t^{\text{grid,in}}$) is minimized at the respective price ($c_t^{\text{el,buy}}$). Since, in this case, the EV can discharge electricity into the public grid, this electricity ($P_t^{\text{EV,discharge,2g}}$) at the respective market price ($c_t^{\text{el,sell,EV}}$) is maximized in each time step.

$$min\left(\sum_{t=1}^{T}\begin{bmatrix} c_t^{\text{el,buy}} \cdot P_t^{\text{grid,in}} \cdot \Delta t \\ -\, c_t^{\text{el,sell,EV}} \cdot P_t^{\text{EV,discharge,2g}} \cdot \Delta t \end{bmatrix}\right) \qquad \textbf{(Eq. 4)}$$

Multi-use cases, where simultaneous participation in different markets should be possible, are implemented in eFlame through sequential trading on the corresponding markets for a set optimization horizon. P_t^{schedule} is introduced via Equation 5, which represents the power balance at the grid connection point, assuming no other loads or power generators are connected apart from the EV. After finishing the optimization for the first market of a respective multi-use case, the electricity purchased and sold on this market (the index i refers to the respective market) is stored in $P_t^{\text{schedule,in,1}}$ and $P_t^{\text{schedule,out,1}}$ and incorporated in the optimization for the next market through Equation 5. More details are provided in [Pub3].

$$P_t^{\text{grid,in,i}} - P_t^{\text{grid,out,i}} + P_t^{\text{schedule,in,i}} - P_t^{\text{schedule,out,i}} = P_t^{\text{EV,charge,i}} - P_t^{\text{EV,discharge,i}} \qquad \textbf{(Eq. 5)}$$

Equation 6 represents the newly implemented objective function for multi-use cases involving behind-the-meter optimization, including a local PV system and in-front-of-the-meter market trading. The equation results from the superposition of Equation 3 and Equation 4. Electricity fed back into the public grid is differentiated for the EV and the PV system, as different prices/ remuneration fees apply.

$$min\left(\sum_{t=1}^{T}\begin{bmatrix} c_t^{\text{el,buy}} \cdot P_t^{\text{grid,in}} \cdot \Delta\text{t} \\ -\, c_t^{\text{el,sell,EV}} \cdot P_t^{\text{EV,discharge,2g}} \cdot \Delta\text{t} \\ -\, c_t^{\text{el,sell,PV}} \cdot (P_t^{\text{grid,out}} - P_t^{\text{EV,discharge,2g}}) \cdot \Delta\text{t} \end{bmatrix}\right) \qquad \textbf{(Eq. 6)}$$

Based on the respective objective function and additional simulation-specific constraints, the IBM CPLEX solver is used in MATLAB to solve the optimization problem. Relevant constraints and boundary conditions are presented in [Pub3]. A unique feature in eFlame that should be mentioned at this point is the possibility of implementing variable charging and discharging losses depending on the respective charging and discharging power. This requires inserting binary variables into the optimization problem (for more details, see [Pub3]). LP thus becomes MILP, which implies significantly increased computational effort. A further model development in the context of this work is the possibility to differentiate between taxes, levies, and grid fees (TLGFs) that apply to purchased electricity and TLGFs that apply to sold electricity (see [Pub3]). This is relevant for V2G use cases in Germany, as electricity fed from the EV back into the public grid is exempted from some of the TLGFs, if this electricity was previously charged into the EV from the public grid.

2.2.2 Selected key results

For the analysis in [Pub2], the following representative single-use cases are selected:

- V2H: PV self-consumption optimization
- V2B: peak shaving
- V2G: spot market trading (day-ahead and continuous intraday market)

A wide variety of input parameters, based on [15] and [44], is used to simulate the use cases with eFlame and determine a broad range of potential cost savings for bidirectional charging from 2020 to 2040 in 5-year steps. To account for additional technology costs, eight different cost components are considered, four of which prove to be quantifiable. By offsetting cost savings against additional costs, four development paths of net cost savings, hereinafter referred to as profits, are created and shown in Figure 7. For V2H, profitability is achieved from 2025 onwards for the optimistic as well as for the gloomy path. V2H use cases are therefore likely to generate profits in the near future. The comparatively small extent of the general profit range indicates that V2H is the least uncertain of the three categories. For V2B, profitability remains uncertain until 2040, yet if optimistic circumstances are considered, very high profits are achievable. The broad profit range for all years implies a high degree of uncertainty due to the heterogeneous electrcity consumption profiles of commercial businesses and industries. Profits for V2G fall in the middle between the two other categories. Profitability until 2040 is not certain but rather probable. Potentially high profits could be achieved in optimistic circumstances.

The assessment of the results shows that location parameters, i.e. existing hardware for metering or discharging, have the greatest influence on the additional technology costs. In terms of cost savings, parameters describing the user behavior, such as the probability of connecting EV and EVSE or driving patterns, are most influential. Price parameters, such as the general price level and price characteristics over time, are additionally important. Concerning future business models, [Pub2] found that the business model design is crucial to mitigate uncertainties and ensure profitability for potential EV users. Firstly, a careful selection of customer segments that fit

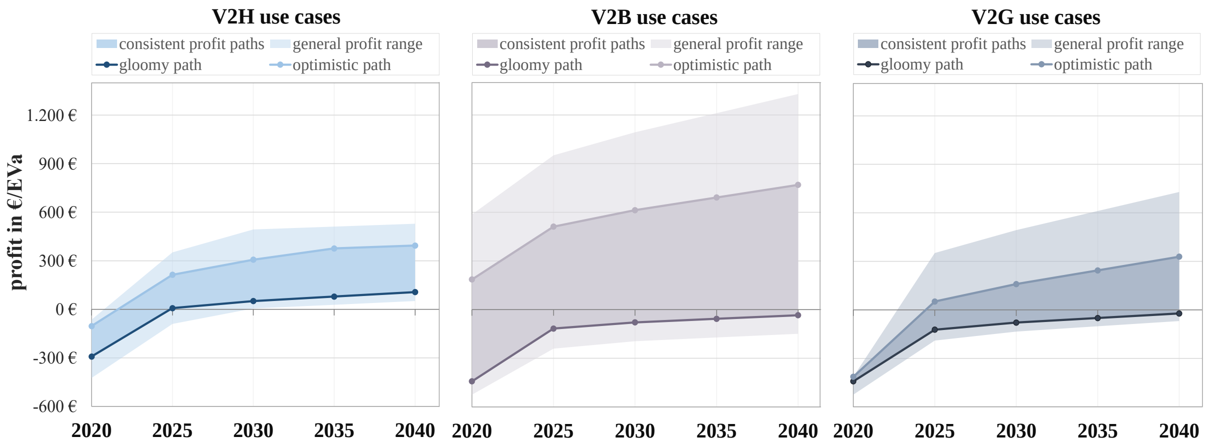

***Figure 7**: General profit ranges and consistent profit paths for the three categories of single-use cases of bidirectional charging [Pub2].*

the particular use case and circumstances is highly important. Secondly, pricing strategies should be tailored to the financial uncertainties of respective use cases, thereby sharing both profits and risks. Thirdly, non-monetary benefits, such as reducing operational GHG emissions or ensuring grid stability, should be incorporated into the value proposition of business models.

In [Pub3], the focus of the analysis is shifted. The primary objective is to evaluate realistic (net) cost savings and emission reductions for both smart charging and bidirectional charging use cases in contrast to direct charging today and in the future. The following three use cases are selected as representatives for this purpose:

- Sequential spot market trading (multi-use case, all three German spot markets) (V2G)
- PV self-consumption optimization (V2H)
- PV self-consumption optimization and spot market trading (multi-use case, continuous intraday market) (V2H + V2G)

Input parameters are defined to obtain as realistic results as possible. Variable losses are implemented, as reduced charging and discharging powers are to be expected at some times. 2021 is set as the base case for today. Relevant restrictions are that TLGFs are only exempted to the extent currently defined by German regulation for discharging electricity from the EV into the public grid and that charging and discharging hours (CHs) are limited to six hours per day to ensure durability of the electronics (see Section 1.1). 2030 is the base case for assessing the future. In 2030, the assumption is made that the amount of TLGFs to be paid on electricity discharged from the EV into the public grid is reduced to the level currently applicable to SBSs in Germany. Similarly, CHs are extended to twelve hours per day. Relevant sensitivities, which are additionally simulated, are restricting the EV users to non-commuters, reducing TLGFs for electricity discharged from the EV into the public grid (similar to base case 2030), lifting the restriction on CHs, and applying prices of 2022.

The results from the eFlame simulations concerning electricity cost savings and operational GHG reductions are summarized in Figure 8. The sensitivity analysis indicates that, similarly to the findings in [Pub2], cost savings range from around 100 €/(EV·a) to 1,300 €/(EV·a) for today and from 300 €/(EV·a) up to 2,700 €/(EV·a) in 2030.

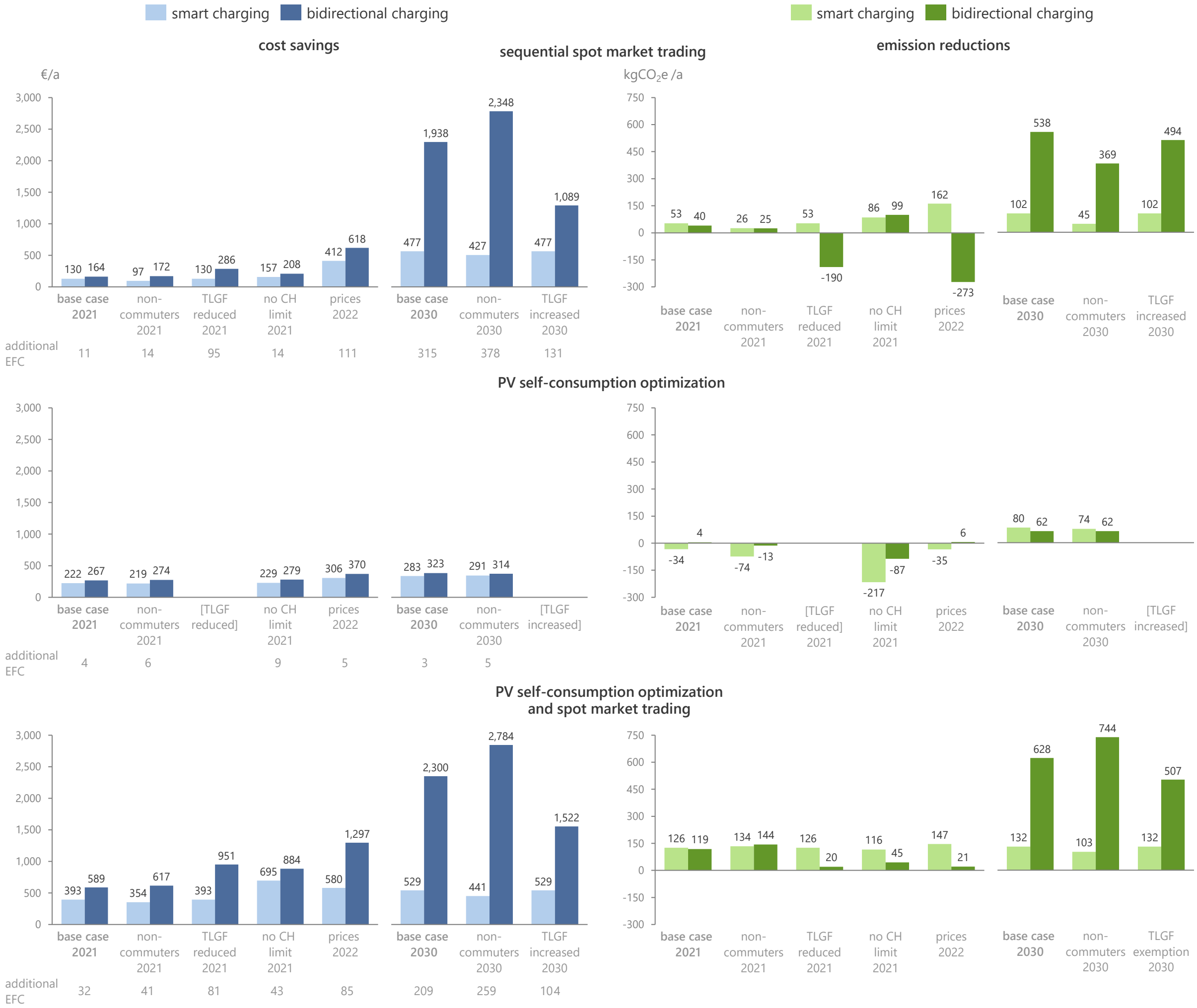

***Figure 8:** Electricity cost savings and operational GHG emission reductions of base cases and sensitivities for smart and bidirectional charging for all three use cases (average of 100 to 200 individual eFlame simulation results) [Pub3].*

Hence, high financial uncertainties accompany the three use cases. Taking additional technology costs into account (see [Pub3]), it is evident that bidirectional charging today is only profitable for sequential spot market trading and PV self-consumption optimization under positive circumstances. The multi-use case PV self-consumption optimization and spot market trading is already profitable for bidirectional charging today. Smart charging has generally lower additional technology costs and is therefore profitable today for all use cases. In 2030, all three use cases are very likely to be profitable, partly due to decreased technology costs.

Regarding operational GHG emission reductions, the results are ambivalent. In most sensitivities, operational GHG emissions are reduced for smart and bidirectional charging compared to direct charging. However, especially for PV self-consumption optimization and partly for sequential spot market trading, increased operational GHG emissions are presented in Figure 8. The main explanation for this finding is that variable charging and discharging losses are implemented in eFlame. For PV self-consumption optimization in particular, low charging and discharging powers occur to utilize self-generated PV power and to supply the household with this electricity. The resulting high losses increase the overall electricity demand, which increases operational GHG emissions. Another aspect of the explanation is that the GHG intensity of today's electricity generation is still comparatively high at certain times. When charging is carried out at these times, the operational GHG emissions increase. Again, it is important to note that the analyzed increased or reduced operational GHG emissions relate to the balance scope of the EV and the local system and thus provide an incentive from the user's perspective. From the system's perspective, however, this analysis does not determine how global GHG emissions change accordingly.

In summary, all three use cases evaluated in [Pub3] can provide benefits for today and 2030 from the user's perspective. Today, smart charging is more likely to be profitable largely because of lower additional technology costs, whereas bidirectional charging requires favorable circumstances to be profitable. Operational GHG emissions can already be reduced today, depending on the use cases and circumstances, but not in every case. In 2030, net cost savings and GHG emission reductions are highly likely for all investigated use cases.

2.3 Number of possible users per use case

Paper Title:	**Smart E-Mobility: User Potential in Germany Today and in the Future**
Authors:	Patrick Vollmuth, Kirstin Ganz, Timo Kern
Journal:	NEIS 2023 - Conference Proceedings, VDE, IEEE (2023)
Own contribution	Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – Original Draft Preparation, and Writing – Review & Editing.
Status:	published (see Appendix [Pub4])

Short summary: To contribute to current research on smart and bidirectional charging and to close an identified research gap, this paper presents a novel approach to calculate the number of potential EV users that can apply a respective use case regardless of the actual number of registered EVs. The number of potential EV users, referred to as user potential in the publication, is determined for 2021 and 2030 to assess developments over time. For a selection of ten single-use cases, two different types of user potentials are methodologically calculated for smart charging: the maximum user potential as an upper estimate of the maximum number of EV users and the achievable user potential as a more realistic measurement of the potential number of EV users that incorporates use case specific premises and further user limitations.
The assessment of the resulting user potentials for 2021 indicates that user potentials of some use cases are very high compared to the number of registered EVs in Germany today. Three of the investigated use cases display more than one million potential EV users as an achievable potential. However, other use cases show a relatively limited number of potential EV users, both as maximum and as achievable potential. In 2030, the user potentials of most use cases are increased. For two use cases, the achievable potential is more than three times as high as in 2021. In relation to the expected number of registered EVs in Germany in 2030, the user potentials are relatively lower than in 2021. The results are also largely applicable to bidirectional charging.

2.3.1 Methods and procedure

The selection of single-use cases to be assessed is based on the list of use cases (see [Pub1] or Table 1, Section 1.1). Those use cases are selected for which the number of potential EV users can be determined with sufficient substantiated data. For different use cases and years (2021 and 2030), different methodologies are used to calculate the two types of potentials, maximum and achievable user potential, for smart charging.

For the location-based behind-the-meter use cases, the number of feasible locations in Germany is determined in most cases. For PV self-consumption optimization, the number of buildings with roof-mounted PV systems of 1 kW to 20 kW nominal peak power is considered for the maximum user potential. For the achievable user potential, the number is reduced through the criterion that only private households are incorporated, as the primary location for this use case is at home (see Table 1). For peak shaving, the maximum user potential is based on the German electricity load curves of the industry and the commercial sector. The number of buildings that are subject to a recording load measurement (in Germany, locations with an annual electricity consumption higher than 100,000 kWh) is considered for the achievable user potential.

For market-oriented use cases (spot market trading, balancing services, redispatch provision via EVs), the number of potential EV users (n^{users}) is calculated via Equation 7 (simplified form). The average available power per EV ($P^{EV,avg}$) is defined as the product of the maximum charging power, the average vehicle availability at the charging location, and the reliable plug-in probability. Dividing the average annual net power traded on the relevant market ($P^{el,net}$) by the average available power per EV yields the number of potential EV users per market-oriented use case.

$$n^{users} = \frac{P^{el,net}}{P^{EV,avg}} = \frac{E^{el,net}/8760h}{P^{EV,avg}} \qquad \textbf{(Eq. 7)}$$

The data basis for $P^{el,net}$ is, in most cases, the amount of electricity that either directly corresponds to the market volume or indirectly reflects the maximum potential market volume ($E^{el,net}$). For the two different types of user potentials and for the two different years, separate data are used.

For day-ahead market trading, the total German final electricity consumption is the basis for the maximum user potential. The underlying assumption is that trading on the day-ahead auction indirectly sets the price for the entire electricity procurement, e.g. also for over-the-counter trading. The difference between the daily minimum and mean residual load constitutes the input for the achievable user potential. For trading on one of the intraday markets (intraday auction or continuous intraday), the traded market volumes are input for the maximum user potential. For the achievable user potentials, the respective market volumes are multiplied by a factor reflecting the times during the year for which market prices are below the daily mean price.

For balancing services (i.e. ancillary services), the tendered balancing power of the different balancing markets is used for the maximum potential. To calculate the achievable potential, the necessary redundancy for the offered balancing power, which will most likely become necessary when participating in one of the balancing markets using EVs, is taken into account. At this point, the issue arises that the achievable potential would become larger than the maximum potential due to the inclusion of redundancy. Hence, maximum and achievable potential are set equal for balancing services. For redispatch provision, the sorted German redispatch need per hour is considered as a data basis [79]. For the maximum user potential, the redispatch need for the 100 hours of the year, where the highest redispatch power is demanded, is considered. For the achievable potential, the respective redispatch need for the 2,500 hours of the highest redispatch power demand is used.

2.3.2 Selected key results

The user potentials 2030 of ten selected single-use cases, for which the number of EV users can be determined with substantiated data, are presented in Figure 9. Although the results are calculated for smart charging, they can equally be interpreted for bidirectional charging. The achievable user potentials for 2021 are displayed as dashed circles to provide a measure of the difference between the two years. The results are compared to each other and related to the number of expected EVs in Germany (8.2 million in 2030, see Figure 1).

The use case day-ahead auction (spot market trading) has the largest maximum user potential, which is larger than the expected number of registered EVs, as the total final electricity consumption in Germany is considered as the main input. The achievable user potential for the day-ahead auction, which takes the German mean residual load into account, constitutes a reduction of more than 40 % of the maximum potential. However, the achievable user potential still exceeds 60 % of the expected number of registered EVs in 2030. In comparison with the achievable user potential for 2021 (dashed circle), the number of potential EV users is more than three times higher. Considering an average available power of 6 kW per EV [Pub4], the achievable user potential for 2030 translates into 31 GW of flexible power. All user potentials of the three considered intraday markets are comparably small due to limited market volumes. Their development over time (compared to 2021) is minor. The sum of achievable user potentials of the intraday markets represents 10 % of the expected number of registered EVs and equals 5 GW of flexible power to be provided by EVs in 2030.

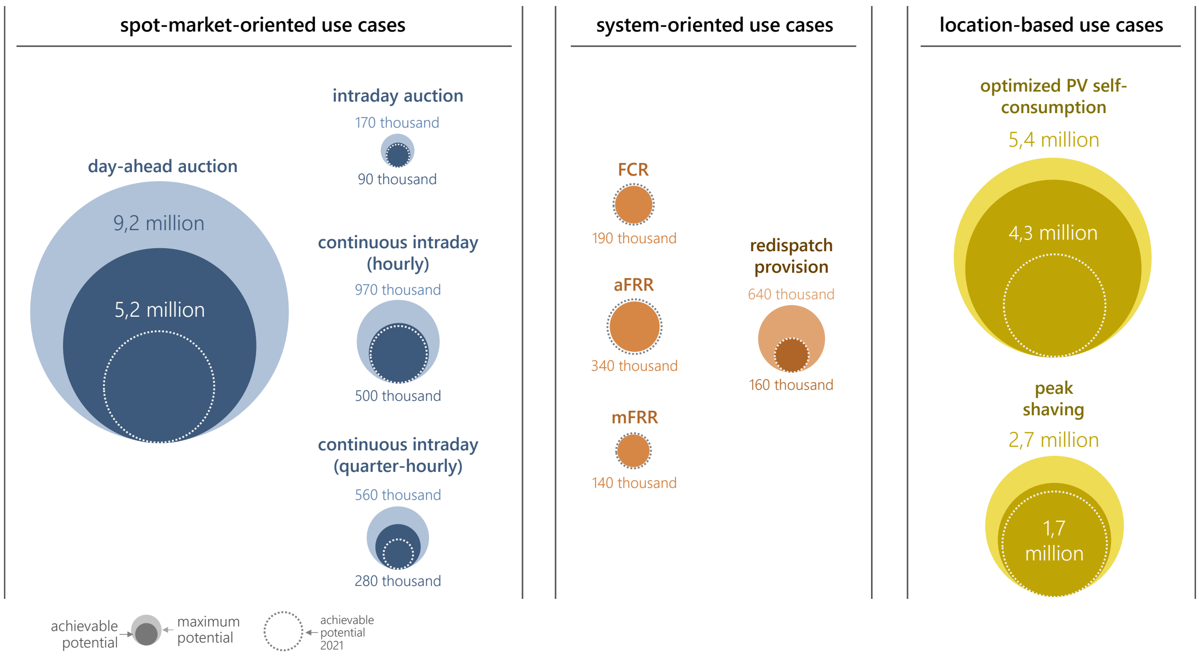

***Figure 9**: Maximum and achievable user potentials (number of potential EV users) for 2030; dashed circle show the achievable potentials for 2021 [Pub4].*

The user potentials of the system-oriented use cases (ancillary services) are comparably small. The user potentials of the three balancing services (FCR, aFRR, and manual frequency restoration reserve (mFRR)) are smaller for 2030 than for 2021. This is caused by a higher average available power per EV for 2030 than for 2021 due to an increased plug-in probability, while the tendered balancing power for the three balancing markets is kept constant in the absence of viable alternatives. The sum of the achievable numbers of EV users performing balancing services represents 8 % of the expected number of registered EVs in 2030 and translates into 4 GW of flexible power. For a potentially market-based redispatch provision via EVs, both maximum and achievable potential are comparably small. The achievable potential is among the smallest of all calculated potentials (2 % of the expected number of registered EVs) and is equivalent to 1 GW of flexible power. However, the difference between the maximum and the achievable potential is high, which reflects the high uncertainty associated with these use cases, where no market design has yet been established.

The user potentials of both location-based use cases are comparably large. The maximum and the achievable user potential of PV self-consumption optimization are both the second largest, following the day-ahead auction potentials. The difference between the two numbers of potential EV users is small, which reflects the reliability of the results for this use case. The achievable potential for 2030 is more than three times as high as for 2021, as a drastic increase in roof-mounted PV systems is projected. The achievable potential equals more than 50 % of the expected number of registered EVs in 2030 and translates into 26 GW of flexible power. For peak shaving, both maximum and achievable are comparably large with only a slight increase over time, since no general change in the regulatory framework or similar is assumed. 20 % of registered EVs in Germany could apply this use case in 2030, equivalent to 10 GW of flexible power.

To sum up, the calculated numbers of EV users vary significantly for the different investigated use cases. For some cases, such as day-ahead auction trading and location-based use cases, high user potentials are determined, especially when set in relation to the existing and projected number of EVs registered in Germany. At this point, it is essential to highlight again that the presented user potentials are not related to the actual number of registered EVs. For the other cases, the intraday markets and the system-oriented ancillary services, the calculated user potentials are relatively small. Consequently, the extent to which these use cases can be applied is limited. It is highly plausible that cannibalization effects of market prices and increasing competition will arise in the future. As an outlook, the underlying methodology could also be applied in a similar way for multi-use cases by calculating, for instance, the intersection of the potentials of the single-use cases involved.

3 Conclusions on the prospects of electric mobility as integral part of the future energy system

This chapter applies the results from Chapter 2 to draw conclusions on the prospects of smart and bidirectional charging. By consolidating and evaluating the results from a user's perspective, single- and multi-use cases that are likely to be implemented in the near future and key factors that influence the implementation prospects for users are identified in Section 3.1. Based on these findings, in Section 3.2, systemic benefits of the investigated use cases are discussed and deductions are made as to which key actions and concrete levers are best suited to promote the implementation of those use cases that are systemically beneficial. Section 3.3 provides a critical reflection on the findings and an outlook on the future of integrated electric mobility.

3.1 Differentiated evaluation of use case prospects from the user's perspective

In the following, the results of the four key publications of this work [Pub1] -[Pub4] are combined, consolidated, and visualized to allow a differentiated evaluation of the investigated single- and multi-use cases from a user's perspective. The results are consolidated by using two different forms of presentation. For one, Table 2 summarizes the results of all analyses by applying a color rating. For the other, Figure 10 illustrates the development of results over time through a timeline that combines the aspects from Table 2 for selected cases.

All single- and multi-use cases assessed in at least one publication are listed in Table 2. Blank spaces in the table indicate that not all aspects are analyzed for all use cases in [Pub1] -[Pub4], but instead representative cases are selected. Results for today are based on the year 2021 for the majority of aspects. Only the net cost savings for peak shaving and balancing services (FCR) are based on 2020 data [Pub2]. 2020 and 2021 show a degree of change in price characteristics due to the COVID-19 pandemic but not the extreme price volatility and surges that mainly occurred in 2022 due to the global gas prices crisis.

The **technical implementation effort** [Pub1] is presented in effort units (no physical equivalent, see Section 2.1) rounded to the nearest ten for two charging locations (at home and at work). The color rating covers the entire range of values from maximum effort value (red) to minimum effort value (dark green).

For the **number of potential users** in million users [Pub4], the color rating ranges from no potential (red) to the highest potential of the respective potential type (dark green).

For **net cost savings**, the annual additional costs for smart charging and bidirectional charging, which are annualized using the approach expressed in [Pub2], are subtracted from the average cost savings resulting from all simulations of the respective use cases for today and 2030 [Pub2]. The net cost savings are expressed per EV and year and rounded to the nearest ten. The color rating extends from negative net cost savings (red) to at least 500 €/(EV·a) savings (dark green) for an average user. Higher values translate into higher profits for the involved parties (users, manufacturers, flexibility service providers) but not necessarily into an overall higher number of use case implementations. Whether a case is, in fact, profitable for all involved parties for net cost savings between 0 €/(EV·a) and 500 €/(EV·a) strongly depends on the circumstances and individual situation,

***Table 2**: Quantitative summary of use case assessments with color rating for each category*

	Technical implementation effort (in effort units)		Today: Number of potential users in mil.		Today: Smart charging		Today: Bidirectional charging		2030: Number of potential users in mil.		2030: Smart charging		2030: Bidirectional charging	
Use cases/ multi-use cases	at home	at work	maxi-mum potential	achiev-able potential	net cost savings in €/(EVa)	emission reduction in kg/(EVa)	net cost savings in €/(EVa)	emission reduction in kg/(EVa)	maxi-mum potential	achiev-able potential	net cost savings in €/(EVa)	emission reduction in kg/(EVa)	net cost savings in €/(EVa)	emission reduction in kg/(EVa)
PV self-consumption optimization	40		1.8	1.4	150	-110	20	-30	5.4	4.3	220	80	190	60
Peak shaving		50	2.6	1.5	60		50		2.7	1.7	110		270	
Market-oriented price signal (based on day-ahead market)	60	70	9.2	1.7	-10	10	-70	30	9.2	5.2	80	60	690	520
Spot market trading (day-ahead market)	80	80	9.2	1.7	10	10	-20	40	9.2	5.2	90	70	900	580
Spot market trading (intraday market)	80	80	1.2	0.6	50	30	70	30	1.7	0.9	270	70	1,330	500
Balancing services (FCR)	80	80	0.2	0.2	80		130		0.2	0.2	120		240	
Emergency power supply	20													
Dynamic grid fees	70	80												
Grid-serving power range dimming (§ 14a)	60	70												
Redispatch provision	90	90												
Reactive power provision	40	40												
PV self-consumption optimization + Spot market trading (intraday market)	90		1.2	0.6	310	130	570	100	1.7	0.9	420	120	2,070	630
Sequential spot market trading (day-ahead and intraday markets)	90	100	1.2	0.6	90	60	150	-10	1.7	0.9	380	70	1,660	470
Market-oriented price signal (based on day-ahead market) + Dynamic grid fees	70	80												
Balancing services (FCR) + Spot market trading	90	90	0.2	0.2					0.2	0.2				
Balancing services (FCR) + Redispatch provision	100	100												
PV self-consumption optimization + Spot market trading + Balancing services (FCR)	100		0.2	0.2					0.2	0.2				
Spot market trading + Balancing services (FCR) + Redispatch provision	110	100												
Spot market trading + Dynamic grid fees + Redispatch provision	120	120												
Balancing services (FCR) + Dynamic grid fees + Redispatch provision	100	120												

maximum effort value/ zero number of users/ negative cost savings/ negative emission reduction

minimum effort value/ maximum number of users/ cost savings above 500 €/EVa/ emission reduction above 500 kg/EVa especially as the savings must be divided among all parties and each party expects a minimum margin of profit. Concerning operational GHG emissions, the average annual **emission reductions** resulting from the simulations of 2021 and 2030 in [Pub3] are presented rounded to the nearest ten. The presented values are not global emission reductions but reductions from the user's perspective. From the system's perspective, reducing operational GHG emissions does not automatically translate into a reduction in global GHG emissions, especially since the EU-ETS applies. Similar to the net cost savings, the color rating ranges from negative emission reductions (red) to reductions of 500 kg/(EV·a) and higher (dark green). Values higher than 500 kg/(EV·a) imply even higher emission reductions but the exact magnitude is not decisive when implementing the respective case.

In Figure 10, the developments of average net cost savings and achievable numbers of users over time are visualized via color-coded, widening planes for smart charging (upper part of the plane) and bidirectional charging (lower part of the plane) from 2024 to 2030 for selected single- and multi-use cases. The selection of cases is made based on sufficient data provided in Table 2. The timeline runs equidistantly from mid-2024 to mid-2030. For the **net cost savings**, the results of today (2020/ 2021) and 2030 are linearly interpolated and displayed from mid-2024 onwards using a similar color rating as in Table 2. Operational GHG emission reductions are not displayed, firstly because operational GHG emissions are calculated only for a reduced number of use cases and secondly because cost savings are generally more relevant in terms of user-driven use case adoption.

For the **achievable number of users**, the values of 2021 and 2030 are linearly interpolated in Figure 10. The resulting user numbers starting from mid-2024 are presented as the total width of the colored planes (no differentiation between smart charging and bidirectional charging). The **technical implementation effort** is accounted for indirectly through the white-colored sections at the beginning of the planes. The length of the white sections is equivalent to the implementation effort. This illustrates that more complex use cases are more likely to be implemented at a later time, as technical complexity is usually accompanied by other challenges, such as the availability of software, providers, or market access. The white section is explicitly not a measure of the availability of technical components necessary to implement the use cases.

The use cases for smart charging and bidirectional charging are evaluated based on the consolidated results of Table 2 and Figure 10. The multi-criteria color rating in Table 2 provides a differentiated picture in this regard. Concerning **single-use cases** today, all cases are rated either as negative or only slightly positive in at least one aspect. Users of cases in which net cost savings or emission reductions are rated as negative are likely to face adverse consequences instead of benefits if they were to implement the respective case today. This holds true for smart charging and bidirectional charging, with the emission reductions being slightly lower for smart charging and the net cost savings tending to be slightly lower for bidirectional charging on average.

PV self-consumption optimization via smart charging and balancing services (FCR) via bidirectional charging are the two single-use cases that display net cost savings of a magnitude that might be sufficient for users to implement the cases today [80, 81]. For PV self-consumption optimization via smart charging today, operational

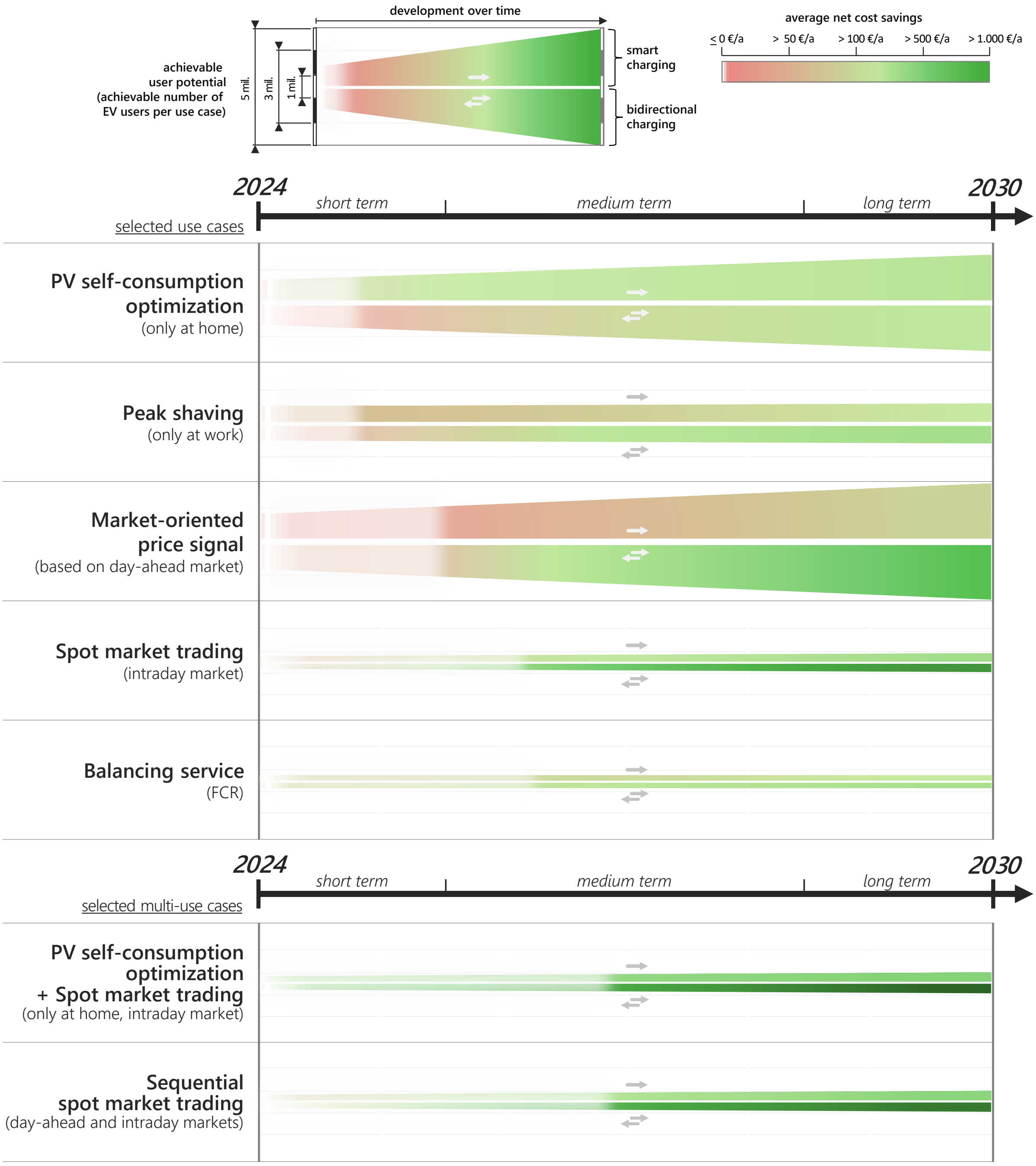

***Figure 10**: Visualization of development of achievable number of users (width of plane) and net cost savings (color of plane, differentiated for smart charging (upper part) and bidirectional charging (lower part)) over time from 2024 to 2030; white sections at beginning of plane represent implementation effort.*

GHG emissions are not reduced but increased (see Section 2.2). For balancing services (FCR) via bidirectional charging today, the number of potential users is comparably small, which translates into a limited FCR market volume (see Section 2.3). Hence, both use cases exhibit unfavorable aspects. Consequently, none of the investigated single-use cases is considered sufficiently beneficial from a user's perspective for smart charging or for bidirectional charging today. The use cases will most likely not be implemented on a large scale in the short term (approximately until the beginning of 2026). The generally positive rating of the technical

implementation effort for single-use cases does not change this conclusion, as the rating alone provides only a partial indication of the technical feasibility of the use cases.
Taking the findings of Figure 10 into account, some single-use cases are likely to be generally beneficial from a user's perspective in the medium term (approximately from the beginning of 2026 until the end of 2028). For smart charging, PV self-consumption optimization is the first case to be reliably profitable for all parties involved. Operational emissions are reduced, and the achievable number of users increases over time (see Table 2). The case will thus provide multiple user benefits at manageable implementation complexity from the early medium term onwards. Secondly, the smart charging use case spot market trading (intraday market) yields sufficient net cost savings and reduced operational emissions in the medium term while the technical implementation effort becomes gradually manageable. Whether profitability or implementation complexity will be the last remaining limiting factor for implementation is uncertain. However, the number of potential users remains limited for the investigated time horizon, representing a limiting factor in possible EV users.
The use cases peak shaving and balancing services (FCR) become sufficiently profitable only in the long term (approximately from the beginning of 2029) when using smart charging since the cost savings are less increasing over time than in other cases. The comparably high implementation effort of balancing services (FCR) will most certainly not be the limiting factor in this case, but relatively low net cost savings are. As for smart charging using a market-oriented price signal based on the day-ahead market, charging cost savings are assessed to be not high enough to consider the case as unequivocally profitable for all parties involved by 2030 when taking the additional costs into account (see [Pub3]). This is the only case that is not highly likely to become financially beneficial by 2030 for smart charging. The same holds true for the use case of spot market trading (day-ahead market) via smart charging, which is not displayed in Figure 10, as it is very similar to the market-based price signal use case.

Different conclusions are drawn for the medium and long term for bidirectional charging. In general, all single-use cases are likely to become profitable for all parties involved by 2030 at the latest. PV self-consumption optimization is not the first use case to become profitable, but the last one. The case is only expected to be profitable in the late medium term. The main reason for this finding is that high additional costs for bidirectional charging render the use case financially unattractive for a considerable time. While electricity cost savings are already relatively high today, simulation results predict that these will only increase slightly until 2030 (see Section 2.2). The degression of additional costs is the main driver that causes the case to become profitable in the late medium term. In terms of profitability, spot market trading on the intraday market shows the highest and earliest economic potential due to substantial arbitrage trading. Operational GHG emissions are also reduced for spot market trading from today onwards. Yet, the comparably high implementation effort still leads to the conclusion that spot market trading is not the first case that will be feasible and beneficial for users.
The same reasoning applies to providing balancing services (FCR) via bidirectional charging. The case is likely to become profitable in the early medium term, but the technical complexity of implementation might limit its actual large-scale implementation to the late medium term. Still, as soon as spot market trading or balancing services become practically feasible for bidirectional charging, the findings suggest that these use cases will be

profitable or, in the case of intraday trading, even highly profitable and thus become swiftly implemented on a large scale. For all V2G cases, the increased levies exemption on electricity fed back from an EV into the grid is assumed for 2030 (see Section 2.2 and [Pub3]). Due to the interpolation between today and 2030, conclusions on net cost savings must be seen as a simplification. In particular, no definite conclusions can be drawn on the actual year of profitability. Another complicating factor is that both use cases are characterized by a low number of potential users that may lead to cannibalization effects (i.e., price erosion due to an excessive supply of flexibility) on the respective markets. Such cannibalization effects, which the applied simulation model does not cover, reduce market price spreads and thus limit potential electricity cost savings.

Unlike smart charging, the two use cases, peak shaving and market-based price signal (based on day-ahead market), are the first to combine financial benefits, manageable implementation efforts and a high number of users when using bidirectional charging. Hence, these two single-use cases of bidirectional charging are likely to be implemented on a larger scale slightly later than PV self-consumption optimization via smart charging.

No substantiated conclusions regarding future prospects can be made concerning single-use cases, which are not analyzed in detail apart from their implementation efforts. Generally speaking, those cases are mostly complex in terms of regulatory requirements (redispatch provision is also complex in terms of implementation effort). Nevertheless, most use cases could become beneficial from a user’s perspective in the medium or, more likely, in the long term. One exception is the case of grid-serving power range dimming (§ 14a). This case is mandatory in Germany as of 2024 and must be implemented across the board in the short term. Despite the obligation for implementation, financial benefits from the user's perspective are likely to arise due to the regulatory-defined reduction in grid charges.

Concerning **multi-use cases**, the results of the implementation effort in Table 2 indicate that none of the multi-use cases will be implemented today or in the short term, as combining multiple cases inevitably leads to increased complexity. Although the case of PV self-consumption optimization plus spot market trading (intraday market) is found to be beneficial today in terms of net cost savings and operational emission reductions, it will most likely only become feasible in the medium term. As soon as this multi-use case becomes feasible, very high profits and high emission reductions are expected. Especially for bidirectional charging, profits as high as 2,000 €/(EV·a) are determined for 2030. From a user's perspective, this constitutes the most beneficial case for both smart and bidirectional charging. However, the number of EV users able to apply this case is limited to the intraday market volumes, such that even the maximum number of potential users does not exceed 1.7 million in 2030. Still, considering the day-ahead market for arbitrage trading in combination with PV self-consumption, the maximum number of users rises to 5.4 million in 2030. The net cost savings of this multi-use case would be less than when trading on the intraday markets but still sufficiently high to render the case profitable as soon as it becomes technically feasible.

The second multi-use case evaluated in detail, sequential spot market trading, is less beneficial today and in the short term than the previously mentioned. Net cost savings when using smart charging may not be sufficiently high today to provide profitability for all parties involved. From the early medium term onwards, net cost savings are most likely sufficiently high. For bidirectional charging, net cost savings are already high enough today, but operational emissions are, on average, increased instead of reduced. This changes over time due to the higher correlation between market prices and GHG emissions, so the case becomes beneficial in all investigated aspects in the early medium term. Hence, similarly to PV self-consumption optimization plus spot market trading, it is likely that sequential spot market trading will be implemented on a large scale as soon it becomes feasible. Especially in comparison to single-use case spot market trading, this case provides the prospect of increased profits with only a slight additional implementation effort. The number of potential users of sequential spot market trading and single spot market trading on the intraday markets is identical. Yet, since different markets are incorporated, the danger of cannibalizing market prices is reduced for sequential spot market trading. Thus, users will likely switch from single market trading to sequential market trading when it becomes possible.

Concerning user potentials, no conclusions are possible for use cases that include any single-use case for which no number of potential users has been determined. Net cost savings are at least as high (most likely higher) as the savings of the most favorable single-use case that is part of the respective multi-use case. The operational emission reductions might be lower for a multi-use case than for any of the included single-use cases, as minimizing emissions is not the objective in any of the cases. Hence, the multi-use case of market-oriented price signal (based on day-ahead market) plus dynamic grid fees will likely be profitable for bidirectional charging in the medium term and for smart charging in the long term at the latest.

Balancing services (FCR) plus spot market trading will be profitable as soon as it becomes feasible for both smart charging and bidirectional charging. Still, the number of users is limited to the potential of the FCR market in this case. Including the aFRR market in the multi-use case could broaden the number of users while net cost savings would most likely not be reduced much (see also Section 1.1), even though the technical requirements for aFRR are different from those for FCR. The same argumentation and implications hold for PV self-consumption optimization plus spot market trading plus balancing services (FCR). For all multi-use cases involving redispatch provision, a high complexity and high implementation effort is predicted, which implies that such use cases will be implemented only in the long term at the earliest. Apart from that, no further conclusions can be drawn, as no redispatch market for small-scale, flexible assets exists as of now.

To sum up, the **main conclusions** from a user's perspective are listed in short:

- None of the assessed use cases combines benefits in all investigated aspects today or in the short term at a manageable implementation effort. Instead, the use cases become holistically beneficial over time.
- For smart charging, PV self-consumption optimization is likely to be the first use case to be implemented on a larger scale, even though operational GHG emissions are not necessarily reduced in the short and early medium term.
- For bidirectional charging, peak shaving is likely to be the first use case to be implemented on a larger scale, whereas PV self-consumption optimization only becomes profitable later in the medium term.
- For some use cases of bidirectional charging, the linear interpolated price degression of additional costs is more decisive for profitability than the change in operational cost savings over time.
- The prospects of multi-use cases are excellent from the medium term onwards, as they are generally more and earlier beneficial than single-use cases in terms of net cost savings and, in some cases,

operational emission reductions. However, implementation complexity and the number of potential users limit their implementation to the medium term.

- All use cases that involve spot market trading (day-ahead and intraday) are likely to be implemented in the future on a larger scale, especially for bidirectional charging, as these use cases show high or even very high net cost savings and high operational emission reductions in the medium and long term.
- Concerning the prospects of use cases that involve intraday and balancing markets, the number of potential users is limited, especially in proportion to the future number of EV users in Germany, regardless of the cases' profitability or operational emission reductions.
- The prospects of all use cases in 2030 are considered very positive, with high net cost savings and operational GHG emission reductions, where bidirectional charging, in contrast to today, is considered even more beneficial than smart charging.

3.2 Cornerstones to integrate electric vehicles into the energy system

While Section 3.1 examines the prospects of smart charging and bidirectional charging from the user's perspective, this section takes a systemic point of view. First, the systemic benefits of the use cases under consideration are briefly discussed to classify the use cases in terms of their value to the system. Second, the evaluation of the user-driven implementation prospects of the use cases, including the most important influencing factors, is merged with the systemic use case classification to establish so-called cornerstones of action. These cornerstones summarize key fields of action that are needed to integrate smart and bidirectional charging into the energy system in a fast and systemically beneficial manner. Concrete levers that facilitate the systemically beneficial use case integration are derived for each cornerstone. The levers are primarily based on the most important influencing factors of the user benefits assessment and relate to the domains of regulation, user behavior, business model design, and technological development.

3.2.1 Discussion of systemic benefits of use cases

From the system's perspective, use cases that reduce overall system costs and emissions are beneficial. As the energy system is complex and many interdependencies exist, different use cases work in different ways and show varying advantages and disadvantages from a system's perspective. Smart charging and bidirectional charging strategies can, for example, increase the overall efficiency of the system or reduce the necessity to invest in other technologies. Some use cases might increase grid stability on the transmission grid level, whereas others may reduce the risk of grid congestions on the distribution grid level. In particular, assessing changes in systemic GHG emissions is challenging, as the EU-ETS represents a system for trading emission certificates within the EU, which could mean that emission reductions in one place may lead to additional emissions elsewhere. The following discussion is structured in accordance with the use case categories introduced in Section 1.1, Table 1.

Grid-serving use cases are generally beneficial for the energy system, as EVs that might otherwise have a negative effect on the electricity grids are charged and potentially discharged in a grid-serving manner. As grid and system stability is the primary objective, use cases in this category are most definitely systemically beneficial. The label grid-serving use case comprises both cases that support the distribution grid and cases that support the transmission grid. At the distribution grid level, the use case grid-serving power range dimming (§ 14a) represents a curative measure to dissolve existing local grid congestions, whereas the use case dynamic grid fees is a preventive measure to reduce peak grid loads in an efficient and non-discriminatory way. Well-designed dynamic grid fees may be more cost-effective than grid-serving power range dimming (§ 14a) [82]. At the transmission grid level, balancing services and redispatch provision represent the relevant ancillary services for the German system. Both use cases are systemically beneficial, as they support the transmission grid stability. For the same reason, reactive power provision is systemically beneficial.

The systemic effects of market-oriented use cases can be beneficial in many situations. Flexibility provided through use cases that involve spot market trading increases supply, particularly at times of high prices, and thus generally reduces procurement costs in the respective market. As shown in [7], spot market trading via bidirectional charging not only reduces electricity prices but also enables better integration of variable RES and lower installed capacities of SBSs and gas- or hydrogen-fired power plants. The main concern with market-oriented use cases is that without appropriate countermeasures, charging and discharging simultaneity of EVs increases significantly due to the uniform price signal to which all available EVs react. In extreme cases, when a high number of EVs participates in the markets, the resulting rise in power demand could lead to an increased risk of grid congestion at the distribution grid level [6] or an increase in redispatch need at the transmission grid level [83]. Combining market-oriented use cases with grid-serving use cases, such as grid-serving power range dimming (§ 14a), dynamic grid fees or redispatch provision, constitutes an effective means to increase systemic benefits for market-oriented use cases. However, obtaining systemic benefits at both the distribution grid and transmission grid level for a multi-use case that includes a market-oriented single-use case is arguably challenging. The charging simultaneity can be additionally reduced for multi-use cases that include market-oriented and local behind-the-meter use cases [35].

Systemic benefits of local behind-the-meter use cases are not always unambiguous, as the primary objective of these cases is local optimization (see Section 2.1). For PV self-consumption optimization, systemic costs are, in fact, reduced, as less electricity generation by renewable energies is curtailed and fewer additional SBS are needed to provide systemic flexibility. The residual load of the system becomes less volatile which entails less volatile electricity prices. At the same time, the market values for renewable energies are increased in 2030. [34] However, the use case complicates the prediction of electricity consumption in private homes for the grid operators, in particular as PV forecasting is necessary. This could, in turn, lead to the application of more grid-serving mechanisms but could also reduce grid load during times of high PV generation. Furthermore, operational GHG emissions decrease for future years but not necessarily today due to high losses (see Table 2 and Section 2.2). The case is thus systemically beneficial in principle but not as conclusive as market-oriented or grid-serving use cases. Concerning peak shaving, the effect of power peaks being avoided or reduced to the lowest possible value through the use case is a systemic benefit. The grid load can be reduced and grid expansion can even be prevented in some situations [6]. Emergency power control has no influence on the system until a power failure in the public grid occurs (blackout). Under such circumstances, the use of bidirectional chargeable EVs enables the local restoration of the power supply in a cost-efficient manner, as no additional assets are required. The power supply with EV batteries is lower in emissions than with fossil-fired generators. The use case is thus systemically beneficial.

For multi-use cases, the systemic benefits of the single-use cases overlap, but not all single-use case benefits are added up. From a system's perspective, multi-use cases are preferable to the included single-use case, which has the lowest systemic benefit. A multi-use case that comprises, for example, a local behind-the-meter use case is most likely systemically more beneficial than the corresponding local behind-the-meter single-use case but not necessarily more beneficial than a different grid-saving single-use case. The systemic benefit of multi-use cases can therefore only be judged with reference to the single-use cases involved.

To conclude, all use cases of smart charging and bidirectional charging can be systemically beneficial, albeit to varying degrees and in different aspects. Grid-serving use cases are generally systemically beneficial and especially, when there is a need for grid-serving measures that limit or prevent grid expansion. The implementation of grid-serving use cases should thus be prioritized in the medium and long term.

Market-oriented use cases are systemically beneficial in different aspects as long as charging simultaneity does not cause systemic instability. In the short and medium term, the risk of frequent grid congestion at the distribution grid level in Germany is relatively low, not only but also because not that many EVs are on the roads yet [6, 82]. At the transmission grid level, high grid loads and potential grid congestions are becoming increasingly common in some regions. Hence, implementing market-oriented use cases today can be systemically beneficial, yet the risk of grid congestion must be mitigated. Multi-use cases that combine both market-oriented and grid-serving aspects are very effective in this regard and the implementation of such multi-use cases should be prioritized over market-oriented single-use cases. Local behind-the-meter use cases are also systemically beneficial in most situations, but their systemic effect is not as positive as in other cases. For this reason, local behind-the-meter use cases are primarily useful for promoting smart and bidirectional charging among users in the short term and advancing technology ramp-up. In the long term, other use cases are more favorable from a system's perspective. Nonetheless, multi-use cases that involve local behind-the-meter cases are a sensible compromise between user acceptance and systemic benefits. In combination with market-oriented use cases, these cases can also be used to reduce charging simultaneity.

3.2.2 Deriving key actions and concrete levers for system integration

The previous discussions and further insights from the field trials within the unIT-e² project [14] constitute the basis for deriving **four fundamental cornerstones of action** for a systemically beneficial integration of EVs into the energy system. For each cornerstone, concrete levers to facilitate the systemically beneficial integration are described.

1) Provide attractiveness and easy use case access for end users

All assessed use cases are systemically beneficial. The aim of the first cornerstone is thus to enable the large-scale adoption of smart charging and bidirectional charging use cases in general. As mentioned above (Section 3.1), the key to large-scale adoption of use cases is providing sufficient user benefits. The following levers intend to increase overall user benefits. Furthermore, users must be equipped to understand the often complex use cases and their benefits. For this reason, additional levers are listed that facilitate the accessibility of smart charging and bidirectional charging.

Concrete levers are:

- Enabling the implementation of local behind-the-meter use cases first: These use cases are not the most systemically beneficial cases, but they are highly attractive for users, also because optimization takes place locally. Both PV self-consumption optimization (at home) and peak shaving (at work) have a significant number of potential users [Pub4]. Thus, the use cases enable the broad adoption of smart charging and bidirectional charging.
- Facilitating reliable user benefits through user-centered business models: From the providers' side, the business model design can mitigate or even eliminate existing adoption hurdles. For instance, regulatory and contractual complexities can be handled by the provider instead of the user being responsible. A possibility to lower the initial investment hurdle, as part of the business model, is to spread the high purchase costs for a smart or bidirectional EVSE over several years rather than charging a single sum at the start [Pub2]. To avoid that users are paying more instead of saving costs due to unfavorable price developments, safety mechanisms can be defined that limit the maximum electricity costs. Such safety mechanisms are already being applied by some of the first existing providers of variable electricity tariffs [46, 47, 49].
- Offering Individualized solutions for specific user groups: As found in [Pub2] and [Pub3], some user groups with replicable behavior patterns display higher user benefits than others. For example, electricity cost savings are generally higher for non-commuters than for commuters [Pub2] due to a higher EV availability at the charging location. As the average annual mileage of non-commuters is lower than the mileage of commuters, batteries of non-commuter EVs could be used to a greater extent for bidirectional charging. Another example is that users, who own a small-sized PV system, might not benefit financially from the use case PV self-consumption optimization, as losses might be too high for the system to operate sufficiently efficiently. Some users might be additionally incentivized by the prospects of reduced operational GHG emissions. Thus, customized consultation tailored to specific behavioral patterns and circumstances as well as setting individualized boundary conditions for implementation enhance user benefits and lead to a faster adoption of use cases.
- Providing explicit but uncomplicated explanations of both personal benefits and expenses associated with smart charging and bidirectional charging for potential users: All relevant information regarding a respective use case should be easily accessible. Complicated matters should be presented in simple terms and users should not be overloaded with information. Nevertheless, both the user benefits and

potential drawbacks should be clearly stated either by the providers (as they are in contact with users) or, in order to convey more credibility, by independent parties (e.g. researchers, associations, consumer protection organizations).

- Developing plug-and-play systems that are easy to put in operation: For users to quickly adopt the technology, the system must be easy to set up and operational right away (plug-and-play). Any kind of technical malfunction or long startup times dissuade users. Especially as many backend connections are currently implemented on the basis of proprietary interfaces [Pub1], this should be taken into account during technical development.

2) Accelerate the implementation of market-oriented use cases

Market-oriented use cases are well suited to combine potentially high user benefits, especially prospects of high cost savings (see Section 3.1), with systemic benefits, i.e. market flexibility and increased integration of variable RES (see Section 3.2.1, [7]). The implementation of these use cases should therefore be accelerated.

Concrete levers are:

- Offering simple, understandable tariffs to users: Users should not be overwhelmed by the complexity of market-oriented use cases. The offer from corresponding flexibility providers should emphasize the financial benefits for the user as simply as possible. This does not necessarily require an understanding of the spot market structures. It is sufficient to create the motivation to connect the EV to the EVSE whenever possible and to grant the provider access to optimize the charging strategy. Simplifying tariffs for the user can be done, for example, by defining fixed time periods during which the charging price is lowered, as offered by [49], or by setting a generally lower but constant charging price, as currently offered by [48].
- Simplifying and clarifying regulations, especially for bidirectional charging: A number of regulatory issues are still unresolved, in particular when it comes to storing electricity and feeding it back into the grid later (V2G). For example, the EVSE has already been defined as the regulatory equivalent of the SBS for some TLGFs [Pub3]. For others (e.g., grid fees or electricity tax), no definition has yet been established and it is still being discussed whether to define a mobile storage (i.e. the EV battery) or the EVSE as the reference point [11]. Furthermore, decisions made at the EU level, such as the European Data Act [84], have not yet been transposed into German law, which creates a degree of uncertainty for all parties involved. Another issue that affects both smart and bidirectional charging is, the fact, that grid codes for connecting EVSE differ from country to country, thus hindering the uptake of smart and bidirectional EVSE.
- Creating a level playing field with SBS: Currently, SBS only have to pay a fraction of the total TLGF on the electricity fed back into the grid, if certain criteria are met. This extensive regulatory exemption on TLGF does not exist to the same extent for bidirectional charging [11]. A concrete regulatory measure

could be to allow the same exemption from TLGF for V2G under the same criteria as for SBS. As a result, increased profits can be expected, which greatly improves the prospects of V2G [Pub3].

- Increasing profits via technological advancement: EV manufacturers can give even greater consideration to the most critical requirements of smart charging and bidirectional charging when engineering the vehicle. Designing the vehicle electronics and the control unit circuits for many operating hours and the EV battery for many equivalent full cycles would greatly benefit the profitability and thus the adoption of market-oriented use cases [Pub3, 44]. The same reasoning applies to the other component manufacturers involved. The better the component is adapted to the requirements of the use cases, the less resource-intensive and more efficient the system operates.
- Providing the appropriate system for a use case or the appropriate use cases for an existing system: The larger the EV's battery capacity, the more energy can be offered on the energy markets, e.g. the spot markets. The greater the charging power, the more power can be offered on capacity markets, such as the FCR market. [Pub2] If, in addition to EVs, other flexible assets such as heat pumps or SBS are available, an EMS for orchestrating the optimization is definitely advisable [Pub1]. Hence, the local technical system should be sized and designed in such a way that it is as suitable as possible for the respective use case or the use case should be selected in such a way that best suits the circumstances and local limitations.
- Taking potential market and user limitations into account: The number of potential EV users for market-oriented use cases is limited by the respective market volume and the EV availability [Pub4]. Market constraints also apply, such as a product length of four hours for FCR. These limitations should be considered in particular when estimating potential profits or operational GHG emission reductions, so that users are given a realistic assessment of the benefits.

3) Ensure that local electricity grids are not affected by smart and bidirectional charging use cases

Grid stability is a prerequisite for a functional energy system. Not only the future increase in EVs, but also the potential rise in smart charging and bidirectional charging use cases complicates the planning processes of grid operators [6]. The use cases are physically restricted by the capacities of the electricity grid and grid overload is not in the best interests of use case providers. Grid constraints and grid-serving use cases should thus be taken into account when designing and implementing a market-oriented or behind-the-meter use case.

Concrete levers are:

- Harmonizing market-oriented and system-serving use cases: Since market-oriented use cases, in particular, could lead to high charging simultaneities and consequently pose the risk of local grid congestions, those cases should be combined with grid-serving use cases and implemented as multi-use cases in the future. As the case grid-serving power range dimming (§ 14a) is already mandatory for private users in Germany, providers of market-oriented cases need to develop appropriate multi-use cases in any case. One way to combine preventive grid-serving use cases with market-oriented use cases is to establish a data exchange between providers and grid operators.

- Implementing the use case grid-serving power range dimming (§ 14a) fast, effectively, and comprehensively: As a curative measure against grid congestion, the use case is finally defined in Germany. The technical implementation has already been tested and approved in the unIT-e² project [9]. The case must now be implemented quickly across all providers. As mentioned above, it should be recognized that in most smart charging and bidirectional charging situations, the case will be part of a multi-use case.
- Reforming the German grid fee regulatory system to create preventative measures that can avert grid congestion: Today, only the curative measure grid-serving power range dimming (§ 14a) is possible in Germany. No other potentially preventative measures are feasible under the current regulation. In the future (medium to long term), however, such measures will be sensible for the distribution grid operators to avoid excessive usage of the curative measure. Possible preventative measures are, e.g., dynamic grid fees, which take into account the time-dependent grid status, an auction mechanism for grid capacities, or a staggered capacity charge [21].
- Digitalizing the electricity distribution grids: At present, hardly any German distribution grid operator is able to predict the local grid status due to a lack of digital data measurement [14]. However, grid status prediction is a prerequisite to implementing preventative grid-serving measures such as dynamic grid fees. Hence, distribution grid operators must digitalize their grids rapidly and on a large scale. The required grid status data should be received both from digitalized transformers and from voluntarily transmitted private data [21]. Private consumption and feed-in data are especially important when local behind-the-meter use cases are increasingly performed, as the standard load profile currently used by distribution grid operators for planning will no longer be valid.

4) Enable responsible parties to implement complex use cases

The levers of cornerstones 2) and 3) imply that the implementation of use cases will become more complex rather than less complex in the future. Combining potentially high user benefits and grid stability is best achieved through multi-use cases consisting of market-oriented and grid-serving use cases. At the same time, cornerstone 1) emphasizes that the corresponding technical systems should be easy for users to set up and operate. Thus, the responsible parties, which are the providers of smart and bidirectional charging business models, must be able to implement more and more complex use cases with as little susceptibility to errors and as much user comfort as possible.

Concrete levers are:

- Prioritizing the further development of multi-use cases: As multi-use cases are generally superior to single-use cases in combining user benefits and systemic advantages [Pub3], their further development should be pursued. To do so, the parties involved (manufacturers, providers, grid operators, etc.) could prioritize developing technical solutions tailored for multi-use cases. For example, a combined power inverter system could be developed that would be utilized both for the PV system and for a bidirectional EVSE, which also reduces the consumption of resources. Specific public funding programs could additionally promote or incentivize the implementation of multi-use cases. Even specific regulations are conceivable in which multi-use, to a certain extent, would be mandatory when applying smart charging or bidirectional charging.

- Standardizing interfaces where it is appropriate: Standardization is the most important means to achieve interoperable interfaces and to create transparency regarding the data to be exchanged. In this sense, standardization of interfaces is in the users' best interest, especially if more complex use cases should be applied. However, the process of standardization is slow, time-consuming, and can ultimately not guarantee that technical components are indeed interoperable in every case [21]. A sweet spot exists between standardized interfaces and proprietary solutions from manufacturers, which offer no transparency and little interoperability but can be implemented rapidly and efficiently. For some interfaces, such as those which connect the user's behind-the-meter system with the distribution grid operator or the energy supplier, standardization is certainly sensible. For others, such as those from the EV to the EV manufacturer's backend, proprietary solutions are adequate. [21] Thus, not every interface needs to be standardized, but the focus should be on those interfaces where standardization brings real added value (transparency and exchangeability of components for users).
- Testing the interoperability of systems end-to-end before commercialization: In many cases, components can be sold claiming to meet a certain standard, even though only minimum requirements for the specific standard are met. In reality, such components often cannot be used adequately for smart charging or bidirectional charging use cases, especially if more complex multi-use cases are implemented [14]. This is why both the end-to-end system required to implement a use case and the interoperability of components within the system should be tested prior to market launch. A possible approach is for component manufacturers to join together in working groups and conduct such plug tests on a larger scale.
- Strengthening the role of the flexibility service provider: A complex use case will most certainly not be managed by users themselves but by a third party, which is referred to here as the flexibility service provider. The provider reduces the system's complexity for the user by carrying out the optimization of the charging strategy, taking into account all boundary conditions, input data, and potential data forecasts. If necessary, the provider can also aggregate several assets, including EVs, into a flexibility pool. In the system, these providers usually take on the role of local energy manager and technical aggregator (see Figure 4). The role of the flexibility service provider is extremely complex and only a few providers have been able to fulfil the role up to today. As the role is crucial, increased funding and development work should be directed to this area.

3.3 Critical reflection and outlook

Smart charging and bidirectional charging play a key role for users to adopt electric mobility and integrate EVs into the energy system. This dissertation provides detailed insights into user benefits and future prospects of single- and multi-use cases. The four research questions (RQ) stated in Section 1.2 are answered in this work.

These answers are briefly summarized and critically reflected in terms of the applied methods, current developments, and possible future progress.

RQ 1: What are the differences in the effort required for technical implementation of the use cases, and what synergies result from the implementation of multi-use cases?

The results presented in Section 2.1, Section 3.1, and [Pub1] show that the technical implementation effort for use cases differs substantially. For some single-use cases, the effort is found to be more than twice as great as for others. The implementation effort for multi-use cases is generally higher than for single-use cases. Yet, the effort does not equal the sum of the individual efforts for the involved single-use cases, but is lower instead. In some cases, the technical implementation effort for multi-use cases is less than half of the sum of efforts for involved single-use cases. Hence, the synergies in technical implementation efforts are significant for some multi-use cases.

Technical restrictions and future technology developments are not the main focus of this dissertation. In this respect, smart charging is already available today, but not every use case can be implemented robustly and interoperably with the current technology [9]. It is expected that the technology for bidirectional charging could be fully available to end users by the end of 2025 [14]. In terms of technological advancements and the respective technical implementation efforts, some assumptions and corresponding findings presented in this work might become outdated in the near future. For instance, the assumption that bidirectional charging is conducted via DC charging using DC EVSEs is valid for Germany today, but in other countries a shift towards AC charging is already apparent (see Section 1.1).

Advancements in battery technologies may reduce or even eliminate issues of cyclical battery aging. Limiting the number of additional EFCs for bidirectional charging might thus become obsolete in the future. Similarly, the operating hours of smart and bidirectional charging could be expanded when EV electronics are enhanced in terms of operating lifespan. Advances in other technical components, software, and standardization might reduce complexity in the technical system required for smart and bidirectional charging use cases. A general reduction in technical implementation effort over time, which is not considered in [Pub1], is therefore generally plausible.

RQ 2: What is the potential range of user benefits of single-use cases and multi-use cases today and in the future?

As discussed in [Pub2] and [Pub3] (see also Section 2.2) and in Section 3.1, profits for single- and multi-use cases are extremely variable and depend on a wide number of factors. For today, profits range from -10 €/(EV·a) to 310 €/(EV·a) for smart charging and from -70 €/(EV·a) to 570 €/(EV·a) for bidirectional charging. Under typical circumstances, few single-use cases are profitable today, as cost savings resulting from the optimized charging strategy are not sufficient to offset the high additional technology costs. For multi-use cases, profitability is already achievable today. In 2030, profits range from 80 €/(EV·a) to 420 €/(EV·a) for smart charging and from 190 €/(EV·a) up to 2,070 €/(EV·a) for bidirectional charging. Thus, all use cases are very likely to be profitable in 2030. Some multi-use cases are even becoming extremely profitable.

The heterogeneity of user behavior and a large number of possible parameter constellations make it difficult to accurately predict the profitability of use cases. Additional simulations applying even more parameter variations to obtain cost savings and emission reductions would certainly contribute to an even better understanding of user benefits. Appropriate model developments are the inclusion of uncertainties (e.g., EV availability, abrupt changes in user behavior, or price forecast uncertainties), the option to select different technical systems (AC/DC charging, different electronic limitations, different loss functions), and the further development of the sub-module on battery aging. Modeling combined systems, including SBS and heat pumps, is also recommended to encompass more complex but plausible systems. In terms of electricity market prices, not only uncertainties in price forecasting but also the effect of market cannibalization should be considered to account for partly limited market potentials. Furthermore, the pooling of EVs could be modeled in more detail, as it is crucial for market participation.

RQ 3: What is the maximum number of users who can carry out the use cases today and in the future?
The calculations of the maximum number of potential EV users per use case from [Pub4] provide an answer to RQ 3. Depending on the use case, the maximum number ranges from 0.2 million to 9.2 million users today. For four use cases, the maximum number of users is higher than the number of registered EVs. In 2030, the maximum number of users is increased for most cases, yet the overall range still extends from 0.2 million to 9.2 million users. The ratio of the maximum possible number of users to the expected number of EVs in Germany for 2030 (8.2 million, see Figure 1) is thus decreasing.
Further research can be carried out to assess limitations in use case participation in more detail. Limitations can be technical restrictions or user-related constraints. A detailed mapping of vehicle availability and traded market volumes over time would be a possible methodological development. The approach of taking the intersection of single-use case numbers as the number of users for multi-use cases could be revised or refined. Incorporating other possible future developments in the assessment for 2030 and conducting a sensitivity analysis based on different scenarios is another possible extension of this work.

RQ 4: What are the prospects for a user-driven implementation of single-use cases, and multi-use cases and which levers are key for a systemically beneficial integration of EVs?
The findings and discussions in Section 3.1 outline that all investigated single-use cases will most likely not be implemented in the short term (until 2026) apart from pilot implementations. Although some multi-use cases can be generally beneficial for users today, those use cases are complex in terms of technical implementation and are therefore also unlikely to be implemented in the short term. In the medium term (2026 to 2028), user-driven implementation of single- and multi-use cases will most probably gain momentum, as potentially high profits and emission reductions are expected with manageable technical complexity. Smart charging tends to be more beneficial in the short to medium term, whereas user benefits for bidirectional charging become significantly higher in the medium to long term. All use cases, apart from one single-use case, are highly likely to become conclusively beneficial for all involved parties by 2030 at the latest, so that many use case implementations are to be expected by 2030.

Regarding systemically beneficial EV integration, four cornerstones of action for smart and bidirectional charging are derived in Section 3.2. For each cornerstone, concrete levers are stated. Among these levers are, for instance, the need for providers to develop user-centered business models, for regulators to simplify and clarify regulations, especially for bidirectional charging, to harmonize market-oriented and system-serving use cases, and to prioritize the further development of multi-use cases. With fitting conditions, which the specified levers can create, all assessed use cases can be implemented in a systemically beneficial way.
The assessment of prospects of the use cases should be viewed in the context of the current state of research, ongoing developments and ever-changing circumstances. Fundamental changes, e.g. trends towards authoritarian governments, the globally rising number of wars, or potential scarcity of resources, may have major consequences for the prospects of smart and bidirectional charging use cases. The findings presented here should therefore be updated if circumstances are drastically changed in the future. With regard to multi-use cases, not all relevant combinations of use cases have been assessed. Focusing research on multi-use cases, whose potential is found to be generally high both from the user’s and the system’s perspective, is a sensible approach that permits evaluating the prospects of these complex cases at an early stage.
Concerning all considered use cases, further in-depth research on user and systemic benefits is recommended. Significantly more energy system simulations with different sensitivities are appropriate, as this work refers to a limited amount of analyses of others. Results from user-centered models could be used as input in the energy system model to determine specific systemic benefits, as done in [34] for PV self-consumption optimization. Sensitivities of energy system simulations should include different EV adoption rates, varying operational and capital costs of smart and bidirectional charging, and different constraints on market participation (e.g., plug-in probability, EV availability, applied market restrictions). Such sensitivities enable the evaluation of even more concrete levers to gradually integrate electric mobility as systemically beneficial as possible.

To sum up, this cumulative dissertation provides a methodological framework to evaluate single-use cases and multi-use cases of smart and bidirectional charging from the user's perspective. The presented multi-criteria assessment comprises quantitative analyses, a MILP optimization model and visualization forms to interpret results. Reliable conclusions about financial and emission-related user benefits, the possible number of users, the future prospects of use case implementation, and the levers for the systemically beneficial integration of EVs can be drawn on this basis.
It is important to emphasized that ultimately, the use cases of smart and bidirectional charging should not serve an end in themselves but rather promote the decarbonization of the transport sector, actively and positively contribute to the system, and reduce the overall consumption of resources. The latter aspect refers to the prospect of flexible EVs partially replacing other technologies, such as SBS or additional flexible assets built for system stability, thereby increasing resource efficiency. It also implies that the large-scale implementation of use cases in the future should result in fewer EVs on the roads instead of more. After all, smart charging and bidirectional charging have the potential to prompt providers and manufacturers to rethink their business

models in a more sustainable way and to consequently alter the behavior of EV users through appropriate, climate-friendly incentives.

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Acknowledgment

First, I thank my doctoral supervisor, Prof. Ulrich Wagner, for his trustworthy guidance, constructive insights, and the open and engaging discussions we had over the past years. This dissertation would not have been possible without Prof. Wagner's support and supervision. Nor would it have been possible without the support of the FfE, which has provided me with exciting research topics and the space and funding to conduct and publish my work. I therefore thank the management of the FfE and the entire FfE family.

For the many fruitful discussions, the constructive feedback, and, above all, for finding and specifying topics at the beginning of my doctorate, I thank my mentor, Christoph Pellinger. Without his guidance, who knows what this dissertation would have looked like? Special gratitude goes to my colleagues Timo Kern and Kirstin Ganz. Both played a particularly important role in shaping the content of my work and offered a lot of feedback on this dissertation. In many conversations, we discussed various topics, exchanged ideas and challenged each other. Above all, however, we always had fun, for which I am very thankful. My colleagues Florian Biedenbach, Valentin Preis, Adrian Ostermann, and Jeremias Hawran, as well as the co-authors of my publications and the students I supervised, have supported my work in various aspects. I express my sincere thanks for their valuable contributions. I am fortunate not only to have the opportunity to work with and learn from exceptionally talented people but also to have built new and lasting friendships.

I also thank my brother, Macl, for his detailed proofreading and constructive feedback and my family and friends for their continued encouragement throughout the years. Finally, the biggest thanks go to my wife, Pia, for your constant support during my doctorate, your patience with me even in stressful times, and the fact that I can always rely on you.

Appendix

Publication 1 [Pub1]: Synergies of Electric Vehicle Multi-Use: Analyzing the Implementation Effort for Use Case Combinations in Smart E-Mobility

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Energies **2023**, 16(5), 2424

Permanent web link:

https://doi.org/10.3390/en16052424

energies

Article

Synergies of Electric Vehicle Multi-Use: Analyzing the Implementation Effort for Use Case Combinations in Smart E-Mobility

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Abstract: Electromobility is generally seen as an efficient means of decarbonizing the transport sector. Ensuring both a broad propagation of electric vehicles and a stable energy system requires intelligent charging strategies in the form of use cases. Most use cases do not combine both the prospect of profit and systemic advantages. This paper analyzes combinations of use cases that merge different use cases to combine profitability and systemic benefits. We present a novel methodological approach for analyzing and comparing the synergies of different use case combinations. The focus is on evaluating the potential for reducing the technical implementation effort resulting from the simultaneous implementation of two to three different use cases. Our findings show that the simultaneous implementation of complex use cases, often involving in-front-of-meter pooling of vehicles, produces the greatest synergies. Combinations that include ancillary services and spot market trading lead to considerable reductions in the implementation effort. Balancing profitability and systemic benefits with little absolute effort requires combinations that include use cases implemented behind-the-meter, for example, optimization of self-consumption. Challenges in the implementation of the combinations investigated arise primarily from technical hurdles and the fact that some use cases have not yet been fully defined in regulatory terms.

Keywords: intelligent charging; implementation effort; aggregator; spot market trading; ancillary service; operating reserve

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Citation: Dossow, P.; Hampel, M. Synergies of Electric Vehicle Multi-Use: Analyzing the Implementation Effort for Use Case Combinations in Smart E-Mobility. *Energies* **2023**, *16*, 2424. https://doi.org/10.3390/en16052424

Academic Editors: Panagiotis Fragkos and Marios Charilaos Sousounis

Received: 27 January 2023
Revised: 15 February 2023
Accepted: 1 March 2023
Published: 3 March 2023

1. Introduction

Electromobility is vital when it comes to reducing carbon emissions in the transport sector. In the absence of a suitable integration strategy, the rapid and widespread distribution of electric vehicles (EVs) risks imposing an additional burden on the energy system and on electricity grids in particular. With the application of intelligent charging strategies in the form of suitable use cases, i.e., applying smart charging to achieve a specific goal it is, however, possible to achieve the opposite effect and actually support the energy system. Several use cases in the field of intelligent charging are oriented towards particular electricity markets with the goal of minimizing charging costs by charging at times of favorable prices. Thus, by exploiting variable market prices, charging costs can be reduced, which serves to increase the attractiveness of investing in EVs [1–3]. The question of whether the potential financial benefits of such a use case can contribute to the propagation of smart electromobility is a subject of much dispute, as is its benefits to the system, particularly the grid [4–6]. Other use cases aim at stabilizing the grid or reducing any additional grid expansion. The profitability of these use cases is uncertain and depends to a large extent on the incentive system [4,7,8]. As both use case groups exhibit advantages and drawbacks with regard to smart electromobility, it can be assumed that in the future, several use cases will be implemented per EV user or location [9,10]. Such combinations of use cases might be able to increase the profitability of EVs and, at the same time, even benefit the electricity grid.

1.1. State of Research

The smart and bidirectional charging of EVs has been the subject of considerable research for some time. Smart charging refers to charging an EV at specific times under defined boundary conditions. Bidirectional charging adds the possibility of flexibly discharging an EV battery. A wealth of publications exist that discuss smart electromobility based on individual use cases, many of which model and simulate optimum charging and discharging strategies for EVs. For this purpose, a use case is defined as follows: "A use case describes the functionality of a system from the user's perspective. It highlights boundary conditions, involved players, contexts, interactions, and the added value created by the use case. A user can be a person interacting with the system, a role, an organization, or another system. [. . .] The goal of defining use cases is to establish a common understanding of the behavior and scope of a system among relevant stakeholders, such as those involved in a project" [11].

To enable a better understanding of current research topics in the field of smart electromobility, we now present some general publications on the subject. Kern et al. [12] look into the integration of bidirectional chargeable EVs in the European energy system. The authors simulate spot market trading in day-ahead and intraday markets as well as trading in the frequency containment reserve (FCR) market to estimate cost reductions (i.e., revenue potentials). The authors conclude that revenue potentials are strongly dependent on the EV pool, user behavior, the regulatory framework, and the structure of the energy system in the country in question. Knezovic et al. [13] identify technical, infrastructural, and regulatory barriers to the implementation of vehicle-to-grid (V2G) services. Gschwendtner et al. [14] give an overview of vehicle-to-x trials and the identified challenges. For the future, they propose evaluating and enabling portfolios with different flexible assets and stacking use cases to increase revenue streams and reduce the risks stemming from variations in driving patterns and charging behavior. Uddin et al. [15] show that V2G can have a positive impact on the lifetime of EV batteries.

There are also numerous publications examining individual use cases. Biedenbach et al. [16] analyze the challenges and opportunities of variable electricity price tariffs in Germany. They draw up a comparison of static, time-of-use, and dynamic pricing mechanisms relating to the spot market. The peak shaving use case is investigated in [17,18] and [19]. Weiß et al. [17] conclude that for intelligent charging, a company's peak load value can be kept constant without imposing significant restrictions on the users. In the case of bidirectional charging, the peak load value can even be reduced by up to 40%. Kern et al. determine a potential revenue of up to 1000 €/EV/a for bidirectional EVs [18]. Malya et al. [2] and Schuller et al. [3] perform comprehensive analyses of the energy arbitrage use case. Both conclude that this use case can be profitable under certain conditions. Blume et al. [7] analyze the potential of variable grid fees. They show that a 24% reduction in overload is achievable, while the median grid fee costs for the customer can be reduced by 33%. Kobashi et al. [20] evaluate the revenues created by increasing the self-consumption rates of combined photovoltaic (PV) and vehicle-to-home (V2H) systems in Japanese households. This is likely to result in a 68% reduction in annual energy costs in 2030, accompanied by a decarbonization rate of 92%. Chukwu et al. [8] calculate the impact of reactive power compensation with EVs on the distribution grid. They find that up to 95% of the power losses in distribution grids can be mitigated.

Publications that examine combinations of use cases are less frequent. Use case combinations are defined in this context as follows: The term "use case combination" refers to the simultaneous implementation of several individual use cases. All use cases in the combination are technically enabled. The use cases can be implemented either sequentially, in parallel, or dynamically (i.e., with an interplay between sequential and parallel). In this way, players are given the opportunity to execute the use case of the combination that delivers the greatest added value at the required time.

The combination of spot market trading and optimized PV self-consumption is modeled and simulated in [21]. The interaction of V2G and V2H represents an important aspect of this analysis. In this publication, a seasonal distribution of these two use cases is found to be the most profitable. Four use cases—peak shaving, increased self-consumption, FCR, and spot market trading, as well as combinations thereof—are analyzed in [9]. A clear trend can be seen, in which revenue increases as more applications are incorporated and more flexibility is enabled. Compared with simple charging, an annual cash flow increases of 960–2220 EUR per vehicle can be achieved. An analysis based on the same use cases is conducted in [22], but rather than EVs, stationary battery storage systems (SBSs) are considered. The detected trend is the same as that in [9], even though the focus of the paper is on comparing methods of allocating battery power and capacity. As there is an overlap between SBS and V2G use cases, the following papers are also considered. Seward et al. [23] show that stacking multiple revenues leads to a decrease in the operating costs of local energy systems, along with improved battery storage, investment viability, reduced degradation, and longer service life. The considered use cases comprise wholesale day-ahead trading, a firm frequency response, and dynamic containment (part of the operating reserve in the United Kingdom). Tian et al. [24] evaluate the revenue from the combination of energy arbitrage, operating reserve, and outage mitigation for a grid-connected SBS in the United Kingdom. The operating reserve had the greatest impact on the stacked revenue in the scenario considered. A different revenue analysis is performed by Litjens et al. [6], in which the use case combination of PV self-consumption increases and automatic frequency restoration reserve (aFRR) is examined and found to be profitable. Braeuer et al. [25] give an insight into the economic potential of SBSs in small and medium-sized enterprises in Germany. They show that the combination of peak shaving and FCR has the greatest impact on the revenue stream, while, in some cases, energy arbitrage results in only a small advantage. Onishi et al. [26] evaluate the benefits of connecting a V2G parking lot to a microgrid consisting of a hybrid PV–wind–hydrogen energy and storage system. They point to a 42% reduction in the system's energy and environmental costs.

The goal of many of the aforementioned studies is to conduct a revenue analysis of use cases (or a combination of use cases). However, none of these publications focus on the implementation of the use cases, but they base their analyses on models and simulations of the operating phase. This is presumably due to a lack of implementation experience. No paper was found that methodically analyzes use case combinations in the field of electromobility. In the list of papers that we present here, the selection of examined use cases is at no time based on any preceding analyses, but rather on the authors' expertise.

1.2. Motivation and Objectives

It is expected that in the future of smart electromobility, combinations of use cases will be applied more frequently than individual use cases. At present, however, there are very few research findings on feasible use case combinations. Against this background, the aim of this paper is to analyze the combination of smart electromobility use cases by focusing on the synergies that result from simultaneous implementation. Damodaran [27] describes synergy as the increase in value generated by combining two entities to create a new and more valuable entity. In the present study, synergies arise from the reduction in the implementation effort expended for two or more simultaneous use cases.

The methodology emphasizes the reduction in effort for the end user of implementing combinations of use cases. Implementation comprises installing the hardware and software required to render a use case operative. A final, scaled technical solution is considered to enable the use case. Other aspects, such as the technical and regulatory challenges posed by the combination of use cases, are also discussed. The methodology can be applied to any number of use case combinations. In this paper, combinations of two and three use cases are analyzed.

This paper is part of the research project "unIT-e^2—Living Lab for Integrated E-Mobility" [28]. The discussed use cases were developed and elaborated within the unIT-e^2

project. The focus is on the intelligent charging of EVs. Bidirectional charging is also possible with these use cases. However, this does not constitute the focus of this research project. The following section describes the developed methodology, while Section 3 presents the findings of the methodology.

2. Methodology

The primary goal of the presented methodology is to enable a holistic evaluation of the synergies of technical multi-use applications in terms of their effort and benefit. In this paper, the methodology is applied to electromobility, but it can also be employed in other fields in the energy sector and beyond.

Our five-step methodology is illustrated in Figure 1. The first step is to define the use cases relevant to the field of application. The field is gradually narrowed down with each step. Steps 2 to 4 assess the synergies associated with the implementation effort along with the obstacles and challenges of multi-use applications. For this purpose, we compare separate implementations of several use cases with the simultaneous implementation of those use cases. This paper is concerned with steps 2 to 4. The fifth step, which concerns the quantitative economic evaluation of use case combinations, involves a very detailed, model-based process that should be considered separately due to the complexity of the individual step. Thus, this step is included here for the sake of completeness, as it is necessary for a holistic view, but it is not part of this work.

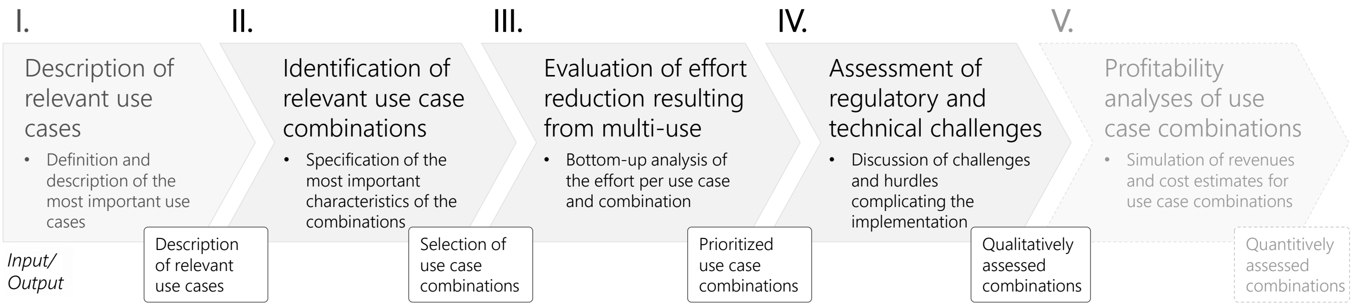

Figure 1. Methodology of analyzing synergies arising from multi-use.

2.1. Description of Relevant Use Cases

The first step of the methodology is to draw up a detailed description of the most promising use cases in the context of this project, with an emphasis on their implementation. This includes such aspects as the following:

- The primary objective of the use case;
- The underlying incentive system;
- The added value to the end user;
- The appropriate period of use;
- The locations where the use case can best be implemented;
- The basic technical implementation framework.

The technical setup comprises a list of all the elements that are considered for each individual use case. We classify elements as players, interfaces between players, and data or information flows and processes (data sets) that are exchanged between the interfaces. For each use case, it is necessary to identify the elements of the three classes that are (a) required and (b) optional (i.e., that add value but are not mandatory) for the implementation of the use case.

2.2. Identification of Relevant Use Case Combinations

The second methodological step is to determine suitable use case combinations. Relevant use case descriptions are the essential input for this step. In general, all use cases that are not based on the same incentive system or that do not follow the same price signal are suitable for inclusion in a combination. A dissimilar incentive system is therefore a necessary criterion for a use case combination. Other aspects, such as a high degree of simultaneity of use, are not deemed as exclusion criteria for a combination since significant synergy effects are possible even with similar use cases.

To begin with, a pairwise comparison is conducted to determine which use cases cannot be combined in a suitable way. Relevant combinations result from the combinatorics of relevant use cases minus use cases based on an identical incentive system. The number of use cases implemented per combination is specified at this point. In the presented methodology, all possible combinations of use cases from 2 to n can be considered for n relevant and combinable use cases. The second methodological step outputs a list of relevant use case combinations.

2.3. Evaluation of the Reduction in Effort Resulting from Multi-Use

The third and most crucial step is the evaluation of the reduction in implementation effort. To carry this out, we compare the implementation effort for a use case combination implemented in a single process (simultaneous implementation) with the effort required for individual implementations of multiple use cases (separate implementations).

First, the individual implementation effort per use case is defined by calculating an effort factor for each use case. The effort factor represents the result of a bottom-up quantification of the implementation effort. The purpose of such quantification is not to define a quantitative scale of absolute effort, but to identify the differences between use case combinations and to draw qualitative conclusions. Equation (1) is used to calculate the effort factor (EF) per relevant use case.

$$EEF_{UC_i} = \sum_m \left[WF_m \cdot \sum\nolimits_k b_{Element_k,m}(UC_i) \right] \tag{1}$$

where EF = effort factor, UC_i = use case i, WF = weighting factor, m = weighting category, $b_{Element}$ = necessity of element, and k = index of element.

For each use case, the effort factor is calculated as the sum of the product of the weighting factor (WF) and the element variable ($b_{Element}$). The list of necessary and optional elements created in the first step is used in the calculation. The discrete variable $b_{Element}$ is now introduced, which includes those elements of the effort calculation that are either necessary or optional:

- $b_{Element}$ is 1 if the element is necessary for the use case.
- $b_{Element}$ is 0 if the element is not necessary for the use case.
- $b_{Element}$ is 0.2 if the element is optional for the use case.

This value assignment reflects the fact that, in the case of an optional element, additional effort is not always required for implementation. At present, 0.2 is an estimated value. The weighting factor (WF) is introduced to address elements whose implementation requires different amounts of effort. The product of WF and $b_{Element}$ yields the quantified effort per element. We propose to introduce WF not per element, but per weighting category (index m), to reduce the amount of effort. For instance, WF can be determined based on expert knowledge. Both the direct assignment of weighting values and a mathematical fitting based on effort factors for exemplary use cases determined by expert surveys are feasible.

The effort factors for separate or simultaneous multi-use case implementation are calculated using the individual effort factors. Figure 2 illustrates the used logic for a combination of two use cases with an example selection of elements. To calculate the effort factor of a separate implementation, the effort factors of the individual use cases are totaled (see Equation (2), Figure 2, top). The logic for calculating the effort of simultaneous implementation (multi-use) is shown in the lower part of Figure 2; it is calculated using Equation (3). The difference is that it is not the whole effort of the second use case (UC_j) that is added to the effort factor of the first use case (UC_i). Rather, the effort factor is increased only by those elements that are additionally necessary or additionally optional by virtue of the combination. The element variable β_{Element} is now introduced for the combinations:

- $\beta_{Element}$ is 0 if the element is already necessary for UC_i or must be implemented in the same way.
- $\beta_{Element}$ is 0.2 if the element is not necessary for UC_i and is optional for implementing UC_j.
- $\beta_{Element}$ is 0.8 if the element is already optional for UC_i and is necessary for UC_j.
- $\beta_{Element}$ is 1 if the element is not necessary for UC_i but is necessary for UC_j.

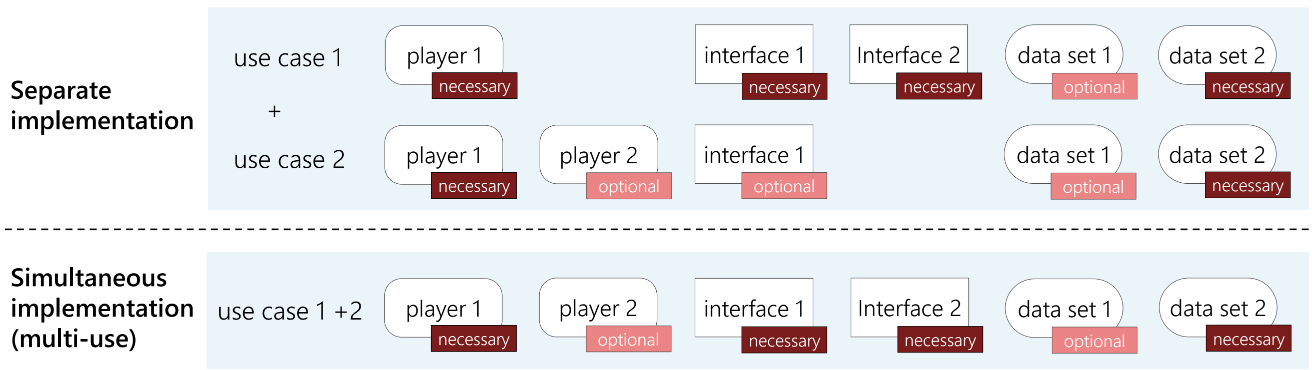

Figure 2. Example visualization of difference between separate and simultaneous implementation.

$$EF_{UC_i} + EF_{UC_j} = \sum_m \left[WF_m \sum\nolimits_k b_{Element_k,m}(UC_i) \right] + \sum_m \left[WF_m \sum\nolimits_k b_{Element_k,m}(UC_j) \right] \quad (2)$$

$$EF_{UC_i+UC_j} = \sum_m \left[WF_m \sum\nolimits_k b_{Element_k,m}(UC_i) \right] + \sum_m \left[WF_m \sum\nolimits_k \beta_{Element_k,m}(UC_j) \right] \quad (3)$$

The weighting factors (WFs) are the same as for the calculation of each individual effort factor. We chose numerical values for $b_{Element}$ and $\beta_{Element}$ so as to render the order of use cases in the calculation irrelevant since in reality, the order of implementations is negligible. The logic can be applied to any number of use cases per combination.

By calculating the effort factors in this way, we can analyze the synergies from implementing multiple use cases simultaneously compared with implementing them separately. The reduction in implementation effort is found using Equation (4), where ER stands for effort reduction.

$$ER = \left(EF_{UC_i} + EF_{UC_j} \right) - EF_{UC_i+UC_j} \quad (4)$$

The resulting numerical effort reduction value (ER) has no direct reference, but only makes sense in combination with the values of the separate or simulated effort factors. To better evaluate the results, a transfer of the quantitative calculation results into a qualitative scale is proposed. This requires various discrete categories, each of which is attributed a qualitative rating for the reduction in the implementation effort. A range of effort reduction values is assigned to each discrete category. It can happen that combinations consisting of highly effort-intensive individual use cases have a high absolute ER. It is recommended to link the qualitative categories to both the absolute ER and the relative effort reduction ER_{rel} (Equation (5)).

$$ER_{rel} = \frac{ER}{EF_{UC_i} + EF_{UC_j}} \tag{5}$$

The minimum value of the lowest and the maximum value of the highest category should be aligned in relation to the minima and maxima of the absolute and relative effort reductions. One way of applying a qualitative scale is, for example, to introduce three to ten discrete categories, ranging from small synergy/reduction to great synergy/reduction.

Based on such a scale, the relevant use case combinations can be evaluated in terms of their synergies. We also recommend prioritizing the use case combinations for the fourth methodological step.

2.4. Assessment of Technical and Regulatory Challenges

The fourth step constitutes an analysis of use case combinations on the technical and regulatory levels. This analysis can vary in its level of detail, depending on the availability of information and the current state of knowledge.

The technical challenges of each use case in the relevant combinations should be discussed. It makes sense to distinguish between current problems relating to digitization/technical availability and general technical feasibility. The assessment should also include key regulatory requirements relevant to the combination of use cases and an evaluation of the regulatory challenges associated with simultaneous implementation. This highlights the resulting challenges and hurdles of simultaneous implementation. We advise against analyzing all use cases, but rather analyzing only those of the highest priority, i.e., with the greatest effort reduction in a simultaneous implementation. Interesting use case combinations that did not result in the greatest effort reduction can also be examined. Once the fourth step is concluded, the qualitative evaluation of the use case combinations is complete.

2.5. Analyzing the Profitability of Use Case Combinations

The fifth step of the methodology adds a quantitative analysis of the profitability of multi-use applications to the qualitative evaluation of synergies attained through use case combinations. This step is an addition to the previous steps and is not conducted in this paper due to the additional level of complexity it would entail. A profitability analysis can be based on either real data or simulation results. Real-world data are often difficult or even impossible to obtain, in which case a simulation model must be used.

In the case of electromobility, an optimization model with appropriate input data (comprising driving profiles, user data, load profiles, and market prices) can be used to simulate EV charging profiles. These can be translated into a cost factor in combination with energy procurement, investment, and running costs. A comparison of cost factors for individual use cases and for the simulation of use case combinations can be used to evaluate the increase in profitability through the simultaneous combination of use cases, similar to the qualitative evaluation of the implementation effort. The simulation of use cases and use case combinations is a major challenge in this process. It depends on the field of application and can be complicated by insufficient data availability. There is a tradeoff here between the level of detail of the simulation and the validity of the results. Some use cases, and, in turn, combinations including these use cases, can even be impossible to simulate. For these reasons, it may make sense to further restrict the selection of use cases resulting from the qualitative evaluation of use case combinations.

Since the goal of this methodological step is to provide a robust, conclusive evaluation of profitability, we argue that it is reasonable to focus on a small number of highly promising use case combinations. The results of the fifth step and the methodology as a whole present a comprehensive picture of implementation effort and profitability synergies, including any challenges or obstacles to the implementation of certain use case combinations.

3. Results

This section presents the results of methodological steps one to four with the aim of qualitatively evaluating the synergies arising from the implementation of multiple use cases. The scope of use cases and the basic principles behind their development are defined in the research project unIT-e^2, which presents a list of use cases relevant to the intelligent charging of EVs [28,29].

3.1. Relevant Use Cases

Differences in the implementations planned for the field trials resulted in forty use cases, both uni- and bidirectional, that are of relevance to the unIT-e^2 project. Variations that result in individual use cases are found in the design of the information and data interfaces as well as in the role distribution among the players involved. The use cases in unIT-e^2 and the methodology behind their development are discussed in [30].

The preliminary investigation included a high-level description of the use cases. Discussions of technical designs in the project enabled us to define the designs of the use cases in this paper. For the purposes of our analysis, forty use cases are too many. Hence, this paper presents a representative selection of use cases that are relevant for implementation. We distinguish between use cases implemented in a single-family home ("at home") and those implemented at a commercial site or in an apartment house ("at work/in apartment buildings"). We introduce this distinction, as the best-fitting implementation varies for the two places, since different players are involved, and different hardware is required. When employed at home, the grid connectee is the vehicle user. In work and apartment locations, the vehicle user is not necessarily the connectee. Charging at home is limited to private charging, whereas at work or in an apartment building, charging can be private or semi-public; hence, public charging is not covered by our investigation.

Table 1 lists the "at home" and "at work/in apartment buildings" use cases that we selected for analysis. In both locations, seven use cases are sufficiently similar, such that they can be presented together for now, even if the location of implementation varies. Two use cases (optimized PV self-consumption and emergency power supply) are only relevant in "at home" locations, as their potential is estimated to be significantly greater than at work or in apartment buildings. For optimized PV self-consumption, most roof-mounted PV systems are owned by private households and their proportion is still steadily increasing [31]. At the same time, the perceived value of a high degree of self-sufficiency is higher among private EV owners than among commercial owners [32]. Peak-shaving is only relevant in work/apartment building settings since no power-based price component is payable at home. The selected use cases cover the entire scope of smart electromobility investigated in the research. The table presents those aspects of the use cases that are relevant to the methodology. More detailed descriptions can be found in [29,30].

An evaluation of synergies requires a structured description of the use cases' technical designs as well as a description of their fundamental characteristics. A technical distinction is made between use cases for unidirectional and bidirectional charging due to differences in the hardware and software, although they share virtually the same general implementation setup. Emergency power supply and reactive power provision are only possible with bidirectional, intelligent charging. All other use cases can be implemented both unidirectionally and bidirectionally. Since the focus of the unIT-e^2 project is on unidirectional, intelligent charging strategies, we use this as the basis of our technical setups in all but two of the aforementioned use cases. The details of the setup stem from intensive discussions with our project partners in the energy industry, as well as in grid operation, information technology, and vehicle manufacturing [29]. Appendix A outlines key technical aspects of the use cases. Section 3.3 discusses key differences in the effort required for technical implementation.

Table 1. Use cases of relevance to smart electromobility.

Use Case	Place of Implementation	Primary Objective	Incentive System	Added Value for End User	Appropriate Period of Use
Optimized PV self-consumption	At home	Direct usage of self-generated PV electricity	Reduced electricity purchase costs; increased self-sufficiency	Increased independence, potential financial value, and reduction in emissions	When vehicle is plugged in and PV electricity is generated
Emergency power supply	At home	Security of electricity supply	Secure electricity supply	Increased supply security	In the event of a power failure (blackout)
Peak-shaving	At work/in apartment buildings	Reduced peak loads	Capacity charge dependent on peak load	Lower capacity charges; optimal use of connection capacity	When vehicle is plugged in and peak load occurs
Market-oriented price signal [1]	At work/in apartment buildings	Utilization of price spreads in the electricity markets	Price spreads in spot electricity markets	Financial added value through price spreads; potential emissions reduction	When vehicle is plugged in
Spot market trading	At work/in apartment buildings	Utilization of price spreads in the electricity markets	Prices in spot electricity markets	Financial added value through price spreads; potential emissions reduction	When vehicle is plugged in
Dynamic grid fees	At work/in apartment buildings	Prevention of grid congestion	Dynamic grid fees billed by grid operator	Financial added value; grid support	When vehicle is plugged in
Grid-serving power range	At work/in apartment buildings	Prevention/resolution of grid congestion	Remuneration of grid-serving flexibility	Financial added value; grid support	When vehicle is plugged in and a power range is set
Market-based redispatch	At work/in apartment buildings	Resolving grid congestion	Prices in a newly defined redispatch market [2]	Financial added value; grid support	When vehicle is plugged in and redispatch is necessary
Operating reserve (FCR, aFRR)	At work/in apartment buildings	Restoration of grid frequency	Prices in balancing markets	Financial added value; grid support	When vehicle is plugged in and operating reserve is necessary
Reactive power provision	At work/in apartment buildings	Maintaining grid voltage	Remuneration of reactive power provision	Financial added value; grid support	Possible at all times

[1] Description and setup of the market-oriented price signal case can also be applied to the emission-based signal use case, wherein time-resolved emission factors represent the incentive system of the charging strategy. However, the effects on market prices and emissions will vary for this case. To reduce complexity, we discuss only the one case in this paper. [2] No redispatch market of this kind currently exists. For the purpose of our analyses, we assume that such a market will be introduced for small, flexible assets, such as heat pumps or electric vehicles, in the future. The market is discussed in more detail in Section 3.4.

To ensure that all the important elements (i.e., players, interfaces, and data sets) are correctly listed (bearing in mind the large number of use cases), a diagram is compiled to illustrate the technical implementations of all the use cases, using the system architecture of the Harmon-E cluster in the unIT-e^2 project as a template (see [30,33]). Figure 3 presents the illustration, which shows the players, technical components, and connections.

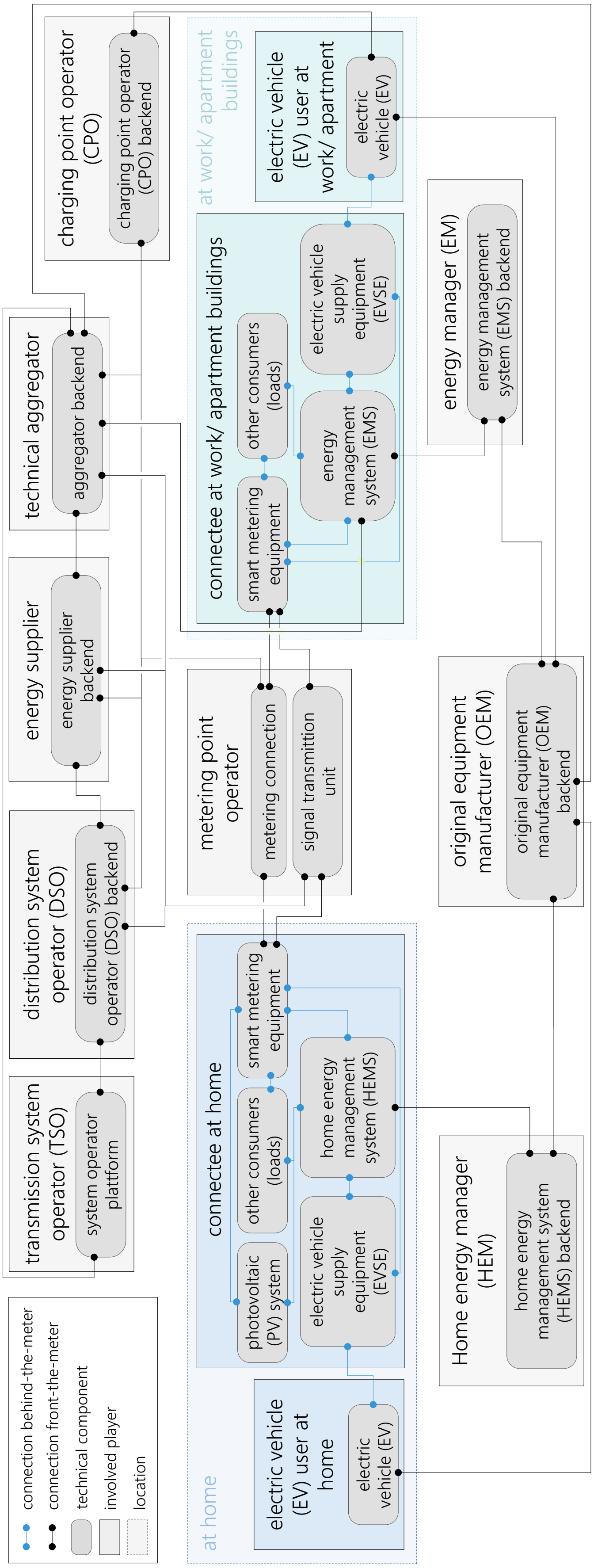

Figure 3. Diagram of technical implementations for all considered use cases.

The distinction between the two locations (at home and at work/in apartment buildings) is retained to highlight the differences in their technical implementation. The illustration refers to implementations in Germany. For other countries, the representation may differ depending on the distribution of roles and the regulatory requirements of the technical components.

The list of elements needed for the next methodological step can largely be obtained from the illustration. For each use case, the players are copied from the figure to the element list. The connecting lines shown between any two technical components in the figure represent the interfaces that are necessary for implementation. These interfaces are also listed. As Figure 3 is not suitable for listing data sets that are transferred via the interfaces for each use case, we identified the data sets required for each interface in discussions with our project partners and transferred them to the element list (see Appendix B). These include the weighting factors for each category, which were determined in expert workshops. The element list represents the conclusion of the first methodological step.

3.2. Relevant Use Case Combinations

For the second methodological step (examining the combinability of relevant use cases), we consider combinations of more than three use cases at the same time to be impractical in the context of electromobility. For one thing, intelligent algorithms must be able to react quickly to adapt to different charging strategies. However, the great complexity and potential differences in data availability result in technical limits. Moreover, conflicts and cannibalization effects can occur if too many use cases are applied at the same time, even if the use cases have different incentive systems. This paper, therefore, analyzes combinations of two or three use cases, for implementation at home as well as at work/in apartment buildings.

We begin by conducting a pairwise comparison to determine which use cases can and cannot be combined. The criterion that uses cases in a combination must not be based on the same incentive system that is met in all but one of the combinations of the aforementioned use cases. The exception is the combination of the market-oriented price signal and spot market trading use cases, since in both cases, the price spreads from the spot markets are used as an incentive for smart charging. Even though the technical implementation of the use cases is different for each case, these two cases are not suitable for combination. This can be seen in Figure 4, which shows the results of the third methodological step. Each colored cell of the matrices (a) and (b) represents a combination of possible use cases from the row and the column, respectively. Since in our method, it does not matter in what order the combinations are made, only the result of the evaluation is shown in the lower left diagonal of each matrix. Since all but one of the use case combinations are regarded as suitable implementation locations, there are 35 possible use case combinations at home and 27 at work/in apartment buildings, with 2 use cases per combination.

Based on the results of the pairwise comparison, 72 use case combinations are suitable at home and 45 at work/in apartment buildings, with 3 use cases per combination. We do not illustrate possible combinations of three use cases as this would be too complex. It is evident that the number of individual use cases has a significant impact on the resulting number of use case combinations. We defined one more relevant use case at home than at work/in apartment buildings, resulting in twenty-seven additional use case combinations that are relevant to implementation at home. In general, the number of use case combinations is already high with three use cases per combination.

(a) use cases at home

	+ optimized PV self-consumption	+ emergency power supply	+ market-oriented price signal	+ spot market trading	+ dynamic grid fees	+ grid-serving power range	+ market-based redispatch	+ operating reserve (FCR, aFRR)	+ reactive power provision
optimized PV self-consumption									
emergency power supply	low (2)								
market-oriented price signal	medium (2)	medium (2)							
spot market trading	medium (2)	low (2)							
dynamic grid fees	medium (2)	low (2)	high (2)	high (1)					
grid-serving power range	medium (2)	low (2)	medium (2)	medium (2)	high (1)				
market-based redispatch	medium (1)	low (1)	medium (2)	high (1)	high (1)	medium (2)			
operating reserve (FCR, aFRR)	medium (2)	low (2)	medium (2)	high (2)	medium (2)	medium (1)	high (2)		
reactive power provision	low (2)	low (2)	low (2)	low (2)	low (2)	medium (2)	low (2)	low (2)	

(b) use cases at work/ apartment buildings

	+ peak shaving	+ market-oriented price signal	+ spot market trading	+ dynamic grid fees	+ grid-serving power range	+ market-based redispatch	+ operating reserve (FCR, aFRR)	+ reactive power provision
peak shaving								
market-oriented price signal	medium (2)							
spot market trading	medium (2)							
dynamic grid fees	medium (2)	extremely high (1)	medium (2)					
grid-serving power range	high (2)	high (1)	medium (2)	high (1)				
market-based redispatch	medium (2)	medium (2)	high (2)	medium (2)	medium (2)			
operating reserve (FCR, aFRR)	medium (2)	medium (2)	high (2)	medium (2)	medium (1)	high (2)		
reactive power provision	low (2)	medium (1)	low (2)	medium (1)	medium (2)	low (2)	low (2)	

Figure 4. Effort reduction in combinations of two use cases (**a**) at home and (**b**) at work/in apartment buildings.

3.3. Effort Reduction Resulting from Multi-Use

The third methodological step evaluates the reduction in implementation effort for a simultaneous use case combination compared with separate implementations of multiple use cases. These are divided into implementations at home and those at work/in apartment buildings.

As discussed in Section 2, we use a qualitative scale to compare the calculated scores. Table 2 presents the classification, which comprises eight discrete categories. The numerical values used for classification are the same for use cases both at home and at work/in apartment buildings. The classification based on an absolute reduction in implementation effort is aligned with the maximum value of the combined effort for separate implementation. For example, an effort reduction of less than 17% of the maximum absolute effort yields a ranking in the low (1) or low (2) categories. The second classification factor is the relative reduction in the implementation effort. This means, for example, that a relative reduction of less than 17% with a simultaneous absolute reduction of less than 17% translates to a low (1) ranking, whereas a relative reduction of more than 17% with a simultaneous absolute reduction of less than 17% translates to a low (2) ranking. The numerical values used for this classification are selected such that the entire qualitative scale is used for all use case combinations considered and to enable sufficient distinctive characteristics between the use case combinations to be found.

Table 2. Discrete qualitative classification categories of calculated results.

Discrete Category		Description of Classification
	Extremely high (2)	Extremely high absolute and extremely high relative reduction
	Extremely high (1)	Very high absolute and extremely high relative reduction or extremely high absolute and very high relative reduction
	High (2)	High absolute and very high relative reduction or very high absolute and high relative reduction
	High (1)	Relatively high absolute and high relative reduction or high absolute and relatively high relative reduction
	Medium (2)	Medium absolute and relatively high relative reduction or relatively high absolute and medium relative reduction
	Medium (1)	Relatively low absolute and medium relative reduction or medium absolute and relatively low relative reduction
	Low (2)	Low absolute and quite low relative reduction or relatively low absolute and low relative reduction
	Low (1)	Low absolute and low relative reduction

3.3.1. Reduction for Two Use Cases per Combination

We begin by discussing the reduction in effort of combining two use cases at home. The methodology described in Section 2.3 is used to calculate the results. Figure 4a shows the qualitative results of the various use case combinations. To aid understanding, the quantitative results of selected use cases (spot market trading) and selected combinations are provided in Appendix C.

There are three use case combinations at home for which the effort reduction is rated as high (2), which is the highest for this implementation:

- Market-based redispatch + Operating reserve (FCR, aFRR)
- Spot market trading + Operating reserve (FCR, aFRR)
- Market-oriented price signal + Dynamic grid fees.

The combination of market-based redispatch and the operating reserve (FCR, aFRR) achieves the highest absolute reduction for simultaneous implementation. The two use cases reveal a high synergy potential since both are ancillary services with similar underlying technical processes, in which a transmission system operator (TSO) determines the demand for the ancillary service (either redispatch or the operating reserve) and requests the service on the appropriate market (as mentioned above, in the case of redispatch, we assume a new market, which does not yet exist). The technical aggregator then places offers for the provision of the ancillary service on the respective markets. The processes triggered when a bid is accepted are virtually identical: The technical aggregator sends a signal to a grid connection point, which is equipped with an intelligent metering system, via the metering point operator, who acts as an active external market participant (aEMT) and a passive external market participant (pEMT). The same interfaces and communication protocols are used to interpret the signal into a charging strategy. The measured data and the recipients are also very similar. Both use cases are comparatively complex when implemented alone, as these are the two use cases with the highest individual effort factors. The combined effort is thus still high in absolute terms compared with other combinations, despite a strong reduction with simultaneous implementation (see Figure A1, Appendix C).

The combination of spot market trading and the operating reserve (FCR, aFRR) shows a high reduction potential in both absolute and relative terms. Since both use cases are market-based, front-of-meter processes are conducted by similar players (a technical aggregator, energy supplier, or metering point operator) using the same or similar communication channels. Pooled flexibility potentials are marketed in both use cases. The technical aggregator determines a power band of flexibly available power per time unit for each EV, based on user and vehicle data received from the backends. These individual power bands are combined (pooled) and offered on the corresponding market. On a technical level, this means that the aggregator processes, which account for a large part of the implementation effort, are very similar, even if different data sets are involved (see Figure 3). An important difference is that in the case of the operating reserve, the TSO acts as an additional player, which makes the implementation of the operating reserve use case more complicated than the spot market trading use case. The measured data and the player to whom the data are transmitted are different in both cases (see, for example, [33]). Behind-the-meter processes are also similar. In the case of the operating reserve, the power capacity of an amount acceptable to the respective market is set aside to be retrieved when needed. In the spot market, the section of the power band allocated by the aggregator to the individual user is converted directly into a charging schedule for the vehicle in question.

The combination of market-oriented price signals and dynamic grid fees represents the highest relative effort reduction and also has a high absolute reduction. Moreover, the absolute and the combined effort of both use cases are relatively low. One important reason for the relatively low effort is that no technical aggregator is required for implementation in either case. In both cases, a time-variable price signal is transmitted to the grid connection point through the metering point operator. Price signal transmission and processing are very similar in both cases. Behind-the-meter, the transmitted price signal is fed into the optimization logic of the home energy management system (HEMS). It does not matter to the HEMS which incentive system the price signal is based on. The major difference and thus the decisive additional effort in combined implementation is that for dynamic grid fees, the distribution network operator (DSO) transmits a price signal to the metering point operator, who acts as the aEMT. For the market-oriented price signal, the signal goes from the energy supplier to the aEMT and on to the grid connection point. The very high effort expended by the DSO to determine a dynamic, time-variable grid fee is not considered here, but it should definitely be taken into account for this use case (see [7]).

As Figure 4a shows, the use case combination of market-based redispatch and the emergency power supply yields the lowest effort reduction category. The two use cases share little similarity in terms of technical implementation. While the front-of-meter effort for market-based redispatch is very high, the emergency power supply use case is primarily implemented behind-the-meter and without any direct connection to front-of-meter players, and it also uses different interfaces and data sets.

For implementation at work/in apartment buildings, five use cases achieve an effort reduction of high (2) or higher (see Figure 4):

- Market-oriented price signal + Dynamic grid fees
- Market-based redispatch + Operating reserve (FCR, aFRR)
- Spot market trading + Operating reserve (FCR, aFRR)
- Spot market trading + Market-based redispatch
- Peak shaving + Grid-serving power range.

The three use case combinations with the highest reduction are the same as the combinations at home. However, the absolute and relative reductions are higher than at home, since implementation at work/in apartment buildings is usually more complex than at home. For all use cases at work/in apartment buildings, a charge point operator (CPO) is required to handle the billing of the vehicle user, since the vehicle user and grid connectee are not the same entity. Since the CPO is required in all use cases, greater synergy effects are achieved in implementations at work/in apartment buildings.

In contrast to implementation at home, the combination of market-oriented price signals and dynamic grid fees promises the greatest reduction in implementation effort at work/in apartment buildings. The main reason for this is the even higher relative reduction in effort that results from additional synergies in the combined implementation in relation to total effort, due to the additional CPO and the use of identical processes.

For the combination of market-based redispatch and the operating reserve (FCR, aFRR) at work/in apartment buildings, there are no fundamental changes in relation to implementation at home. Due to the generally higher effort in both use cases, the effect of the additional synergies created by the CPO is not as strong here as with the combination of market-oriented price signals and dynamic grid fees.

The reduction in implementation effort for the combination of spot market trading and a control reserve (FCR, aFRR) is not as high as one might anticipate. For spot market trading at work/in apartment buildings, we examine a slightly different implementation than at home. Since at work/in apartment buildings the connectee is not necessarily the vehicle user, and since the technical aggregator does not wish to be dependent on the metering infrastructure at the grid connection point, the latter transmits the power band specification resulting from spot market trading directly to the energy management system (EMS). The EMS translates the power band specification into charging schedules for the connected EVs. This process has the additional advantage that individual charging points can be provided directly with a power band specification. The disadvantage is that, at least in Germany, the technical implementation does not make use of a certified smart metering infrastructure, although this should be available in the future. Nevertheless, we discuss this implementation variant here to demonstrate the different possibilities of the technical setup. For the operating reserve, we consider a certified, intelligent metering infrastructure to be indispensable, as ancillary services require a high standard of data privacy and security. Hence, the two cases differ more here in terms of implementation than at home, resulting in a slightly smaller reduction in effort.

For the combination of spot market trading and market-based redispatch, the conclusions are similar to those for the previous combination. Again, the main difference between both cases and between implementation at work/in apartment buildings and at home is the way the power band is transmitted to the EMS. However, the combination achieves a higher scoring category at work/in apartment buildings than at home. Once again, this is due to the additional synergies created by the CPO.

Another combination that promises a high reduction in effort is that of peak shaving and a grid-serving power range. Peak shaving is performed exclusively behind-the-meter, wherein the EMS optimizes the power demand at the grid connection point, and it is characterized by low complexity. This use case comprises the transmission of a specified power range curve from the TSO via the metering point operator as aEMT to the grid connection point. Behind-the-meter, the power band specification can be interpreted as an additional constraint on optimization at the EMS. Combining both use cases, both the front-of-meter effort and the behind-the-meter effort are moderate, with most synergies arising behind-the-meter.

The combination of reactive power provision and the operating reserve (FCR, aFRR) displays the lowest reduction in effort at work/in apartment buildings, in both absolute and relative terms. Nevertheless, the effort reduction is high enough not to fall into the low (1) category (see Figure 4b). The main reason for the low score achieved by this combination is that the market processes of the operating reserve case are not needed in the implementation of reactive power provision. Instead, additional interfaces and data sets are transmitted.

Overall, the results for the combinations of two use cases show that the simultaneous implementation of two use cases results in high synergy potentials in terms of effort reduction. A relative reduction in implementation effort of up to 45% is identified for both use cases at home and at work/in apartment buildings. It was also found that more complex use cases, especially ancillary services and market-based ones, are often found in combinations with a high reduction in effort.

3.3.2. Reduction for Three Use Cases per Combination

Figure 5 shows the effort reduction for combinations of three use cases. As with the combinations of two use cases, we present the quantitative results of selected combinations in Appendix C. As can be seen in Figure 5a, three use case combinations at home achieve an extremely high (2) rating, which is the highest qualitative category of effort reduction. Three further case combinations attain a very high (1) score, just below the threshold for the very high (2) category. Thus, our focus lies on six use case combinations at home:

- Market-based redispatch + Spot market trading + Operating reserve (FCR, aFRR)
- Market-based redispatch + Dynamic grid fees + Operating reserve (FCR, aFRR)
- Market-based redispatch + Dynamic grid fees + Spot market trading
- Market-oriented price signal + Dynamic grid fees + Grid-serving power range
- Market-based redispatch + Dynamic grid fees + Grid-serving power range
- Optimized PV self-consumption + Spot market trading + Operating reserve (FCR, aFRR).

The combination with the highest absolute and relative reduction in implementation effort at home consists of the spot market trading, market-based redispatch, and operating reserve use cases. The analysis with two use cases per combination shows that each pairwise combination of these three use cases already results in a high degree of effort reduction. Since a large proportion of the implementation effort occurs front-of-meter and since many processes run in a similar way from this point, a 59% saving in implementation effort can be achieved with this combination compared with separate implementation. The absolute effort is still considerable (see Figure A2, Appendix C).

The combinations with the second and third highest reductions in implementation effort all include market-based redispatch and dynamic grid fees. Although these use cases have fundamentally different incentive structures and starting points, many of the technical processes involved are similar. In each case, a signal is transmitted via the aEMT to the grid connection point and implemented behind-the-meter. The combination of market-based redispatch, dynamic grid fees, and the operating reserve is particularly interesting, as it represents the combination of three grid-serving use cases involving the same players with the same or similar interfaces.

The combinations with the fourth and fifth highest reduction potentials include the grid-serving power range, which is not among the top three combinations for two use cases. Both combinations include dynamic grid fees. The combination of a grid-serving power range and dynamic grid fees in combination with an additional use case thus leads to a high reduction in effort with simultaneous implementation. One reason for this is that both have the same origin of the incentive signal, which is the DSO. In terms of interfaces and players, the two use cases hardly differ; only the implementation in the HEMS is different. In the case of the grid-serving power range, a constraint is set for optimization, whereas in the case of dynamic grid fees, dynamic prices are used as the optimization variable. The use case added in each combination, either market-oriented price signals or market-based redispatch, builds on existing front-of-meter and behind-the-meter interfaces. Differences are mainly found in the transmitted data sets and, in the case of redispatch, in the additional integration of the technical aggregator and TSO.

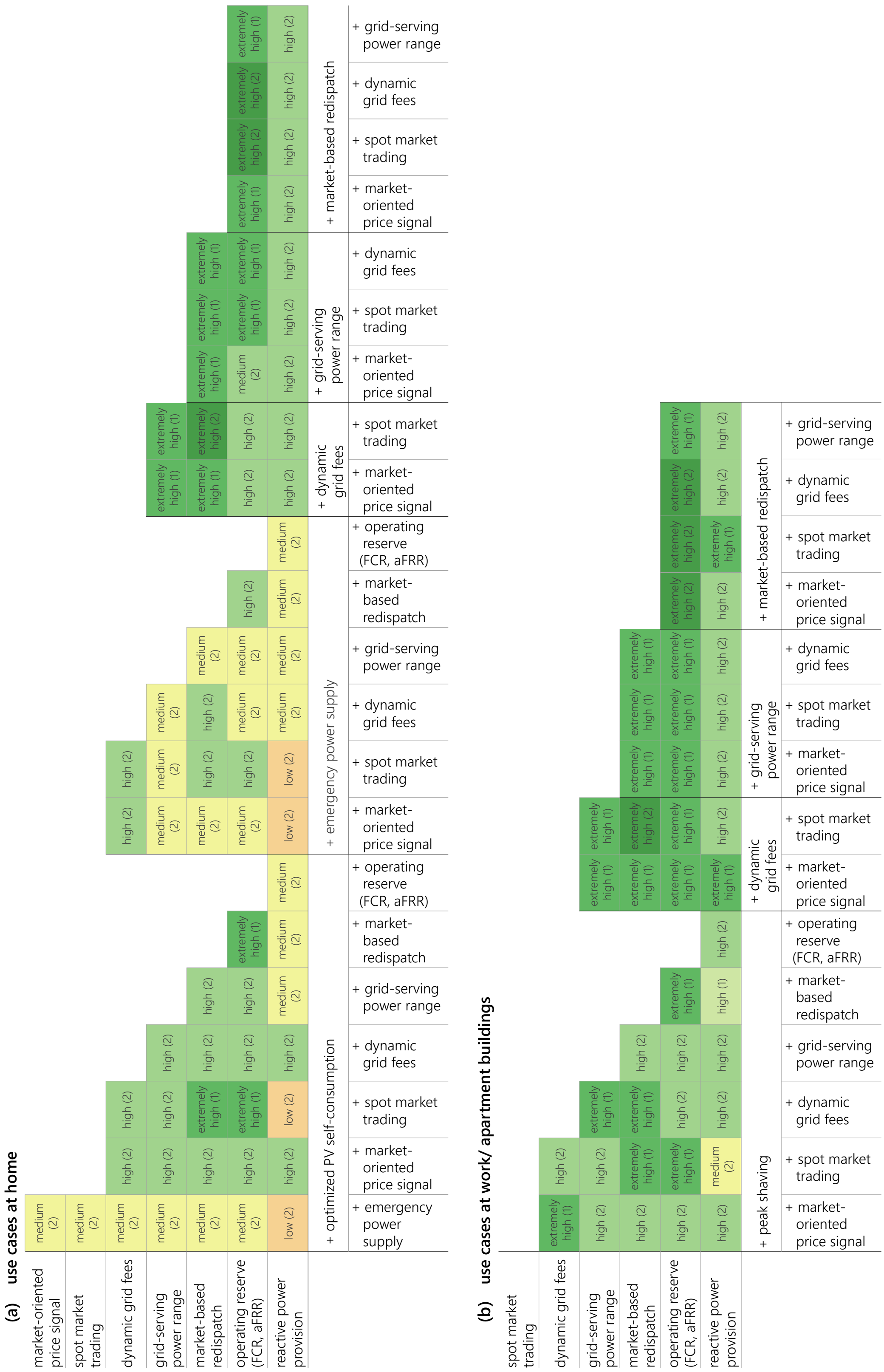

Figure 5. Effort reduction for combinations of three use cases (**a**) at home and (**b**) at work/in apartment buildings.

The sixth listed combination is the first to include optimized PV self-consumption. Since this case requires relatively little implementation effort and takes place exclusively behind-the-meter, the synergy potential is limited. For the combination of spot market trading and the operating reserve, however, it can be seen that sufficient synergies are achieved behind-the-meter to yield high absolute and relative reductions in effort. In general, the reduction potential is rather low for combinations that include the reactive power provision and emergency power supply use cases (see Figure 5). As discussed above for combinations of two use cases, these two use cases require unique interfaces and data sets. At the same time, since the implementation effort is generally not as high as for other cases, the synergy effects are not as strong.

The results for implementation at work/in apartment buildings are similar to those at home, although with generally greater effort reductions, as shown in Figure 5b. The six use cases with the highest effort reductions at work/in apartment buildings are as follows:

- Market-based redispatch + Spot market trading + Operating reserve (FCR, aFRR)
- Market-based redispatch + Dynamic grid fees + Operating reserve (FCR, aFRR)
- Market-based redispatch + Dynamic grid fees + Spot market trading
- Market-oriented price signal + Market-based redispatch + Operating reserve (FCR, aFRR)
- Market-oriented price signal + Dynamic grid fees + Grid-serving power range
- Market-oriented price signal + Dynamic grid fees + Peak shaving.

The use cases and rankings of the best three combinations are the same as for implementation at home. The underlying numerical values of the reductions are slightly higher at work/in apartment buildings, as with the combinations of two use cases. Again, this is due to the additional synergies of the CPO, which is required in all use cases. Moreover, the technical aggregator is involved in more use cases at work/in apartment buildings. The findings discussed in the previous analysis of use case combinations at home also apply to the combinations implemented at work/in apartment buildings. Likewise, the use case combinations listed fourth and fifth have already been discussed for home implementation, but the order here is reversed.

The sixth use case combination, consisting of peak shaving, dynamic grid fees, and market-oriented price signals, represents a new combination since peak shaving is only relevant to locations at work/in apartment buildings. First, the combination of dynamic grid fees and market-oriented price signals shows high synergies, especially front-of-meter (see the analysis of two use cases). Second, behind-the-meter interfaces and data sets are very similar when additionally combined with peak shaving, which is why the relative effort reduction in particular is very high (56%).

As with implementation at home, combinations with reactive power provision display lower effort reductions than other combinations for implementation at work/apartment buildings. Nonetheless, in comparison with the combinations at home, higher reduction values are achieved (only one result is medium (2), and all others are higher).

The results of the combinations consisting of three use cases all show higher effort reductions for simultaneous implementation than for separate implementation. At home, the relative effort reduction is between 28% and 59%, while at work/in apartment buildings, the reduction is as high as 40–60%. The ancillary service use cases market-based redispatch and the operating reserve are most frequently encountered in the combinations with the highest reductions. Both cases are associated with a high implementation effort, but also show high synergies due to their complexity.

The dynamic grid fees and spot market trading use cases are found with similar frequency. The case of dynamic grid fees shows a high reduction potential if signals are transmitted via the aEMT anyway or if the DSO is already involved in other use cases of the combination. The spot market trading case leads to high synergies if the technical aggregator needs to be integrated anyway or if the flexibility potentials of the EVs must be marketed in some way. A final critical discussion of the effort reductions determined for the use case combinations is given in Section 4.

3.4. Technical and Regulatory Challenges

When use cases are combined, existing technical and regulatory challenges can be amplified or reduced, or new hurdles can emerge for the first time. The fourth methodological step evaluates the most crucial challenges to the simultaneous implementation of use case combinations in the context of smart electromobility. Where possible, any options for overcoming or resolving the identified challenges and hurdles are addressed. Due to the very large number of possible use case combinations, we limit our analyses to those that are the most relevant in consideration of effort reduction. In the following, each of the most important use cases or sets of use cases is discussed in a separate section.

A general challenge to the implementation of the described use cases is the use of a smart metering infrastructure. In the case of Germany, the rollout of certified smart meters has proven to be a complex process and one that continues to be delayed due to the need to accommodate legal and political considerations [34]. In other European countries, the rollout of smart metering is progressing much faster and, in some cases, it has already been completed [35,36]. A large-scale rollout is a prerequisite of technical implementation, as a smart metering infrastructure is a crucial factor in all but one of the use cases (the exception being emergency power supply), both for the measuring data needed for billing and for transmitting price or command signals to the grid connection point and beyond. In the following sections, we assume that the implementation of single use cases is technically feasible. Regulatory aspects concerning the considered use cases are discussed wherever relevant.

3.4.1. Combining Market-Based Use Cases (Ancillary Services and Spot Market Trading)

Ancillary services, market-based redispatch, and the operating reserve (FCR, aFRR), as well as spot market trading, are use cases that involve similar technical processes, once the available power has been allocated on the basis of the market processes. No major difficulties arise in terms of interfaces or data transmission. As they use the certified smart metering infrastructure in Germany, the collection and transmission of metering data do not pose any major problem or security risk. This applies to all cases using this infrastructure. The main challenge lies with the aggregator, who must market different shares of his pooled flexibility potentials on the various markets while seeking to optimize profits. Herein, the aggregator needs reliable algorithms that enable him to allocate the shares of the available flexible power to the different markets. Market requirements must be considered, such as the availability of the operating reserve for a period of four hours in the event of allocation. The aggregator should in any case connect its decentralized assets, in our case, EVs, to form a virtual power plant.

To be able to act in the most effective way and to avoid, for example, offering capacities on one market that would then generate more revenue on another market, forecasts of redispatch, the operating reserve, and spot market demand are essential for the aggregator. Since such forecasts are currently not reliable in the case of ancillary services, this poses a major challenge, which can only be mitigated by improving forecasts. Countertrades, i.e., the re-trading of already marketed flexibilities, are less practicable and riskier for markets of ancillary services than for combinations including other use cases. Thus, it could be of advantage to the aggregator to include spot market trading as a use case with a more reliable source of revenue in its portfolio. From the aggregator's perspective, the advantages of planning security may outweigh the technical challenges. We suggest that aggregators should only allocate one market per grid connection point or flexible plant so as not to further complicate the processes. In doing so, only one control signal is transmitted to the grid connection point, which can be processed behind-the-meter without much effort by the respective EMS.

From a regulatory perspective, an evaluation of combinations including market-based redispatch is difficult, as no market exists at present. As a market-based process for redispatch will be important for aligning grid stability and end-user interests, there are sure to be challenges similar to the introduction of redispatch 2.0 in Germany [37]. Other challenges to be faced in the future include the definition of a market design and the automated post-prequalification of small-sized assets. These challenges are, however, specific to each use case and are not caused by combining use cases. The challenge to the aggregator is to meet different regulatory requirements at the same time, which results in an additional effort in prequalifying all assets for the different markets and in obtaining all the necessary market licenses. This involves a great deal of legal work, which, although time-consuming, does not in fact represent an insurmountable hurdle. Once market access has been established, there are no further major regulatory challenges of relevance to the combination, but the aggregator is responsible for balancing the amounts of electricity purchased from the energy supplier in the respective balancing zone (refer to [38] for more information). It can be seen that the combination of these markets requires experience both in the individual markets and in balancing zone management. These challenges must all be dealt with by the aggregator.

3.4.2. Combining Grid-Serving Use Cases

For grid-serving use cases, the combination of dynamic grid fees with market-oriented price signals demonstrates a high synergy potential. As the findings of the previous chapters show, the implementation of market-oriented price signals and dynamic grid fees is the same from the transmission point of the price signal by the aEMT to the grid connection point and for all behind-the-meter processes. Thus, the technical implementation of interfaces and data transmission does not pose a challenge, although handling the simultaneous price signals could do so. Since dynamic grid fees and market-oriented prices occur simultaneously at the EMS, the algorithm must be able to translate both signals into a single charging strategy. The greatest technical challenge lies with the grid operators and stems from the use case of dynamic grid fees. Determining these fees requires detailed knowledge of the distribution network and accurate forecasts of the short-term grid load and potential grid congestion. Up to now, grid operators do not, to the best of our knowledge, have the necessary data and are thus not able to calculate dynamic grid fees. Nevertheless, this hurdle is use-case-specific and not caused by the combination of use cases.

On the regulatory side, some obstacles exist for the use cases and in turn for the use case combinations. One relevant aspect that might affect the grid-serving character of the combination is that market prices and grid fees could interfere with each other, with high market prices sometimes canceling out low grid fees that incentivize grid-serving behavior. Grid fees can only be varied to a certain degree under current German regulations, with a maximum spread of fees ranging between zero and the regular grid fees, whereas market prices can have much wider spreads, so such interference is by no means unlikely. One way of mitigating this problem is to define certain limits for the variable market price signals that apply at certain times to allow dynamic grid fees to prevail. This strategy would be applicable to market-oriented price signals but not spot market trading. In Germany, less than 20% of the total electricity price charged to private households is attributable to energy procurement and only about 5% to grid fees [39]. The remainder stems from other fees, i.e., levies and taxes. Hence, for both use cases, there is a limited incentive to change charging behavior. An additional issue with dynamic grid fees is that the regulatory framework for grid fees in Germany must undergo fundamental reform, based on a recent case at the European Court of Justice. Therefore, it is impossible to predict what types of dynamic grid fees will be possible in the future. More information on this is published in [40].

Other use case combinations with promising synergies that imply a grid-serving incentive include the grid-serving power range. Technically, this case is very similar to those relating to ancillary services (redispatch and the operating reserve). As the grid operator has profound knowledge of his distribution grid that enables him to transmit a power range curve, the challenges are similar as to those for dynamic grid fees. There are no major hurdles in combination with other use cases because the power range curve can be processed behind-the-meter as an additional constraint to the optimization of the EMS.

In regulatory and legal terms, the grid-serving power range represents a major challenge. In short, there is a trade-off between the grid operators' interest in ensuring grid stability and effectively resolving grid congestion on the one hand and the manufacturers of EVs and other flexible assets, who do not want to impose any significant restrictions on the end user for the use of assets, on the other. If the grid-serving power range is combined with another use case, the financial or other added value of this case is inevitably reduced by the grid-serving power range. In addition, depending on the design, there is always the risk of restrictions, for instance, if the electric car cannot be fully charged. Hence, the grid-serving power range case must be thoroughly and consensually designed. In Germany, no regulatory framework has so far been put in place to resolve this trade-off. In the unIT-e^2 project, we plan to develop a proposal for this regulatory framework that consolidates the views of both manufacturers and grid operators.

3.4.3. Combining Behind-the-Meter Use Cases with Others

Finally, we examine optimized PV self-consumption at home and peak shaving, i.e., use cases that are implemented solely behind-the-meter. In general, these use cases are technically less complex than others and lend themselves well to combinations with others. The technical effort lies primarily with the EMS, which has to coordinate and prioritize the behind-the-meter processes. Both a parallel implementation, in which the EMS decides dynamically which use case is to be executed, and a sequential implementation, in which one use case takes place at a time, are plausible. It is possible that the end user might be able to choose which use case to prioritize.

In terms of regulation, both optimized PV self-consumption and peak shaving are well-defined use cases. If combined, restrictions or requirements of the other use cases apply, but for intelligent charging, there are no regulatory or legal conflicts to take into account. The situation is more complicated with bidirectional charging, due to the fixed feed-in tariffs for generated PV electricity. As such issues are not discussed in detail in this paper, please refer to [21] for more information.

4. Conclusions

The methodology presented here aims at evaluating synergies in the implementation effort for use case combinations and at identifying the further benefits and downsides of multi-use applications. Our findings in applying methodological steps one to four in the field of electromobility demonstrate that many use cases are suitable for combination and that substantial reductions in implementation effort can be attained when use cases are implemented simultaneously. With regard to the synergies attainable with the selected use cases, the following conclusions can be drawn:

- Combinations of use cases including market-based redispatch and the operating reserve (FCR, aFRR) show the highest reduction potential in terms of implementation effort.
- By themselves, the implementation effort of these use cases for ancillary services is relatively high, yet when combined, the additional implementation effort is often low and technical hurdles are manageable.

- For market-based redispatch, an additional thorough analysis of regulatory challenges has to be conducted if a market design has been defined.
- Spot market trading is highly suitable for combinations and displays a particularly high reduction potential when combined with use cases for ancillary services (market-based redispatch and the operating reserve).
- Similarly, combining the market-oriented price signal use case with use cases for ancillary services or grid-serving results in significant reductions in the implementation effort.
- Technical and regulatory issues need to be addressed for the dynamic grid fees use case itself.
- If dynamic grid fees are possible, however, combining this with market-oriented price signals will enable great reduction potentials in terms of implementation effort.
- The grid-serving power range use case must also be defined in more detail by the regulatory authority if it is to be feasible.
- This would lead to high reduction potentials in terms of implementation effort, especially in combination with dynamic grid fees, spot market trading, and ancillary services.
- The synergies of optimized PV self-consumption and peak shaving in terms of reducing implementation effort are unexceptional, as the individual implementation effort required for these use cases is relatively low.
- Nevertheless, both cases are suitable for use in combinations as they are technically not complex and incur few regulatory restrictions.
- The smallest synergies are for emergency power supply and reactive power provision, as these have specific requirements in terms of their technical implementation, which share little overlap in terms of interfaces or data sets.

As can be seen by comparing complex use cases with less complex ones, such as market-based redispatch with optimized PV self-consumption, one limitation of our methodology is that use cases with a high individual implementation effort often display a high reduction potential in terms of implementation effort when combined. We mitigate this effect by introducing relative effort reduction as an additional measure by which to qualitatively describe our results. Depending on the field of technology to which the methodology is applied, further emphasis could be given to this relative effort reduction. Moreover, it is important to underline that the calculation and evaluation of effort reduction potential must always be completed in the fourth methodological step (the analysis of technical and regulatory challenges) in order to obtain a consistent, holistic qualitative assessment. This additional step does make the methodology more time-consuming, but without it, we risk drawing conclusions solely on the basis of synergies relating to implementation effort.

Our hope is that this paper will make a significant contribution to the field of smart electromobility, such that combinations of use cases are tested and implemented in a target-oriented, efficient way. To this end, a quantitative evaluation of the profitability of relevant use case combinations should be conducted as the final methodological step. We intend to simulate selected use case combinations from the user's perspective using our modeling environment eFlame, which is well suited to this purpose [21]. This will enable optimized charging profiles to be obtained, which can be translated into revenue potentials. Profits in the context of market-based redispatch can be neither simulated nor predicted, as no market exists at present. The same is true for the grid-serving power range use case. Herein, it is first necessary to establish a well-defined regulatory framework before the financial benefits and effects can be evaluated. Emergency power supply and reactive power provision are also difficult to model, and it is unlikely that we will be able to conduct a financial evaluation of these use cases. To better understand and hopefully overcome the technical challenges relating to the use case combinations, a series of field trials of selected use case combinations (e.g., combinations of spot market trading, grid-serving power range, and FCR) will be conducted in the unIT-e^2 project. With regard to regulatory hurdles, we intend to draw up a legal review that will address in detail the regulatory challenges arising from individual use cases. In general, many further investigations and simulations can and will be conducted on the basis of the findings presented here.

Author Contributions: Conceptualization, methodology, visualization, and writing—original draft and editing, P.D.; investigations, formal analysis, and writing—review and editing, M.H. All authors have read and agreed to the published version of the manuscript.

Funding: The work described was conducted within the unIT-e^2 project, which is funded by the German Federal Ministry for Economics and Climate Action (BMWK) under the funding code 01MV21UN01.

Data Availability Statement: No new data apart from the presented figures were created or analyzed in this study. Additional data sharing is not applicable to this article.

Acknowledgments: We wish to thank our partners at the unIT-e^2 research project and especially our partners in the Harmon-E cluster, who provided valuable practical input and productive discussions, without which this paper would not have been possible. In addition, special thanks go to our colleagues Louisa Wasmeier and Michael Hinterstocker, who supported us in the development of the methodology, and Valerie Ziemsky, who contributed her regulatory expertise.

Conflicts of Interest: The authors declare that they have no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of the data; in the writing of the manuscript; or in the decision to publish the results.

Nomenclature

Abbreviations

aEMT	active external market participant
aFRR	automatic frequency restoration reserve
CPO	charge point operator
DSO	distribution system operator
EMS	energy management system
EV	electric vehicle
EVSE	electric vehicle supply equipment
FCR	frequency containment reserve
HEMS	home energy management system
pEMT	passive external market participant
PV	photovoltaic
SBS	stationary battery storage system
TSO	transmission system operator
V2G	vehicle-to-grid
V2H	vehicle-to-home

Parameters

$b_{Element}$	necessity of element
$\beta_{Element}$	necessity of element for additional use case
EF_{UC}	effort factor per use case
ER	absolute effort reduction
ER_{rel}	relative effort reduction
UC	use case
WF	weighting factor

Appendix A.

The following section contains a brief description of the key technical aspects of the relevant use cases as they relate to electromobility. In general, smart metering technology is a crucial factor in all the use cases, with the exception of emergency power supply. The smart metering infrastructure must be capable of (1) measuring data that are both relevant and certified for billing and (2) transmitting price signals or other command signals to the grid connection point and beyond. In Germany, the intelligent metering system including a smart meter gateway and a smart metering device is well suited to this task. All backend connections must be standardized and scalable. We presume that data relating to the status of EVs (state of charge, state of health, etc.) are the property of the vehicle manufacturers and thus stored at the manufacturers' backend. User data (preferences, departure time, etc.) are collected and stored both at the manufacturers' backend or directly at the EMS backend. Front-of-meter signals to the grid connection point are always transmitted to the HEMS or EMS, respectively, where they are incorporated into the algorithms as constraints or optimization objectives. Charging signals are always transmitted from the HEMS or EMS to the vehicle via electric vehicle supply equipment (EVSE).

At home, it is assumed that a HEMS and a HEMS operator exist for all use cases. If no vehicle status data are needed, the required user data are collected by the HEMS operator. All other specifications at home are described in Table A1 for each individual use case.

Table A1. Relevant technical specifications for use cases at home.

Use Case	Location of Optimization	Key Tasks for Players	Required Data	Other Aspects
Optimized PV self-consumption	Behind-the-meter	HEMS operator to provide optimized self-consumption based on PV forecasts.	User and additional PV-forecast data.	Only data relevant for billing to be recorded.
Emergency power supply	Behind-the-meter	-	-	No data relevant for billing to be recorded.
Market-oriented	Behind-the-meter	Energy supplier to transmit price signals securely.	User and vehicle status data.	Grid operator to be informed of the tariff.
Spot market trading	Front-of-meter	Aggregator to pool and trade flexibility potentials and transmit command signals securely.	User and vehicle status data.	High-resolution data to be recorded, and grid operator to be informed about the tariff.
Dynamic grid fees	Behind-the-meter	Grid operator to convert grid status data into grid fees and transmit these price signals securely.	User, vehicle status, and additional grid status data.	General conditions for dynamic grid fees to be defined.
Grid-serving power range	Behind-the-meter	Grid operator to convert grid status data into power range and transmit command signals securely.	User and additional grid status data.	General conditions for grid-serving power range to be defined.
Market-based redispatch	Front-of-meter	Grid operator to determine redispatch demand. Aggregator to pool and trade flexibility potentials and transmit command signals securely.	User, vehicle status, and additional grid status data.	Market place for redispatch to be provided and coordinated.
Operating reserve (FCR, aFRR)	Front-of-meter	Aggregator to pool and trade flexibility potentials and transmit command signals securely.	User and vehicle status data.	High-resolution data to be recorded.
Reactive power provision	Behind-the-meter	Grid operator to determine reactive power demand and transmit command signals securely.	User and additional reactive power demand.	General conditions for reactive power provision to be defined.

At work/in apartment buildings, it is assumed that a CPO is always necessary for billing purposes. In each case, there is also an EMS and an EMS operator. If no vehicle status data are needed, the required user data are collected by the EMS operator. All other specifications are listed in Table A2.

Table A2. Relevant technical specifications for use cases at work/in apartment buildings.

Use Case	Location of Optimization	Key Tasks for Players	Required Data	Other Aspects
Peak shaving	Behind-the-meter	EMS operator to optimize the peak load at the grid connection point.	Only user data.	Only data relevant for billing to be recorded. No aggregator needed.
Market-oriented	Behind-the-meter	Energy supplier (or aggregator) to transmit price signals securely.	User and vehicle status data.	Grid operator to be informed of the tariff. Aggregator is optional.
Spot market trading	Front-of-meter	Aggregator to pool and trade flexibility potentials and transmit command signals securely (not necessarily via grid connection point).	User and vehicle status data.	High-resolution data to be recorded, and grid operator to be informed of the tariff.
Dynamic grid fees	Behind-the-meter	Grid operator to convert grid status data into grid fees and transmit these price signals securely.	User, vehicle status, and additional grid status data.	General conditions for dynamic grid fees to be defined. Aggregator is optional.
Grid-serving power range	Behind-the-meter	Grid operator to convert grid status data into power range and transmit command signals securely.	User and additional grid status data.	General conditions for grid-serving power range to be defined. No aggregator needed.
Market-based redispatch	Front-of-meter	Grid operator to determine redispatch demand. Aggregator to pool and trade flexibility potentials and transmit command signals securely (not necessarily via grid connection point).	User, vehicle status, and additional grid status data.	Market place for redispatch to be provided and coordinated.
Operating reserve (FCR, aFRR)	Front-of-meter	Aggregator to pool and trade flexibility potentials and transmit command signals securely (not necessarily via grid connection point).	User and vehicle status data.	High-resolution data to be recorded.
Reactive power provision	Behind-the-meter	Grid operator to determine reactive power demand and transmit command signals securely.	User and additional reactive power demand data.	General conditions for reactive power provision to be defined. No aggregator needed.

Appendix B.

All elements used for the technical description and subsequent investigation of synergies arising from simultaneous implementations are listed in Table A3. The list results indirectly from detailed discussions with our project partners (see [29]) held during the preparation of field tests for the use cases. The outcomes of the discussions are aggregated and synthesized to create a generally applicable use of the presented method.

In addition, the table presents the weighting factors (*WFs*) for each weighting category. We determined the weighting factors through workshops held with experts from our project partners. Each of these experts provided an absolute effort value for example use cases. We then fitted the numerical weighting factors via a mathematical solver so as to obtain the average effort values given by the experts when calculating the effort factor per use case.

Table A3. List of all elements used for the analysis of implementation effort including weighting factors.

Category	Element Title	Short Description	Weighting Factor (*WF*)
Players involved	EV user	Main user of the EV; often but not always also the owner of the EV.	3.52
	Grid connectee	The owner of a property or building that is connected to the electricity grid (not necessarily the user of the grid connection point).	3.52
	Metering point operator	Responsible for installation, operation, and maintenance of the metering technology. This includes reading and transmitting the data to the energy supplier and grid operator (pEMT) and transmitting signals to the grid connection point (aEMT).	3.52
	Distribution system operator (DSO)	Operates electricity grids for distribution to end consumers, ensures maintenance and dimensioning at low-voltage, medium-voltage, and high-voltage grid levels.	3.52
	Transmission system operator (TSO)	Operates the infrastructure of the transregional electricity grids for the transmission of electrical energy and ensures maintenance and dimensioning in line with demand.	3.52
	Energy supplier	Provides companies and end consumers with energy (relevant here: electricity) as a producer or distributor.	3.52
	Aggregator	Pools small energy assets (e.g., EVs) and can utilize them within the scope defined by the user, e.g., to trade parts of the available power.	3.52
	(Home) energy management system operator	Delivers the energy management system and operates it via its own backend.	3.52
	EV manufacturer backend operator	EV manufacturer who operates its own backend to provide data to third parties that only it can collect (e.g., state of charge of EV battery).	3.52
	Charge point operator (CPO)	Responsible for installation, service, and maintenance of charging stations as well as for procuring the necessary electricity and billing.	3.52
	EVSE–(H)EMS	To standardized transmit charging strategy from (H)EMS to EVSE.	2.21
	Energy supplier–DSO	To allow information exchange between energy supplier and DSO (e.g., for prevention of grid congestion).	2.21

Table A3. *Cont.*

Category	Element Title	Short Description	Weighting Factor (*WF*)
Interfaces	EV–EVSE	To standardized transmit charging strategy (charging schedule) from EVSE to EV.	2.21
	Aggregator–grid operator	To exchange information/data between aggregator and grid operators (e.g., for the provision of ancillary services).	2.21
	DSO–TSO	To exchange information/data between grid operators of different voltage levels (e.g., for coordinating ancillary services).	2.21
	Intelligent metering system–metering point operator (pEMT)	To transmit measurement data to the pEMT, who can then pass it on to authorized third parties in a standardized way.	2.21
	Metering point operator (aEMT)–(H)EMS	To transmit price or command signals to the (H)EMS (behind-the-meter), in a standardized way.	2.21
	Metering point operator (pEMT)–DSO	To standardized transmit relevant measurement data from the grid point to the DSO in a standardized way.	2.21
	Metering point operator (pEMT)–energy supplier	To transmit relevant measurement data from the grid connection point to the energy supplier in a standardized way.	2.21
	Metering point operator (pEMT)–aggregator	To transmit relevant measurement data from the grid connection point to the aggregator in a standardized way.	2.21
	DSO–metering point operator (aEMT)	To transmit price or command signals from the DSO to the aEMT, who transmits the signal on to the grid connection point, in a standardized way.	2.21
	Energy supplier–metering point operator (aEMT)	To transmit price or command signals from the energy supplier to the aEMT, who transmits the signal on to the grid connection point, in a standardized way.	2.21
	Aggregator–metering point operator (aEMT)	To transmit price or command signals from the aggregator to the aEMT, who transmits the signal on to the grid connection point, in a standardized way.	2.21
	EV–EV manufacturer backend	To store relevant vehicle status data (state of charge, etc.) and optionally user data in the EV backend.	2.71
	Aggregator–(H)EMS	To directly transmit relevant information/data from the aggregator to the (H)EMS, optionally, price or command signals.	2.71
	EV manufacturer backend–aggregator	To transmit relevant vehicle status data (state of charge, etc.) and, optionally, user data to the aggregator.	2.71
	EV manufacturer backend–(H)EMS operator	To transmit relevant vehicle status data (state of charge, etc.) and, optionally, user data to the (H)EMS operator/backend.	2.71
	EMS operator–CPO	To directly transmit relevant information/data relevant for billing from the EMS to the CPO.	2.71

Table A3. *Cont.*

Category	Element Title	Short Description	Weighting Factor (*WF*)
Data sets/data processes	Energy quantities from intelligent metering via pEMT to energy supplier	At least quarter-hourly measurements of energy quantities (consumption or generation) relevant for billing of the energy supplier (among other things).	2.01
	Energy quantities from intelligent metering via pEMT to aggregator	At least quarter-hourly measurements of energy quantities (consumption or generation) relevant for billing of the aggregator (among other things).	2.01
	Feed-in power from intelligent metering via pEMT to DSO.	Feed-in power of generation plants to be read out and sent as part of an energy management measure.	2.01
	Grid status data from intelligent metering via pEMT to DSO.	Grid status data for the DSO's planning processes, which are sent at fixed, equal intervals or when certain events occur.	2.01
	High-frequency energy quantities from intelligent metering via pEMT to aggregator	High-frequency provision of measured data as a basis for implementing value-added services (e.g., relevant for market trading, etc.).	2.01
	User data from EV user to (H)EMS	Relevant user data, such as planned departure or minimum state of charge, with possibility of adjustment via app of the (H)EMS operator.	1.76
	User data from EV user to EV manufacturer backend to aggregator	Relevant user data, such as planned departure or minimum state of charge, with possibility of adjustment via app of the EV manufacturer.	1.76
	Vehicle status data from EV to EV manufacturer backend	Relevant vehicle status data (state of charge, charging requirements, etc.).	1.76
	Vehicle status data from EV manufacturer backend to (H)EMS	Relevant vehicle status data (state of charge, charging requirements, etc.).	1.76
	Vehicle status data from EV manufacturer backend to aggregator	Relevant vehicle status data (state of charge, charging requirements, etc.).	1.76
	Emergency power demand	Automatically requested demand of emergency power at the grid connection point.	1.76
	Flexibility data from (H)EMS to aggregator	Individual power band of flexibly available power at the grid connection point for aggregator to determine total flexibility potential.	1.76
	PV forecast data	Forecast data of short-term solar radiation to predict future electricity generation through PV.	1.76
	Grid-serving power range from DSO to aEMT	Power range that must not be exceeded at the grid connection point, determined by DSO to resolve grid congestion.	2.00
	Ancillary service prices from market to aggregator	Prices from respective markets (balancing markets and possibly redispatch market) relevant for trading processes of the aggregator.	2.00
	Ancillary service signal from aggregator to aEMT	Command signal resulting from aggregator trading for ancillary service use cases.	2.00

Table A3. *Cont.*

Category	Element Title	Short Description	Weighting Factor (*WF*)
	Reactive power signal from DSO to aEMT	Command signal determined by DSO based on reactive power demand.	2.00
	Price tables from energy supplier to aEMT	Price signals determined by energy supplier based on spot market prices and corresponding tariff.	2.00
	Spot market prices from market to aggregator	Prices from respective markets (day ahead market and intraday market) relevant for aggregator trading processes.	2.00
	Updated available power signal from aggregator to aEMT	Power range that must not be exceeded at the grid connection point, determined by the aggregator based on data of available flexibility and trading processes.	2.00
	Updated available power signal from aggregator to EMS	Power range that must not be exceeded behind-the-meter, determined by the aggregator based on data of available flexibility and trading processes.	2.00
	Dynamic grid fees from DSO to aEMT	Price signals determined by the DSO to prevent grid congestion.	2.00
	Charging schedule from (H)EMS to EVSE	Resulting charging schedule determined by the (H)EMS to comply with restrictions and/or achieve optimization objective.	2.00
	Charging schedule from EVSE to EV	Charging schedule originally from (H)EMS transmitted via EVSE.	2.00
	Reactive power measurement	Data of reactive power demand measured at certain measuring points in the electricity grid.	1.97
	Additional grid status data	Grid status data for the DSO's planning processes, which is additionally measured at transformers and other measuring points.	1.97
	Notification of use of flexibility from aggregator to energy supplier	When flexibly available power is successfully marketed and delivered by the aggregator, the energy supplier is notified for planning purposes.	1.97
	Notification of use of flexibility from energy supplier to DSO	When flexibly available power is successfully used by the energy supplier or the aggregator, the DSO is notified for planning purposes.	1.97
	Notification/verification of use of flexibility from aggregator to TSO	When flexibly available power is successfully marketed and delivered by the aggregator, the TSO is notified for planning purposes.	1.97
	Notification of use of flexibility from DSO to energy supplier	When flexibly available power is successfully used by the DSO in a grid-serving manner, the energy supplier is notified for planning purposes.	1.97
	Self-consumption optimization process of HEMS	Process of optimizing self-consumption behind-the-meter based on all available data.	2.98

Table A3. *Cont.*

Category	Element Title	Short Description	Weighting Factor (*WF*)
	Process of emergency power supply at HEMS	Process of suppling emergency power behind-the-meter when necessary.	2.98
	Peak shaving process of EMS	Process of reducing peak load or keeping peak load below specified limit behind-the-meter based on all available data.	2.98
	Process of cost minimization of (H)EMS	Process of minimizing electricity costs behind-the-meter based on all available data, most importantly price tables/signals.	2.98
	Process of cost minimization via spot market prices of aggregator	Process of minimizing electricity costs front-of-meter based on all available data, most importantly spot market prices.	2.98
	Process of cost minimization via ancillary service prices of aggregator	Process of minimizing electricity costs front-of-meter based on all available data, most importantly prices from the ancillary service markets.	2.98
	Process of maximizing reactive power provision at EVSE	Process of maximizing reactive power provision based on all available data, most importantly reactive power demand.	2.98

Appendix C.

As an example of the calculation of the effort factor for an individual use case, the spot market trading use case at home is selected. Implementing the use case comprises the elements that are listed in Table A4. All elements, which are neither necessary nor optional, are not included in the table. The effort factor for the use case is calculated by summing the products of the element variable and weighting factor per element (see Equation (1)). As a result, the effort factor of this use case is 82.3. For comparison, the emergency power supply use case has the lowest effort factor with 23.7 and the market-based redispatch use case has the highest factor with 92.6 for the location "at home".

Table A4. List of elements, which are necessary or optional to implement the market-oriented price signal use case at home.

Category	Element Title	Element Variable ($b_{Element}$)	Weighting Factor (*WF*)
Players involved	EV user	1	3.52
	Grid connectee	1	3.52
	Metering point operator	1	3.52
	Distribution system operator (DSO)	1	3.52
	Energy supplier	1	3.52
	Aggregator	1	3.52
	(Home) energy management system operator	1	3.52
	EV manufacturer backend operator	1	3.52

Table A4. *Cont.*

Category	Element Title	Element Variable ($b_{Element}$)	Weighting Factor (*WF*)
Interfaces	EV–EVSE	1	2.21
	EVSE–(H)EMS	1	2.21
	Energy supplier–DSO	1	2.21
	Intelligent metering system–metering point operator (pEMT)	1	2.21
	Metering point operator (aEMT)–(H)EMS	1	2.21
	Metering point operator (pEMT)–energy supplier	1	2.21
	Metering point operator (pEMT)–aggregator	1	2.21
	Energy supplier–metering point operator (aEMT)	1	2.21
	EV–EV manufacturer backend	1	2.71
	Aggregator–(H)EMS	1	2.71
	EV manufacturer backend–(H)EMS operator	1	2.71
Data sets/data processes	Energy quantities from intelligent metering via pEMT to energy supplier	1	2.01
	Energy quantities from intelligent metering via pEMT to aggregator	1	2.01
	High-frequency energy quantities from intelligent metering via pEMT to aggregator	1	2.01
	User data from EV user to (H)EMS	1	1.76
	User data from EV user to EV manufacturer backend to aggregator	0.2	1.76
	Vehicle status data from EV to EV manufacturer backend	1	1.76
	Vehicle status data from EV manufacturer backend to (H)EMS	1	1.76
	Flexibility data from (H)EMS to aggregator	1	1.76
	Spot market prices from market to aggregator	1	2.00
	Updated available power signal from aggregator to aEMT	1	2.00
	Charging schedule from (H)EMS to EVSE	1	2.00
	Charging schedule from EVSE to EV	1	2.00
	Notification of use of flexibility from aggregator to energy supplier	1	1.97
	Notification of use of flexibility from energy supplier to DSO	1	1.97
	Process of cost minimization via spot market prices of aggregator	1	2.98

Figures A1 and A2 show the quantitative results of the use case combinations with the highest absolute and relative effort reductions as well as the combination with the lowest effort reduction. For (a) use cases at home and (b) use cases at work/in apartment buildings, the respective effort factors of simultaneous (blue) and separate (grey) implementation are displayed.

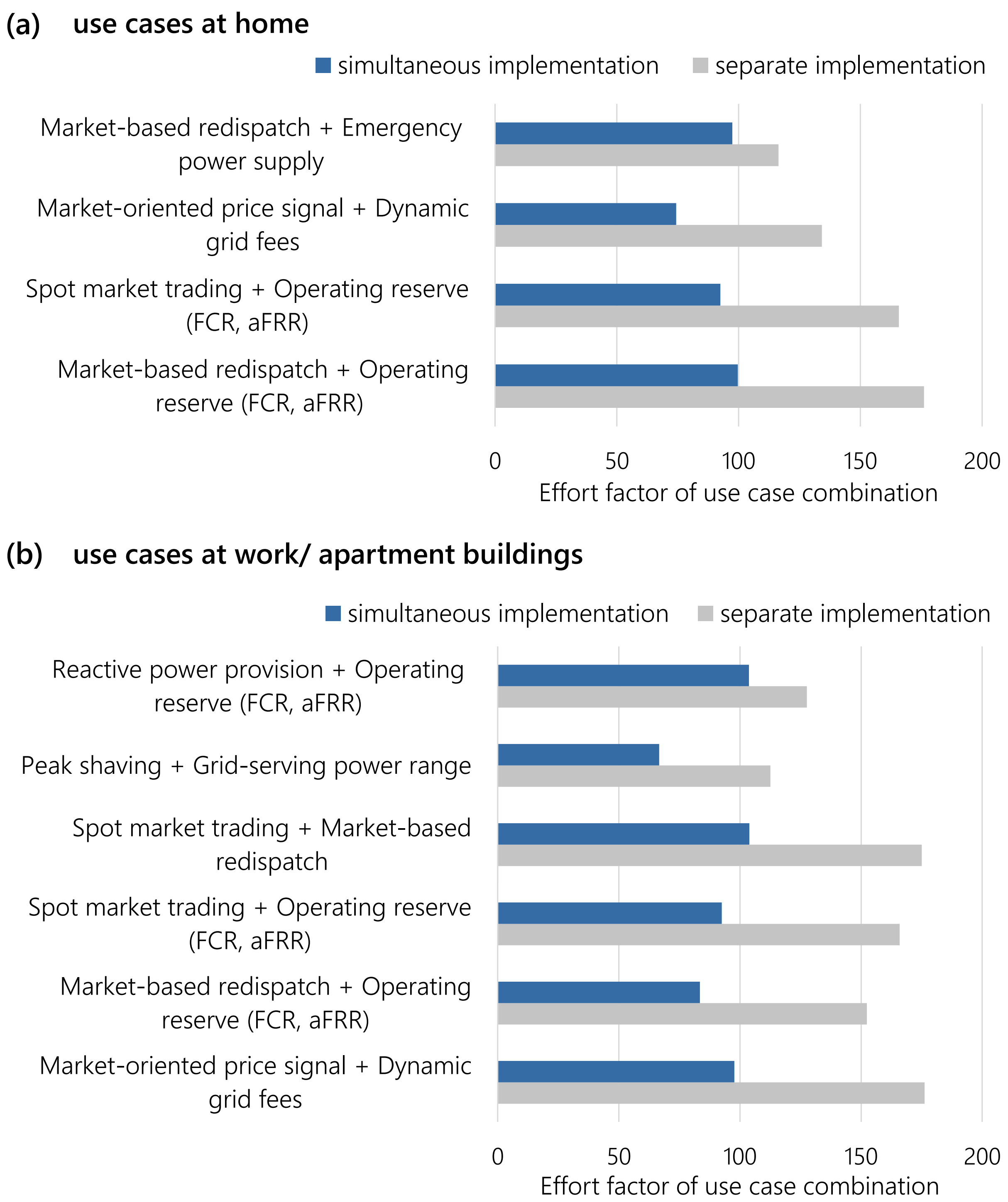

Figure A1. Effort factors calculated for selected combinations of two use cases at home (**a**) and at work/in apartment buildings (**b**).

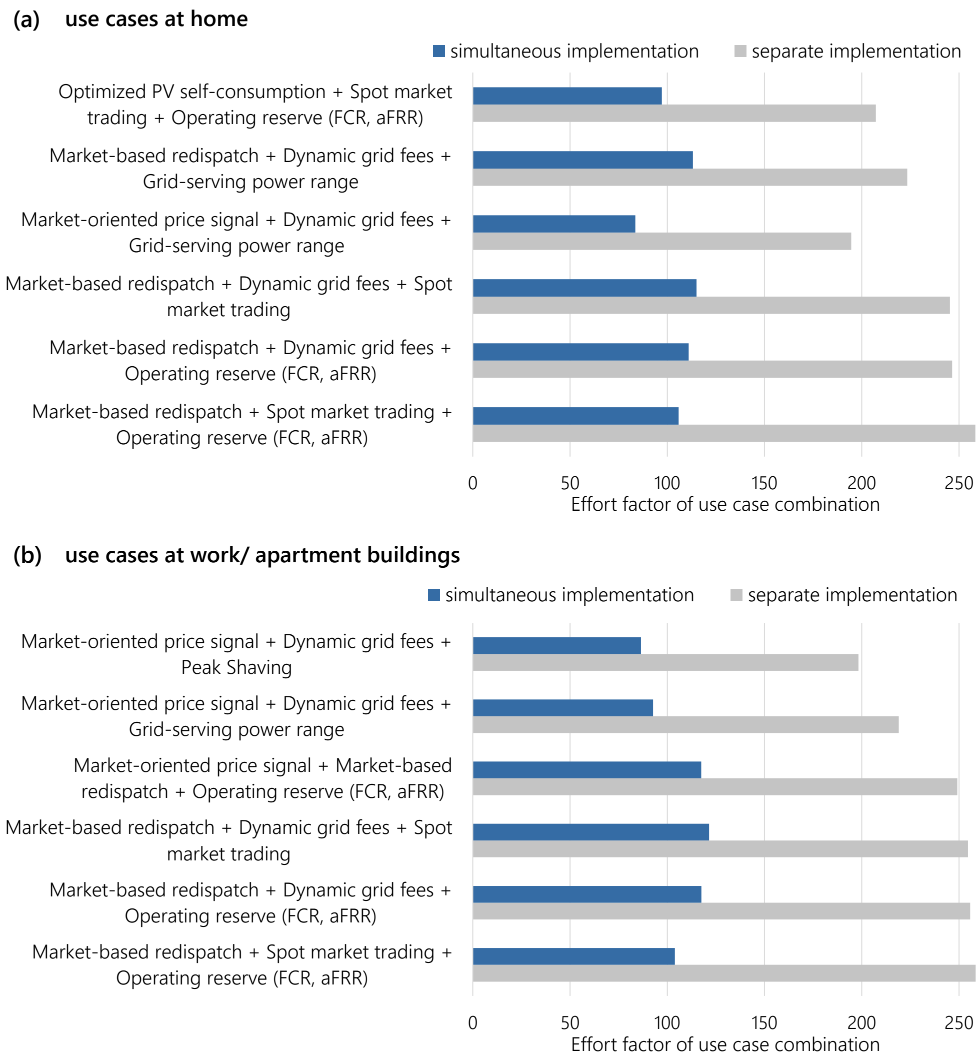

Figure A2. Effort factors calculated for selected combinations of three use cases at home (**a**) and at work/in apartment buildings (**b**).

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Publication 2 [Pub2]:
Profitability of V2X Under Uncertainty: Relevant Influencing Factors and Implications for Future Business Models

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Energy Reports **2022**, 8(16), pp. 449-455

Permanent web link:

https://doi.org/10.1016/j.egyr.2022.10.324

Available online at www.sciencedirect.com
ScienceDirect
Energy Reports 8 (2022) 449–455
www.elsevier.com/locate/egyr

7th International Conference on Advances on Clean Energy Research, ICACER 2022 April 20–22, 2022, Barcelona, Spain

Profitability of V2X under uncertainty: Relevant influencing factors and implications for future business models

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Received 10 October 2022; accepted 14 October 2022
Available online xxxx

Abstract

Intelligent, bidirectional charging strategies (vehicle-to-X, V2X) are a crucial part of the decarbonization of the transport sector. To facilitate the successful rollout of business models associated with V2X, we identify revenue potentials for different use cases, additional costs, and resulting profits for future years. Our assessments result in ranges of profits for different V2X types with the spread of profits providing a measure of uncertainty. The profit analysis shows that some V2X types can most certainly become profitable in the near future. For vehicle-to-home (V2H), for instance, profits of 390 € per vehicle and year in 2040 are determined, if viewed optimistically. Other V2X types (vehicle-to-business, V2B, and vehicle-to-grid, V2G) are subject to high uncertainties, where high as well as low or no profits are possible for future years. External circumstances are found to be of great impact regarding V2X profitability with user type and location being most relevant. Based on this, we derive business model implications and draw conclusions for a well-considered business model design. To mitigate uncertainties and increase the change of profitability, the focus of business model development should be on customer segments, revenue streams and value propositions.

Peer-review under responsibility of the scientific committee of the 7th International Conference on Advances on Clean Energy Research (ICACER 2022).

Keywords: Bidirectional charging strategies; Electric vehicle integration; Revenue potentials; Additional costs; Vehicle-to-home; Vehicle-to-business; Vehicle-to-grid; Business model design

1. Introduction

At present, E-mobility is considered as a well-suited mean to decarbonize private transportation [1]. For customers to buy and use electric vehicles (EVs), high initial costs and possibly limited mobility constitute critical obstacles [2]. For the electric grid, potential power peaks due to simultaneity in EV charging poses a threat [3,4]. The technology of bidirectional charging, or vehicle-to-X (V2X), where electricity can pass from the EV to another entity and vice versa, offers a way to overcome these obstacles and to advance the expansion of E-mobility. It promises

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https://doi.org/10.1016/j.egyr.2022.10.324

Peer-review under responsibility of the scientific committee of the 7th International Conference on Advances on Clean Energy Research (ICACER 2022).

to compensate for high initial costs and other obstacles through additional revenues. We distinguish between three V2X types: applying the technology directly at the home of an EV owner (vehicle-to-home, V2H), or at a commercially used site (vehicle-to-business, V2B), or feeding electricity into the grid regardless of the exact location (vehicle-to-grid, V2G).

To harness economic advantages of V2X, fitting business models are needed. Apart from maximizing profits, such business models must face and mitigate uncertainties due to several technical novelties and possibly further user constraints. In this paper, we thus present a methodology to determine the range of potential profits for V2X use cases within a reasonable margin of certainty. Based on a profitability analysis, we draw conclusions as to which elements of business models should be designed most thoroughly. Our investigations are part of the 'Bidirectional charging management' (BCM) project, which analyses technical, economic, and regulatory issues of bidirectional charging [5].

2. Methodology

To assess V2X charging strategies under uncertainty, we devised a multi-step methodology presented in Fig. 1. In a first step, the scope of investigation is set by selecting relevant use cases for V2X charging strategies of EVs. Criteria for the selection process are feasibility, data availability, and expected relevance based on anticipated additional revenues. To provide reliable revenue potentials in the second step, we simulated V2X charging strategies with the optimization objective of minimizing costs (i.e. maximizing revenues) for various user types and circumstances as well as for different years. Based on these sensitivities, we specified spans of revenue potentials for each use case per vehicle and year, where the differences in costs between unmanaged charging and optimized V2X charging strategies constitute additional revenues. The third step involves listing all relevant components that evoke additional costs for EV owners and users compared to unmanaged charging. We determined the differential costs of those components for present and future years. All relevant components, whose additional costs are not quantifiable for now, are taken into consideration during subsequent analyses.

In the fourth step, the spans of revenue potentials and additional costs are combined to develop a general profit range. For this purpose, we matched maximum additional costs with minimum revenues for a lower limit and minimum additional costs with maximum revenues for an upper limit, which represent the absolute extremes of potential profits for the respective charging strategies. Additionally, we developed two consistent profit paths to obtain an indication of potentially realistic profits: one path of an optimistic development with promising revenues at moderate costs, and another path displaying attenuated revenues at high costs. In the fifth step, the profitability of the respective use cases is examined and placed in the context of future implementation. By examining various profit sensitivities (variations of input parameters), the most relevant influencing factors affecting the profitability are derived. The sixth step aims to transfer the findings of the previous step to the field of business models. We link profitability prospects and influencing factors to elements of potential business models, defined as building blocks by Osterwalder et al. [6]. Business elements that are subject to strong economic uncertainties are identified and examined. On this basis, strategic options, that can be applied when designing business models in the field of V2X charging strategies to reduce uncertainties and thus to improve the prospects of success, are derived.

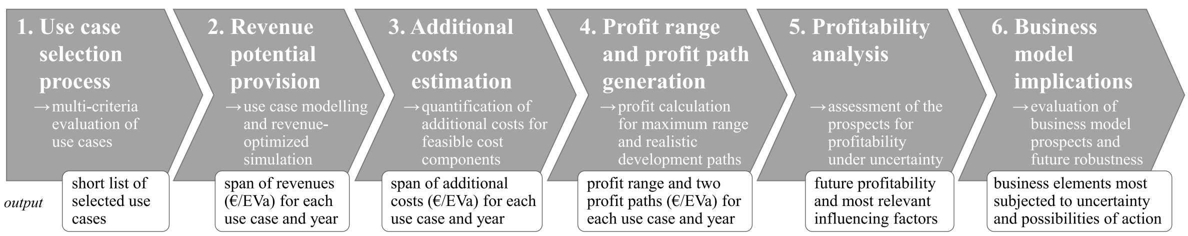

Fig. 1. Schematic representation of the methodology.

3. Profitability analysis

To start the analysis of V2X profitability, we selected the most promising use cases based on the aforementioned criteria from a list of potentially relevant use cases identified in the BCM project [7]. To reduce complexity, each of the three V2X types is represented by one selected use case. For V2H, we selected the use case of increased photovoltaic (PV) self-consumption. For V2B, peak shaving to reduce the overall demand peak constitutes the most relevant use case. For V2G, the use case of optimized arbitrage trading in spot markets (intraday and day-ahead) is selected. We assume that for every charging point exactly one EV is in use. Revenues, costs, and profits are presented as the difference between unmanaged charging and bidirectional charging with real prices related to the year 2021. All investigations are conducted for Germany and its regulatory framework. The base year is 2020. Future analyzed years are 2025, 2030, 2035 and 2040.

3.1. Revenue potential

To determine realistic spans of additional revenues for the three V2X types, we used three different modeling approaches and ran multiple simulations with different sensitivities for each model. The three models and parameter configurations for relevant simulation runs are described in previous publications [8–11]. For the revenue spans presented in Table 1, we selected suitable simulation runs for the upper and lower revenue limits for V2H, V2B, and V2G respectively.

Table 1. Additional revenue span for V2X in €$_{2021}$/(EV a) compared to unmanaged charging.

	2020	2025	2030	2035	2040
V2H	100–350	150–500	200–600	200–600	200–600
V2B	0–1000	0–1100	0–1200	0–1300	0–1400
V2G	0	50–500	60–600	70–700	80–800

The lowest spread of additional revenues is determined for V2H, where we determined moderate to high additional revenues. Here, simulation results are generally sound and reliable due to detailed modeling [8,11]. In contrast, V2B simulation results display the highest spread of revenues and thus the highest uncertainty caused by highly variable potentials for demand peak reduction and power prices depending on the exact location [9,11]. While we found that very high revenues are possible, we cannot dismiss the possibility that no additional revenues are generated at present and in the future. For V2G, zero additional revenues are determined in 2020, as the German regulatory framework is not yet prepared for a viable implementation of such use cases. For future years and a different plausible regulatory classification of a bidirectional EV, we found that additional revenues range from relatively low to high amounts per EV and year [10,11].

3.2. Additional costs

We identified the following relevant cost components of V2X use cases evoking additional costs for EV owners:

1. purchase of EVSE fitted for V2X use cases
2. installation of EVSE fitted for V2X use cases
3. installation and operation of metering equipment
4. additional hardware/software for V2X use cases
5. purchase of EV fitted for V2X use cases
6. operation of EV fitted for V2X use cases
7. operation of EV supply equipment (EVSE) fitted for V2X use cases
8. processes of registration, permits and/or contracts additionally necessary for V2X use cases

Additional costs are quantified for components one to four. Various configurations of installation are considered, each of which requires different metering equipment and installation effort, resulting in minimum and maximum additional costs [11]. For the three V2X types, the spans of additional costs turn out to be identical, such that no distinction between V2H, V2B, and V2G is made. Except for the costs of metering equipment, all cost components are initially attributed with prices per unit. For comparability, we converted these one-time costs into equivalent annual costs (EACs) by dividing the net present value by the present value of annuity factor. We assume a real interest rate of 1.7% based on a nominal interest rate of 3% and an inflation rate of 1.3% (German average of the last ten years [12]). Components' lifespans are set to 20 years for minimum and 15 years for maximum costs [13]. Table 2 shows the resulting differential EACs.

Table 2. Additional costs span for V2X in €$_{2021}$/(EV a) compared to unmanaged charging.

	2020	2025	2030	2035	2040
EVSE purchase	340–400	120–160	80–115	65–90	50–70
EVSE installation	50–70	5–25	5–25	5–25	5–25
Metering equipment	20	20	20	20	20
Additional hardware	5–35	5–35	0–35	0–35	0–35
Total	415–525	150–240	105–195	90–170	75–150

The highest additional costs of all components by some margins are the EVSE purchase costs, which mainly result from the extra power inverter required for V2X. For 2020, V2X-EVSE purchase costs are estimated at 6000 € per unit based on [14], whereas standard unmanaged EVSEs are sold at 300 to 700 € per unit [15]. For future years, we consulted with EVSE manufactures and bulk purchasers. A span of 2800 to 2300 € per unit in 2025 and 1400 to 1000 € per unit in 2040 was agreed upon for EVSEs suitable for V2X. For EVSE installations, we considered working time costs of technicians including journey time as well as material costs. Among the cases of different configurations and circumstances at the charging point, two extreme cases are identified: The maximum case, where neither an electricity nor a network cable is available and empty conduits with two wall openings must be laid (∼1530 €). The minimum case, where electricity and network connections are already in place (∼550 €). Here, additional costs mainly result from the network connection to be provided for V2X charging. Additional costs in absolute terms span from 60 to 350 €, which is a moderate amount in comparison to the absolute installation costs.

Regarding metering equipment for V2X, we considered costs for additional modern measuring devices and smart meter gateways (SMGWs), which are mandatory under certain circumstances in Germany [16]. At least one additional modern measuring device is needed in any case, including the case of minimum costs, the price of which is 20 €/a. For the case of maximum costs, we assume a SMGW to be mandatory due to a high annual electricity consumption regardless of the use case. Hence, only the one additional modern measuring device must be installed in both cases. For additionally needed hardware or software, we agreed on the approach in the BCM project that either an optocoupler (∼100 €), an additional smart energy meter (∼450 €), or a SMGW is required for a functioning V2X charging strategy [11]. For the minimum case, a SMGW is assumed to be installed in 2030, such that additional costs are zero from 2030 on, whereas maximum additional costs remain relatively high for all years.

Additional costs of components five to eight are set to zero in this paper. For the EV purchase price, we decided to exclude additional costs in consultation with the vehicle manufacturer in the BCM project, as additional costs due to V2X technology are to be allocated through appropriate margins in a revenue plan. For additional operating costs of EV and EVSE, exact values were not available to us either from manufactures or from literature. Likewise, it is not yet apparent whether and, if so, what costs could arise for additional organizational and administrative efforts. As additional costs of these components are not quantified during this step, the respective stakeholder must account for them in their profit calculations.

3.3. Range of profits

The general profit range for V2H, V2B, and V2G use cases is directly derived from the spans of revenue potentials and additional costs and shown in Fig. 2. The two consistent profit paths are also displayed, which we developed by using explicit values for additional revenue and additional costs. For the optimistic path, we chose revenue potentials and costs given excellent external circumstances (fitting regulation, good conditions on site, etc.) and well-suited user types (i.e. non-commuters). The less optimistic path, presented as gloomy path, results from revenue potentials and costs under poor external circumstances (regulatory obstacles, poor conditions on site, etc.) for less fitting user types (i.e. commuters). The results show that profitability can be achieved for all three types of V2X use cases, where profits generally increase with time. While in 2020, V2H and V2G use cases portray negative profits, from 2025 onwards profitability can be expected for many sensitivities. In 2040, even in the case of relatively negative development, such as in the gloomy path, only slightly negative profits are obtained.

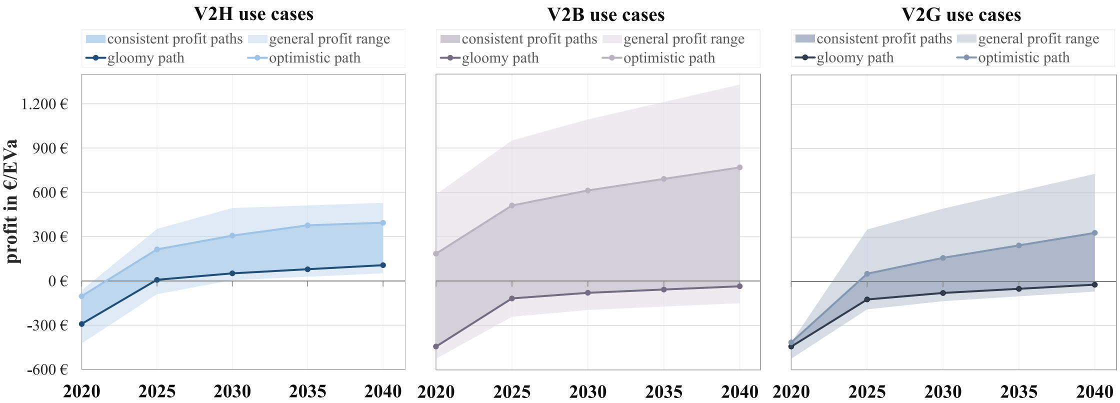

Fig. 2. General profit ranges and consistent profit paths for (a) V2H, (b) V2B, and (c) V2G use cases.

Differences between V2X types are found with regard to the range of profits, development over time, and the level of profits. V2H shows the smallest range of profits (maximum spread of 490 €/(EV a)), which is mainly a result of the relatively high certainty of revenue potentials. In 2025 and all following years, profitability is achieved not only for the optimistic but also for the gloomy path indicating a bright prospect for the profitability of these use cases. As few stakeholders besides the owner of the property (usually also EV owner and user) are interested in a direct share of profits, the level of expected profits is sufficiently high for a profitable implementation with optimistic profits of 390 €/(EV a) in 2040.

For V2B, we determined a large range of profits (maximum spread of 1480 €/(EV a)). Both the highest positive and highest negative profits are obtained, which implies a high degree of uncertainty due to highly variable revenue potentials and a high dependency on input parameters. While V2B is already profitable today in optimistic terms, profitability is not expected by 2040 for the gloomy path. Yet, if V2B is profitable, the level of profits is high, such that up to 770 €/(EV a) in 2040 are generated in the optimistic path. Similar to V2H, few stakeholders must share these profits making V2B both highly compelling and risky at the same time.

V2G represents the middle ground in terms of profit uncertainty among the three V2X types, with a maximum profit spread of 800 €/(EV a), while the lowest level of profits is displayed. Due to high regulatory obstacles, V2G is categorically unprofitable in 2020. The optimistic path suggests positive profits from 2025 with optimistic profits reaching up to 330 €/(EV a) in 2040. The gloomy path projects a slightly unprofitable future up to 2040, such that profitability is not entirely certain for V2G, especially as necessary pooling and trading involves a large number of stakeholders, who most certainly must share the profits.

3.4. Most relevant influencing factors

The main influencing factors are those which affect the profitability of each V2X type the most. From a cost perspective, significant differences originate from the circumstances at the location, i.e. existing connections and metering technology. For revenues, user types are highly relevant for all three V2X types with non-commuters generally generating higher revenues than commuters. Location parameters are most relevant in the case of V2H and V2B. As discussed in [9], the dimensioning and feed-in tariff of the PV system and the household's electricity consumption are decisive factors for respective V2H revenues. For V2B, location-specific power prices, EV and EVSE characteristics and the specific load and EV profiles of commercial sites mainly shape the revenue potentials [11].

For V2G, we found that location parameters are less important, but EV parameters have a great influence, where the size of the EV's battery is most relevant for arbitrage trading. The regulatory framework (exemptions from levies and charges), price characteristics (spot market price spread), and limited vehicle availability are further important influencing factors [10].

4. Business model implications

For the investigation of business models, the point of perspective changes. Previously declared EV owners and users, from whose perspective costs were defined, become customers in the business model. Other relevant stakeholders are *key partners* apart from the actual provider of the business model. Simply put, business model creation comprises nine defining elements: *value proposition, key resources, key activities, key partners, customer segments, channels, customer relationships, revenue streams,* and *cost structure* [6]. Here, the *cost structure* differs from the additional costs stated above, as the provider faces different costs (e.g. technological development costs) than the customer (e.g. costs for acquisition and installation). Similarly, *revenue streams* are obtained through applied pricing strategies, whereas the previously presented revenue potentials constitute the sum of all possible revenues to be shared between all relevant stakeholders. In this section, we refrain from discussing the elements *cost structure* and *revenue streams* directly but derive broadly applicable implications through our assessment. Hence, no explicit business models are developed, and no respective provider is specified.

To start with, the profit analysis indicates that revenues and costs, and consequently the economic viability of the business model, are significantly dependent on the locality of implementation and the EV user type, which in turn is defined by the targeted customer. The choice of *customer segments* addressed by a business model thus has a great effect on its profitability prospects, such that a carefully considered targeting of *customer segments* can effectively mitigate economic uncertainties especially for V2H and V2B. *Customer segments* for V2X business models range from customers with large homes and large EVs to customers with small EVs and no own EVSE, and from purely profit-driven to sustainably motivated EV customers. For V2H, well-suited customers own a PV system with little to no feed-in tariff and have a high household electricity consumption. Such customers with own homes, own PV systems and an interest in large EVs are likely to generate reliable profits and should be targeted. For V2B, customers should be individually addressed. Here, commercial sites with highly volatile load profiles in regions with high power prices must be pinpointed, as such businesses are likely to generate high profits. For V2G, not the location but the EV user type itself is crucial to maximize profitability and mitigate uncertainty. In these cases, non-commuting customers with sufficiently large EVs should be primarily targeted.

Furthermore, *revenue streams* must be aligned with the *customer segments* and essential *key partners*. The expressed *value proposition* needs to take these relationships and resulting effects on profitability into account. As previously discussed, few stakeholders participate in the V2H use cases, where moderate to comfortable profits are anticipated from 2025 on. Thus, key stakeholders might claim a share of profits from 2025 on with a relatively high level of certainty, where sufficient margins are expected for each stakeholder. As a fitting pricing strategy, we suggest a subscription model, where customers pay part of the initial costs directly and the remaining part as well as service costs continuously through recurring fees. In turn, all revenues generated over the period of use belong to the customer. The *value proposition* can therefore include the likely prospect of profitability. Yet, the efficient, direct use of green, renewable electricity and the increase in self-sufficiency and autarky are at least as important to be mentioned.

In the case of V2B, where few stakeholders are involved, profitability is not entirely certain. The possibility of slightly negative profits is opposed by the opportunity of high profits depending on the individual circumstances. To motivate respective customers to consistently reduce relevant demand peaks, the largest share of the related revenues should be received by the customers. A fixed payment strategy can be defined, e.g. a one-time payment for hardware and software components with a reasonable margin for the provider, such that all generated revenues are allocated to the customer. In this way, the business model provider minimizes his own financial risk and can still state the prospect of relatively high profits in the *value proposition* with reference to a degree of uncertainty. Similarly, for V2G, profitability cannot be guaranteed with total certainty. Yet, as the profit range is small, uncertainty is low. Even in favorable circumstances, moderate profits are generated to be shared by the relatively large number of stakeholders. Under these premises, we suggest a pricing strategy in which all actively involved stakeholders participate in the continuously generation of revenues thereby sharing the economic risks. An “as-a-service” model is suitable, in which actively operating stakeholders can offer their services for a basic fee. A share of the generated revenues could be passed on to the customers, while the rest of the share is distributed proportionally among the *key partners*. Thus, an incentive is created for all participants to operate the use case in the most profitable way. For the *value proposition*, we suggest highlighting the prospect of actively participating in the spot markets. The potential of reducing direct emissions of EV charging due to an increasing correlation between spot market prices and greenhouse gas emissions for arbitrage trading could also be promoted.

5. Conclusions

Our findings show that V2X use cases could become profitable in the near future given the right circumstances. Revenue potentials are mainly dependent on external circumstances, especially location, EV type, and regulation, as well as user types, which is why substantial revenue variations are taken into account for the different V2X types. In terms of costs, purchase costs of EVSE fitted for V2X use cases constitute inevitable additional costs for V2X users. Location parameters have the greatest influence on other relevant additional costs. Regarding the profit analysis, profitability for V2H is most probable in the near future at a sufficiently high level of expected profits. V2B profits are subject to significant uncertainties, which especially depends on the circumstances at the exact location. Yet, V2B can result in high profit prospects for individual cases. V2G may become profitable in the medium term with profits at a mediocre level and moderate uncertainty. The strength of these use cases is the independence from the exact location of the EVSE.

From a business model perspective, suitable and well-considered business models can reduce economic uncertainties through design choices that lead to profit prospects near the optimistic path. Well-targeted *customer segments* for the respective use cases have a major effect on reducing uncertainties in business models. Pricing strategies should be aligned with economic uncertainty to share both profits and risks resulting in different strategies should for different V2X types. Lastly, we recommend including additional non-monetary benefits in the *value proposition* besides the prospects of profit so that customers' expectations are not limited to financial factors alone.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Acknowledgments

We thank our partners of the BCM project funded by the German federal ministry for economic affairs and climate action (BMWK) under the funding code 01MV18004C, who provided valuable input in the development of realistic cost ranges.

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Publication 3 [Pub3]:
Prospects of Electric Vehicle V2G Multi-Use: Profitability and GHG Emissions for Use Case Combinations of Smart and Bidirectional Charging Today and 2030

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Applied Energy **2024**, 371, 123679

Permanent web link:

https://doi.org/10.1016/j.apenergy.2024.123679

Applied Energy 371 (2024) 123679

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Prospects of electric vehicle V2G multi-use: Profitability and GHG emissions for use case combinations of smart and bidirectional charging today and 2030

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HIGHLIGHTS

- A novel modeling approach for sequential market trading and combining market trading and PV self-consumption is presented.
- Results show that the use case combination yields significantly more electricity cost savings than single use cases.
- In 2030, cost savings for smart charging range from 280 –530 €/EVa and for bidirectional charging from 310 –2,780 €/EVa.
- Key influences on cost savings are price characteristics, charging hour restrictions, charging power, and user behavior.
- Operational emissions today are only reduced in some cases depending on emission intensity and charging losses.

ARTICLE INFO

Keywords:
PV self-consumption optimization
Spot market trading
Battery aging
Prospective life cycle assessment
Price forecasting

ABSTRACT

Smart charging (ability to manage charging processes by time shifting and power control) and bidirectional charging (additional discharging of electric vehicles (EVs)) are essential to decarbonize the power sector. To accelerate EV adoption, use cases should provide a financial benefit for private EV users. We thus evaluate the use cases spot market trading, PV self-consumption optimization, and the combination of both (multi-use) for smart and bidirectional charging for German households using the *eFlame* model. Our approach involves sequential spot trading on the day ahead, the intraday, and the continuous intraday market. For multi-use, both use cases are applied simultaneously. Key features of this paper are realistic scenarios for today (2021,2022) and 2030, incorporating additional costs, and assessing operational greenhouse gas (GHG) emissions expressed in kgCO2-equivalents. Our results reveal that smart charging is profitable in most cases today and in all cases in 2030, yielding annual electricity cost savings of up to 530 €/EVa compared to direct charging. Bidirectional charging, today profitable only for the combined PV self-consumption and spot market trading use case, becomes universally profitable in 2030, with electricity cost savings ranging from 310 €/EVa to 2780 €/EVa. Influential factors include year-specific price characteristics, user behavior, charging restrictions, and regulations for discharged electricity. Concerning emissions today, some charging strategies reduce operational GHG emissions while others increase emissions. Applying smart and bidirectional charging today is consequently not always beneficial in terms of emissions. In 2030, emissions decrease across all cases, positively influenced by a lower GHG intensity of the German electricity mix and less restrictive constraints on charging and discharging processes.

1. Introduction

In the transportation sector, the climate crisis requires inter alia electric mobility as a means of decarbonization. As the mere electrification of the sector entails risks such as local grid congestion or inefficient use of resources in the energy system [1,2], smart unidirectional as well as bidirectional charging strategies are essential facilitators to successfully enable the transition. As a reference, for direct

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https://doi.org/10.1016/j.apenergy.2024.123679
Received 6 December 2023; Received in revised form 23 April 2024; Accepted 8 June 2024
Available online 15 June 2024

charging, the charging process of an electric vehicle (EV) is unmanaged and starts as soon as the EV is connected to the electric vehicle supply equipment (EVSE). Smart charging implies an intelligent control that allows interruptions or delays in the charging process using forecasting under defined boundary conditions. The objective of such intelligent control can be to reduce grid load or save electricity costs using variable electricity prices [3]. Bidirectional charging goes one step further. Not only can the EV be charged intelligently, but it also becomes possible to discharge the EV battery at appropriate times. While smart charging is slowly but surely becoming available to users, bidirectional charging is still under development in some respects, and the first bidirectional chargeable EVs are becoming available only now [4,5].

To be implemented on a large scale, use cases of smart and bidirectional charging (see Section 2) must become profitable for private users, which are usually also the EV owners and hold around 47 million cars in Germany today. Use cases that allow for electricity cost savings are, for example, the smart use of time-variable electricity prices or the increased usage of self-generated renewable energy. Only when such initial use cases are profitable for users will a broader spread of smart charging technologies become possible, which in turn will ensure the implementation of other systems - or grid-serving use cases. In this regard, the combination of different use cases (multi-use) offers great potential. By superimposing various features per use case (cost reduction, emission reduction, systemic advantages), use case combinations provide the most significant situational benefit for users and the system. The technical development of such combinations is, however, still in an early stage. In this paper, we compare the profitability of selected single use cases against combined use cases and examine our results from the user's perspective.

2. Objective and background

The main objective of this paper is to provide up-to-date results on the benefits of smart and bidirectional charging of private EVs to outline future prospects for integrating EVs into the energy system. We simulate private EVs' charging and discharging strategy by an elaborate MATLAB model (see Section 3). This paper is part of the large-scale electric mobility project unIT-e^2 [3]. The basis of this paper are preceding works described in [6] in combination with the work of [7]. Fig. 1 shows the scope of this paper, where smart and bidirectional charging of private users at home is compared to direct charging. We only assess use cases which are considered as most attractive for private users of EVs within the unIT-e^2 project. These use cases are spot market trading and photovoltaic (PV) self-consumption optimization. Other use cases, such as balancing services or redispatch provision, are out of scope for different reasons. For some cases, the potential to reduce electricity cost or the number of potential EV user applying the use cases is limited [8]. Other cases are generally more complex, such that the unIT-e^2 project partners only consider them feasible in the medium or long term.

A short description of these use cases is part of Table 1. For simplification, we generally consider the EV user to also be the EV owner. In reality, this may not always be the case. In addition, we model and assess the combination of both use cases (multi-use). All other use cases are not analyzed. For PV self-consumption optimization, a private roof-mounted PV system is considered (no additional stationary battery storage or heat pump is taken into account). Public charging or charging at work are not a part of this work to keep the focus on prospects for private users. In the case of bidirectional charging, the power conversion from alternating current (AC) to direct current (DC) takes place inside the EVSE, not in the EV. To provide further background regarding the use cases and previous work, Section 2.1 to 2.3 summarize relevant literature.

The scientific novelty of this paper comprises three aspects:

1. The first-time use of consolidated model developments with a focus on private EVs and **use case combinations**
2. The utilization of most recent data for today (2021, 2022) and for the **future (2030)**
3. The assessment not only of potential financial profits but also of **environmental impacts** of charging and discharging strategies

Extensive work has already been done in the area of modeling single use cases of smart and bidirectional charging (for literature, see Section 2.1). Use case combinations have already been simulated, but most recent simulations focus on EV fleets or heavy-duty vehicles (Section 2.3). As many model developments have not yet been unified and implemented for private users, this paper addresses these developments jointly. Furthermore, a simplified approach of sequential spot market trading is presented (see Section 3.3.2). Within the project unIT-e^2, we updated input data, which is relevant for modeling the use cases. We present the most recent data regarding smart and bidirectional charging today, such as technological costs, market prices, or charging parameters. Most data relates to the two years 2021 and 2022. Concerning technological costs, prices are anticipated for the expected bidirectional charging market ramp-up in the next year, as this technology is not yet available. In addition, parameter settings for realistic results for the future, e.g., 2030, including novel market data forecasting and

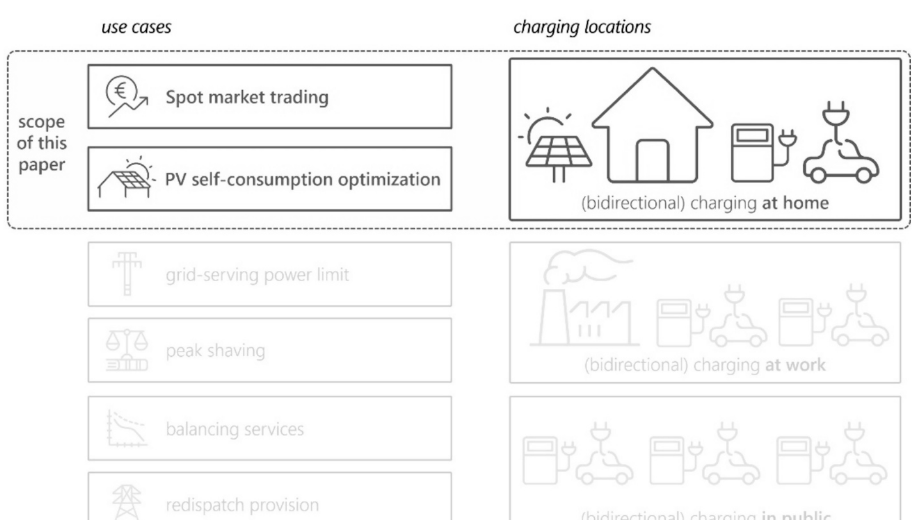

Fig. 1. Scope and schematic setup (ecosystem) of smart and bidirectional charging at home.

Table 1
Short description of relevant use cases for private users.

Use case	Short description	Added value for user
Spot market trading	Dynamically fluctuating prices on the electricity spot markets are used to charge the EV at times of low prices and – for bidirectional charging – discharge the EV into the electric grid at times of high prices. Trading can take place on either one or several markets.	Reduced electricity costs and additional revenue through electricity sales
PV self-consumption optimization	Self-generated PV electricity is used for EV charging and – in the case of bidirectional charging – discharged to best cover the household electricity demand (no discharging into the public electric grid).	Reduced electricity costs and increased self-sufficiency
PV self-consumption optimization and spot market trading (multi-use)	Self-generated PV electricity and dynamically fluctuating prices in the electricity spot markets are used to optimize EV charging and – for bidirectional charging – EV discharging, such that as much self-generated PV electricity as possible is consumed locally and dynamic price fluctuations in the spot markets are exploited in the best possible way.	Reduced electricity costs, additional revenue through electricity sales and increased self-sufficiency

consideration of the most essential sensitivities are derived and included in the simulations (see Section 4.1 and 4.2). As not only financial but also environmental benefits are important for the integration of electric mobility, we not only examined costs and profits but also applied a method to investigate lifecycle-based operational greenhouse gas (GHG) emissions for the different use cases using time-resolved emission factors of electricity (see Section 3.4).

2.1. Spot market trading (V2G)

As stated in Table 1, dynamic prices on the electricity spot markets can be used to reduce EV charging costs and, for bidirectional charging, to generate additional revenues (arbitrage trading). Trading can take place either in one or in several of the existing markets. In Germany, three spot markets exist: (1) The day ahead auction (DA), which takes place at noon one day before delivery and where hourly products are traded. (2) The intraday auction (IA) takes place at 15:00 one day before delivery and quarter-hourly products are traded. (3) Continuous intraday (CI) trading takes place up to five minutes before delivery and quarter-hourly products are traded [9]. It is important to note that actual market trading is much more dynamic and faster than conventional time-of-use tariffs (see [10]). As the minimum bid value to participate in a German spot market is 1 MW, single EVs cannot trade individually. A so called aggregator is needed to pool a number of assets, including EVs, and thus to trade at least 1 MW on the markets [11,12]. The pooling of assets involves securing against the risk that assets, such as EVs, are not available at the originally assumed time or with the originally assumed power.

Apart from the EV availability for charging, two aspects can limit the trading capability from a technological side. On the one hand, cyclical battery aging can be a constraint, as battery aging reduces the battery's capacity over time and thus its lifespan [13]. The amount of energy charged and discharged in and out of an EV battery determines the cyclical battery aging and depends on the battery technology, among other aspects [14]. A key figure to measure battery aging is the equivalent full cycle (EFC). Whether spot market trading should be limited to a set amount of additional EFCs is subject to an ongoing debate [3]. On the other hand, EV operating hours can be a limiting factor. Conventionally, the electronics of vehicles, including EVs, are designed for a specific lifetime in hours. In the past, it was not necessary to design vehicles for an average of more than a few hours per day, as on average, vehicles are only driven for short periods and not charged for long [3]. This changes with smart and bidirectional charging due to significantly longer charging times. Electronics in EVs are not yet designed for these long operating hours, meaning charging and discharging hours. For future years, advancements in this regard are likely, but still a limit of charging hours below 24 h per day is probable to not needlessly raise the price of vehicle electronics.

Especially the use case of spot market trading using bidirectional charging (also known as V2G, vehicle-to-grid) still needs to be applied on a larger scale. Several field trials with real users have been conducted or are currently being conducted [15–17]. Researchers model and simulate spot market trading in different variations to obtain information regarding its benefits and prospects. A previous work to which this paper's spot market trading approach refers is [18]. We modeled and analyzed V2G with various sensitivities, including DA market prices of other countries and DA forecasts for 2030 to 2050. Results suggested substantial cost savings for bidirectional charging today and in the future for several countries. Due to the high computational effort, the number of individual simulations per case was relatively small, and some aspects, such as variable efficiencies or regulatory exemptions, were not considered [18]. A study modeling V2G use cases in California found that cost savings for bidirectional charging are modest, especially with regard to smart charging, and could even decrease in the future [19]. In [20], where determining an optimal fleet size for V2G was the focus, findings suggest that cost savings of spot market trading range widely and are lower than for balancing services. Concerning smart charging modeling approaches, in [21] researchers present consecutive trading on DA and IA market via a rolling horizon approach. Their results indicate only a slight decrease in EV electricity costs. In contrast, simulation results of combined DA and IA trading in [22] suggest that >50% savings compared to fixed prices could be realized. The authors of [23] deduce that CI trading can be more profitable for EVs than utilizing a stationary battery storage when considering the stationary battery storage investment costs. Results for literature regarding cost savings and profits from smart and bidirectional charging range greatly, but all imply that spot market trading can be profitable.

Some additional works focus on the uncertainty of user behavior or user satisfaction when using time-variable pricing [24,25]. Yet, elaborate optimization models to develop charging strategies are not utilized. None of the mentioned literature focuses on comparing realistic cost savings for today with future years, and accompanying emissions are not examined either. In this respect, both [26,27] show emission reductions for V2G using sophisticated modeling, yet not spot market trading but balancing services and not private users but vehicle fleets are considered.

2.2. PV self-consumption optimization (V2H)

PV self-consumption optimization, which is the cost-optimized usage of self-generated PV electricity when applying smart charging or bidirectional charging, is a use case that is considered as realistic for the near future due to its technically rather uncomplicated implementation. At the same time, the use case is especially attractive for private users, as electricity costs can potentially be reduced while increasing self-consumption rate and the degree of self-sufficiency [4]. Regarding optimization and modeling, this work updates and extends the research published in [6], in which vehicle-to-home (V2H) use cases were modeled and cost savings of around 300 € per year and vehicle were identified. A similar mixed-integer linear programming (MILP) regarding V2H cost optimization is presented in [28], where similarly substantial cost savings were determined for private users regardless of the respective heating system. Regarding influencing factors, [29] identify PV tariff, weather, and EV driving behavior as key influences on cost savings, which is consistent with the findings in [6]. As we pointed out in [30], location parameters, such as PV system size, EVSE power, and local annual electricity demand, are additional important influencing factors. Beyond those modeling approaches, which optimize EV charging and discharging processes, a number of recent studies concern the development and optimization of energy management systems that enable complex PV self-consumption optimization involving EVs [31–33], but without the objective of reporting cost savings from the user's perspective. None of the researched literature explicitly highlights emission reductions that can be achieved by smart charging or bidirectional charging of an EV. If emissions are considered, not the changes in emissions due to an intelligently charged EV are emphasized, but the general emission reductions of a PV system compared to a site without PV system, as for example in [34].

2.3. Combining V2G and V2H use case

The combination of both use cases, spot market trading and PV self-consumption optimization, merges the benefits of both individual use cases. For smart charging, electricity is charged either from the on-site PV system or, depending on whether it is cheaper or when no PV electricity is available, from the grid at times of low spot market prices. For bidirectional charging, electricity can either be additionally charged from the PV system to later supply the household, or electricity can be additionally charged from the public grid at times of low market prices to later discharge back into the grid at times of high prices (arbitrage trading). From a practical implementation perspective, this multi-use application is most complex because, on the one hand, the metering concept must be very detailed for accounting reasons, and, on the other hand, the optimization must take several factors and constraints into account. To our knowledge, no actual implementation of this use case combination currently exists. Synergies resulting from the technical implementation of both use cases have been analyzed from a scientific point of view [11].

From a research perspective, two publications constitute cornerstones of modeling multi-use applications using EVs. First, in [35], a MILP model combines different use cases of bidirectional charging. In the objective function, use cases are considered in a stacked approach and evaluated in different combinations for a commercial building. Charging and discharging efficiencies are kept constant. Additional EFCs or charging hours are not restricted, but a semi-empirical degradation model accounts for battery aging. The authors found high cost savings for the different multi-use applications. These include PV self-consumption optimization and spot market trading, but the combination of only those two was not investigated separately. Still, as a broad estimate, cost savings of around 1000 € per EV and year are possible for PV self-consumption optimization and spot market trading with this model. Second, [6] present a previous version of the optimization model used in this work. Similarly to [35], the researchers used MILP for the combination of V2G and V2H. Use cases are not stacked in the objective function, but only one use case is considered at a time. Variable charging and discharging efficiencies and restrictions for EFCs and charging hours are introduced. The results of [6] show just over 500 € per EV and year, i.e. significantly less than [35]. The main differences between those two results are the different investigated sites (commercial versus domestic site) and the different spot market prices (ID 2020 versus DA 2018). An additional relevant publication is [7]. Even though the focus lies on the heavy-duty vehicle segment, the optimization model is already very similar to the one presented in this paper. The model, however, does not cover sequential spot market trading, variable charging and discharging efficiencies, and the restriction of additional EFCs and charging hours. Due to the different scopes, cost savings from [7] are not comparable. Similarly to PV self-consumption optimization, annual operational GHG emissions are not considered in any of the investigated publication.

3. Methodology

Fig. 2 shows the five-step methodological approach for evaluating the value of use cases and use case combinations for private users today and 2030. In the following sections, we explain each step.

3.1. Scope definition and scenario development

The first part of step 1, scope definition, has already been described in Section 2 to establish the focus of this paper. The scenario development comprises the definition of input data for subsequent simulations to derive realistic simulation results of the different use cases in a conclusive and robust manner. For each scenario, we define various sub-scenarios - so called cases or sensitivities - to capture the entire realistic range of this paper's scope, as private users of electric mobility are a heterogeneous group. Two main scenarios are defined: (1, today) Realistic results for today are generated using 2021 as a base case. Even though bidirectional charging was not available for private customers in Germany in 2021, prices of 2021 are a good representation of the last couple of years, which is why this year is selected as a base year. As a vital sensitivity, 2022 is considered as input year because in 2022, extreme prices occurred in the spot markets. Additional sensitivities represent relevant subgroups of users or relevant deviations from the base case. (2, future) We generate realistic results for the future using the base year 2030 and additional sensitivities, as smart charging and bidirectional charging are likely to be sufficiently established by this time.

For all cases/ sensitivities, we run 200 individual simulations (step 3 of the methodology), except for the sensitivity non-commuters, where only half the amount of simulations is used. For each simulation, we assume an individual user behavior. This user behavior is translated into a household load profile, in case a household is part of the use case, and a matching driving profile (see Section 3.3 and [36]). More details regarding the profiles are provided in Appendix B.1. Parameters relating to households, PV systems, and similar are average values for Germany based on statistical data. For 2030, we keep these parameters constant to ensure comparability. The parameters related to electric mobility result from a long consultative process in the unIT-e^2 project with relevant stakeholders from the automotive industry and mobility providers. Few parameters vary for 2030 due to expected advancements or developments. For the EV battery, the net/ useable capacity is considered. For 2021 and 2022, electricity prices are actual historical prices (constant or spot market prices depending on the use case). For 2030, time series are based on the methodology described in Section 3.3.4. For more information, see Appendix B.1.

3.2. Costs assessment

The second step, costs assessment, relies on the gathered input data. This step aims to determine the additional costs associated with smart and bidirectional charging as holistically and accurately as possible. We listed potential cost components, reviewed literature regarding such costs, and discussed cost assumptions with experts within the project. The four cost components, for which costs can be derived conclusively, are purchase costs of the respective EVSE, installation costs of EVSE, and other necessary equipment, installation, operation and maintenance of

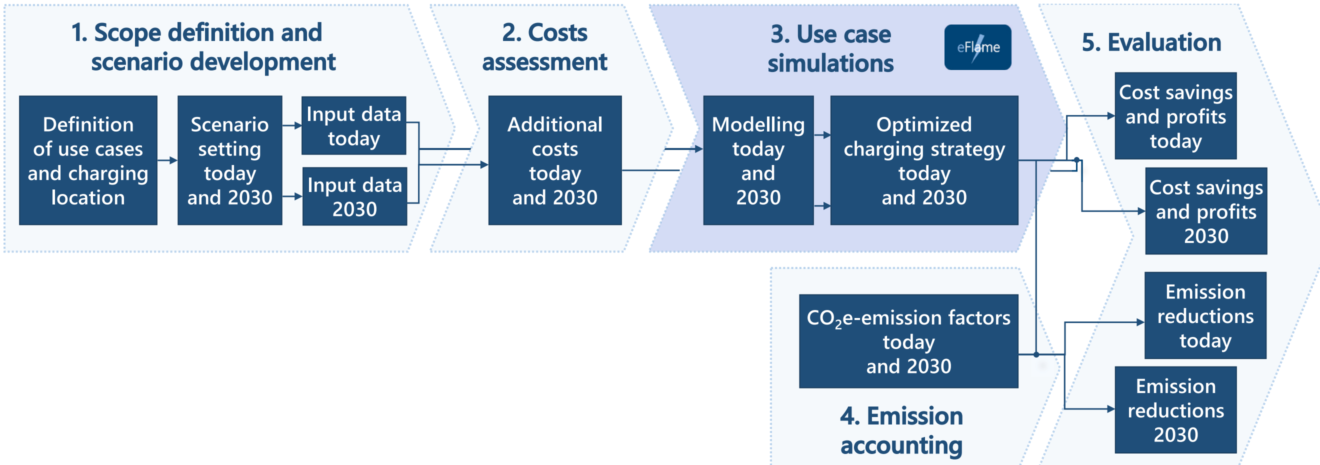

Fig. 2. Methodological procedure of this paper.

metering equipment, and additionally needed hardware for control. Additional costs of the EV are not taken into account, as we assume that these costs are not directly included in the EV purchase price. The indirect costs of increased aging of the EV battery caused by bidirectional charging due to additional EFCs are also not priced directly. Instead, additional EFCs are accounted for and classified in the later discussion of simulation results. For those cost components for which valid costs estimates for today and for 2030 are possible, minimum (MIN) and maximum (MAX) costs are derived for direct charging, smart charging and bidirectional charging based on costs assessment conducted in [30]. The assessment is updated and refined by data from reviewing most recent market developments as well as through discussions with experts from the unIT-e^2 project. Realistic middle values (MID) between minimum and maximum costs are additionally defined based on expert assessments concerning current and future developments. All other potential cost components are disregarded. The difference between direct charging and smart charging as well as between direct charging and bidirectional charging constitutes the additional costs of the respective charging strategy and year.

3.3. Use case simulations

The third methodological step comprises the modeling and simulation of the use cases using the optimization model *eFlame*. The objective is to optimize the charging and discharging strategy of an EV connected to the public electric grid via a grid connection point (GCP). Fig. 3 shows a simplified schematic illustration of the *eFlame*, which comprises two different structural parts: The preparation and handling of input data

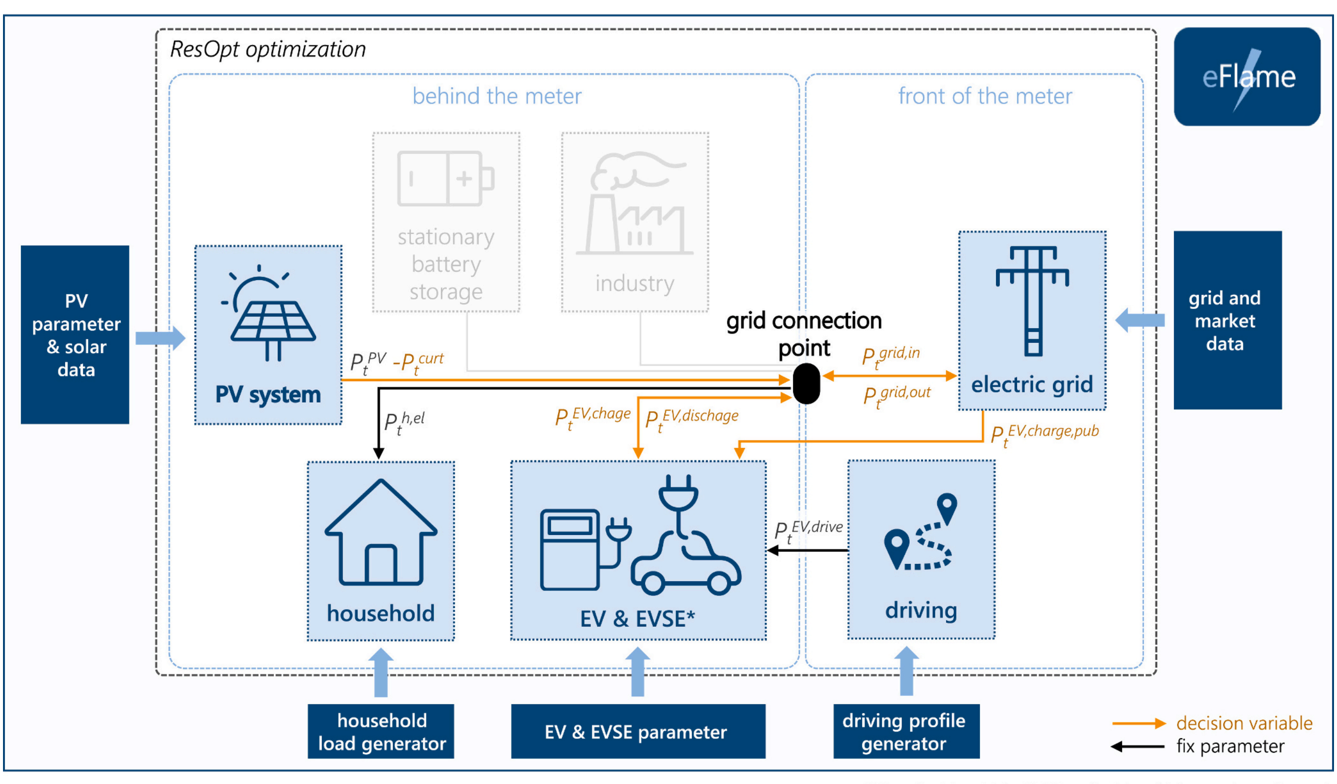

Fig. 3. Simplified illustration of the optimization model *eFlame* (unused model components grayed out).

(dark blue boxes in Fig. 3) and the actual optimization (labeled as *ResOpt optimization*). Input data are specified in the second methodological step (see Fig. 2). Model components, which are relevant for this paper, are the electric grid, the household (electric load), the EV and EVSE, the driving profile of the EV, and the PV system in the case of PV self-consumption optimization. Via the two sub-modules, household load generator and driving profile generator, household load profiles and matching driving profiles can be generated [36].

As for *ResOpt optimization*, the EV's optimal charging and discharging strategy for one year is determined by solving a mathematical optimization problem comprised of an objective function, decision variables, and constraints. The model implementation used for the two single use cases PV self-consumption optimization and spot market trading is not new, but is published in [6,18], respectively. The general objective is to minimize the user's electricity costs, expressed in the following equation:

$$min\left(\sum_{t=1}^{T}\left[c_t^{\text{el,buy}} \cdot P_t^{\text{grid,in}} - c_t^{\text{el,sell}} \cdot P_t^{\text{grid,out}}\right]\right) \tag{1}$$

In the equation $c_t^{\text{el,buy}}$ represents the costs at which electricity is bought and $c_t^{\text{el,sell}}$ the costs at which electricity is sold. $P_t^{\text{grid,in}}$ is the power with which electricity is drawn from the electric grid at the GCP. $P_t^{\text{grid,out}}$ is the power with which electricity is supplied from the GCP to the electric grid at the respective time step t. For PV self-consumption optimization, $c_t^{\text{el,buy}}$ is the constant household electricity price. As only surpluses from the own PV electricity generation are sold, $c_t^{\text{el,sell}}$ is the respective fixed remuneration rate for PV electricity. For spot market trading, $c_t^{\text{el,buy}}$ and $c_t^{\text{el,sell}}$ are variable market prices of the respective spot markets, including applicable taxes, levies, and grid fees (TLGF). These additional TLGF vary for charging and discharging, since in Germany bidirectionally chargeable EVs are exempted from a small part of the levies for the amount of electricity fed back into the public grid [37]. The reason for this exemption is that the energy stored in battery storages is charged twice with TLGF: first, when the energy is charged and stored in the battery storage, and second, when it is discharged into the grid and purchased elsewhere. With regard to the minimum bid value of 1 MW in the spot markets, the modeling is based on the assumption that the EVs are integrated in a sufficiently large pool of assets. Individual EVs can therefore use their full flexibility potential and trade without market restrictions or risk mitigation strategy. This is a simplification that tends to overestimate cost savings, but greatly simplifies the simulation of individual EVs. Relevant constraints, regarding for example the conservation of power and energy or the EV's battery energy level (state of charge, SOC), are listed and explained in Appendix A.1.

3.3.1. Variable charging and discharging efficiency

A key feature of eFlame is the modeling of variable efficiencies for EV charging and discharging. As analyzed in [6], efficiencies deviate substantially from the maximum efficiencies at powers that are significantly lower than the nominal power. This is due to the EVSE's power electronics components to convert AC to DC power when charging or DC to AC power when discharging. For use cases such as PV self-consumption optimization, where low charging and discharging powers often occur during the year, losses vary greatly when calculating with variable efficiencies instead of constant efficiencies [6]. All use cases of this work are therefore modeled with variable efficiencies.

We account for constant losses (due to EV and EVSE control systems and similar electronics) as well as variable inverter losses. Constant losses occur whenever the EV is connected and ready to charge or discharge. Variable inverter losses can be expressed as a quadratic function of the corresponding output power [38]. As described in [6], for given nominal charging and discharging efficiencies ($\eta^{\text{EV,charge}}$, $\eta^{\text{EV,discharge}}$), the variable losses, stated as functions of the AC-side power, are linearized for both charging and discharging, resulting in linear loss functions (Eq. 2 and 3) and thus in MILP. In Eqs. 2 and 3, m^{charge} and $m^{\text{discharge}}$ are the gradients of the linear loss functions. $n^{\text{EV,charge}}$ and $n^{\text{EV,discharge}}$ are minimum losses at zero power, that is the constant losses. In Appendix A.2, we display the efficiency curve of the EVSE inverter and the curve of variable losses.

$$P_t^{\text{EV,loss,charge}} = m^{\text{charge}} \bullet P_t^{\text{EV,charge}} + n^{\text{EV,charge}} \bullet b_t^{\text{charge}} \tag{2}$$

$$P_t^{\text{EV,loss,dis charge}} = m^{\text{discharge}} \bullet P_t^{\text{EV,discharge}} + n^{\text{EV,discharge}} \bullet b_t^{\text{discharge}} \tag{3}$$

3.3.2. Sequential spot market trading using a rolling horizon with limited charging hours

A valuable novel feature of *eFlame* regarding the modeling of spot market trading use cases is the inclusion of all three spot markets in Germany (DA, IA, and CI) in the optimized trading strategy. In contrast to [18], where trading at the respective market takes place at the specific auction time, we simplified the implementation to reduce the computational time, which in turn enables a detailed use case assessment on the basis of many individual simulation runs. The implementation used here to account for all three spot markets is a sequential approach, where each market is considered separately for the entire optimization horizon regardless of the actual time of auction. Only the time of the physical electricity delivery is accounted for. This implementation uses a rolling horizon approach instead of optimizing an entire year at once. The whole optimization period of one year is divided into a series of smaller optimization horizons. These optimization horizons are overlapping, as illustrated in Fig. 4. The MILP optimization problem is solved for each optimization horizon, one after the other, but only optimization results for a set part of the optimization horizon are saved. The remaining overlapping results are discarded. The results of the saved optimization horizon are passed on as start values for the next optimization step. By introducing an overlapping horizon, constraints at the end of the horizon do not have a distorting effect on the results.

Fig. 4 also represents the sequential spot market trading approach, with each of the three markets illustrated in a different shade of blue. Starting at the bottom of the graph, we first use prices of the DA to optimize the charging and discharging of the respective EV for the first optimization horizon. Next, we use IA prices for the same horizon, just as in the third step with the timeseries of CI prices. Only the first optimization with DA prices is not subject to additional constraints but is similar to the case of single spot market trading. After this first optimization, the charging and discharging strategy of the EV is initially set. What follows at the second step with IA prices can be interpreted as an iteration or update of the previous trading. If higher price spreads occur at other times at the IA than at the DA, the energy is countertraded. For instance, the electricity that was previously purchased for charging at the DA can be sold at the IA if prices are sufficiently high. Since there is now a shortage of electricity for charging, it is purchased again at other times during the optimization horizon at the IA. The times of actual physical charging and discharging of the EV are changed after the second optimization. The previous DA trading is not discarded but taken into account for calculating electricity costs and revenues. After the IA optimization, the third optimization with CI prices is carried out just like the IA optimization before.

In eFlame, subsequential trading is accounted for by introducing the variables $P_t^{\text{schedule,in,i}}$ and $P_t^{\text{schedule,out,i}}$. The label *schedule* refers to the notion that we regard optimization results of a previous market trading as a schedule for the next market. The index i indicates the finalized optimization steps within the optimization horizon ($i = 1$ for after DA trading, $i = 2$ for after IA trading and $i = 3$ for after CI trading, see Fig. 4). We define $P_t^{\text{schedule,in,i}}$ and $P_t^{\text{schedule,out,i}}$ via Eqs. 4 and 5 as the sum of a previous schedule and electricity passing through the GCP for the previous optimization step. We implement the additional constraint by incorporating $P_t^{\text{schedule,in,i}}$ and $P_t^{\text{schedule,out,i}}$ into the power balance at the GCP for each optimization step of sequential spot market trading (Eq. 6,

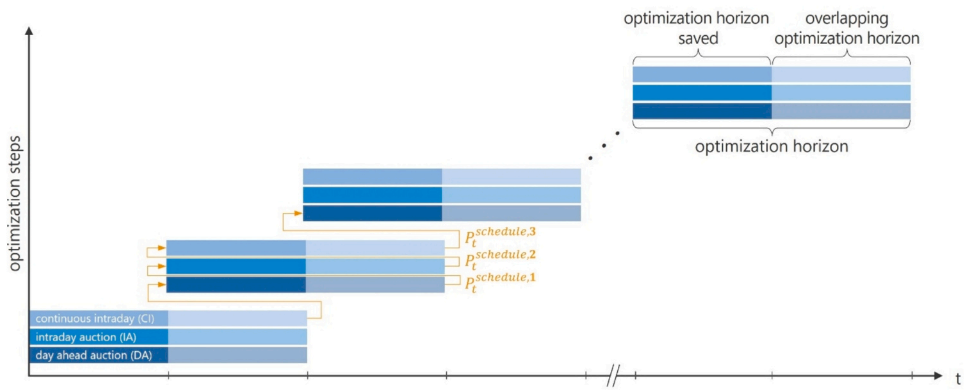

Fig. 4. Schematic display of rolling horizon approach including sequential spot market trading.

compare to Eq. 2). $P_t^{\text{schedule,in,3}}$, which is the power passing through the GCP after CI trading, is saved and passed on to the following optimization horizon as part of the starting values.

$$P_t^{\text{schedule,in,i}} = P_t^{\text{schedule,in,i}-1} + P_t^{\text{grid,in,i}-1} \tag{4}$$

$$P_t^{\text{schedule,out,i}} = P_t^{\text{schedule,out,i}-1} + P_t^{\text{grid,out,i}-1} \; (i \,\varepsilon\, \{1,2,3\}) \tag{5}$$

$$\begin{aligned} &P_t^{\text{grid,in,i}} - P_t^{\text{grid,out,i}} + P_t^{\text{schedule,in,i}} - P_t^{\text{schedule,out,i}} \\ &= P_t^{\text{h,el}} - P_t^{\text{PV}} + P_t^{\text{curt,i}} + P_t^{\text{EV,charge,i}} - P_t^{\text{EV,discharge,i}} \end{aligned} \tag{6}$$

An additional feature that we use for the simulations is the limit of daily EV charging and discharging hours. As described in Section 2.1, charging and discharging hours can constitute a relevant constraint for smart and bidirectional charging for the years to come. The possible charging and discharging hours are limited per day via Eq. 7. Here, $\text{CH}_{max,day}$ is the limiting value of (dis)charging hours per day and T is the total number of timesteps of the defined optimization horizon. b_t^{charge} and $b_t^{\text{discharge}}$, which are the parameters that represent the number of timesteps in which the EV can be charged and discharged, are limited by this constraint.

$$\frac{\sum_{t=1}^{T}\left[b_t^{charge} + b_t^{\text{discharge}}\right]}{T} \bullet 24 \leq \text{CH}_{max,day} \tag{7}$$

3.3.3. Model developments for use case combination

A further development of *eFlame* concerns the combined optimization of PV self-consumption optimization and spot market trading. The generalized objective function of Eq. 1 is modified, and the applied input data used in the objective function are different. As for the single use case spot market trading, electricity buying costs ($c_t^{\text{el,buy}}$) are the variable spot market prices of the respective year, including all applicable TLGF for electricity purchase. The selling costs ($c_t^{\text{el,sell,EV}}$) of electricity, which is discharged from the EV into the public grid ($P_t^{\text{EV,discharge,2g}}$), are the respective variable spot market prices, including the TLGF for electricity sale (some of the TLGF are exempted, more details see Appendix A.3). In contrast to single spot market trading, a PV system is applied. Surpluses in PV generation are sold at the respective fixed remuneration rate for PV electricity ($c_t^{\text{el,sell,PV}}$) in addition to the electricity, which is discharged from the EV in the case of bidirectional charging. The modified objective function is:

$$min\left(\sum_{t=1}^{T}\left[\begin{array}{c} c_t^{\text{el,buy}} \cdot P_t^{\text{grid,in}} \\ -c_t^{\text{el,sell,EV}} \cdot P_t^{\text{EV,discharge,2g}} \\ -c_t^{\text{el,sell,PV}} \cdot \left(P_t^{\text{grid,out}} - P_t^{\text{EV,discharge,2g}}\right) \end{array}\right]\right) \tag{8}$$

Concerning the conservation of power and energy as well as all other constraints, the equations stated in Appendix A.1 also apply to the use case combination. In [7], where this model feature was first published for the application of electric heavy-duty trucks, a different way of description is used for the same feature. A major difference between this approach and the model implementation in [6] is that in the implementation presented here, both use cases are applied at the same time. In each time step, self-generated PV power can be used for self-consumption, and at the same time spot market trading can take place.

3.3.4. Price forecast for future years

To assess future potentials, we simulate spot market trading for the year 2030. DA prices are used from [1], where we model the impact of an increasing number of EVs on the European energy system in the energy system model ISAaR. IA and CI prices are derived based on these DA prices as well as the resulting residual load from [1]. The IA and CI prices, which are represented by the ID1 price index (volume-weighted quarter hour price of each hour), of the year 2023 (January till September) are projected onto the year 2030. This projection is based on the distinctive characteristics of the quarter-hourly intraday prices in relation to the hourly DA prices.

Historically, within one hour, the intraday price in the first quarter hour tends to be higher, and the last quarter hour tends to be lower than the DA price when the residual load declines in that hour and vice versa [39,40]. While the hourly products of the DA market cannot capture changes in the residual load within one hour, these have to be balanced on the intraday markets. We capture this characteristic by regression of price deviations between DA and intraday prices and deviations in the quarter-hourly residual load forecast for the hourly average of this forecast in 2023 (January till September). We then project the regression to the residual load forecast 2030 from [1], which is interpolated from hourly to quarter-hourly resolution to obtain price deviations between the DA and intraday prices. Both IA and the CI trading are modeled with this methodology, using the characteristic of the reference time period of the IA or the ID1 index, respectively. For the reference time period, the correlation of price and residual load deviations is stronger for the IA than for the ID1 index. This is due to the closer temporal proximity of the IA towards DA trading, leading to less unexpected events and changes in the renewable and load forecast compared to CI prices, which cause price deviations independently of the described characteristic and are not captured by the regression. In Appendix B.1, we present additional information regarding these price forecasts.

3.4. Emission accounting

In the fourth step, environmental impacts of smart charging and bidirectional charging are accounted for. In an increasingly renewable-based power system, the upstream chain of power plants, i.e. including the extraction of raw materials and the production phase, gains importance. We calculate annual operational GHG emissions by using emission factors, which have been determined through a Life Cycle Assessment (LCA) for each relevant case and year. For the operational impact, we use LCA results for the impact category of climate change, i.e. the Global Warming Potential (GWP) with the unit of kgCO2-equivalents (kgCO2e). Other impact categories, such as human toxicity or metal depletion, are out of scope. As the two primary input datasets, the resulting charging profiles for the simulation in eFlame are combined with hourly, lifecycle-based emission factors of electricity generation of the respective year. The annual operational emissions result from the amount of charged electricity multiplied by the respective emission factors in the hours of charging. We follow the approach of [41]. Accordingly, in times of EV discharging or feeding electricity from PV into the public grid, emissions enter the balance with a negative sign leading to a reduction of emissions. This allocation approach follows the assumption of replacing electricity in the grid in these hours that otherwise would require production from power plants. In the case of bidirectional charging, this often concerns fossil-based generation due to a correlation of high prices with high emission factors.

Overall, the derived emission factors are determined through the method of an LCA as defined in the ISO norms 14,040:2021/14044:2006 to consider the entire lifecycle of power generation, including combustion-based (direct) emissions but also emissions from the upstream chain, e.g., material extraction, production phase. For the emission factors of historical years (2021, 2022) and the future (2030), however, different approaches and data are required. The applied emission factors in this study originate from [42] for the historical years and [43] for the future year 2030. The following sections summarize the vital methodological steps and data sources.

3.4.1. Historical years

As outlined in [42], the two main data sources for calculating the hourly emission factors include electricity generation by generation type (power plant) on the one hand and type-specific emission factors on the other. Data on the net electricity generation originate from the "Transparency Platform", an open-data portal of the European Network of Transmission System Operators for Electricity (ENTSO-E) [44]. It provides data on net electricity generation by generation type on an hourly basis. Using a scaling factor, the German data on electricity generation is adjusted to the energy balances from Eurostat [45] to counteract systematic deviations from statistical data. To determine the scaling factor, statistical data on gross electricity generation is converted to net electricity generation by using the self-consumption of power plants, which we calculate from [46]. The scaled net electricity generation from ENTSO-E is combined with the lifecycle-based emission factors per kWh of electricity to determine the final hourly time series of emissions for the years 2021 and 2022. These emission factors include different GHG emissions, which are comparable by using the 100-year global warming potential (GWP100). For Germany, the German Environment Agency (UBA) provides direct and upstream emission factors per electricity generation type in [47]. However, these values are primarily energy-related. To determine the required emission factors per kWh of electricity generation, primary energy-related emission factors are divided by the efficiency for each generation type. The efficiency is derived from Eurostat data on energy input and electricity output [45]. For electricity generation from combined heat and power units, the allocation uses the "efficiency method" according to the GHG Protocol [48]. As we follow a consumption-based approach, we consider not only GHG emissions from the electricity produced but also imports and exports. Imports and -exports of electricity (data from ENTSO-E [49]) are included using the "flow tracing" method (see [50,51]). To determine the GHG intensity of imports and exports, IPCC emission factors are used [52]. Additionally, data from the Council of European Energy Regulators (CEER) is used to include country-specific grid losses in the emission factors [53].

3.4.2. Prospective year

Similar to the historical emission factors, the two main data sets used in [43] to determine emission factors for the year 2030 are the hourly electricity generation and specific emission factors by production type. For electricity generation, input data stems from a modeled climate policy scenario for the electricity sector in Germany by 2030. The modeling is conducted with the energy system model ISAaR. Details on the model's function and landscape are outlined in [51]. The underlying scenario represents an expanded version of the solidEU scenario described in [1]. For the developments in the system (e.g., deployment of renewable energies capacities), the scenario considers regulatory framework conditions of the European Green Deal and the Ten-Year-Network-Development-Plan of the European Network of Transmission System Operators for Electricity (ENTSOG & ENTSO-E). For Germany, the scenario further considers the latest national policy package ('Easter Package') [54] and the Federal Climate Change Act [55], including targets for renewable energy expansion and national ceilings for direct (combustion-based) GHG emissions.

Unlike the lifecycle-based approach for historical emission factors, the method in [43] follows a prospective LCA (pLCA) approach. The idea of a pLCA is the consideration of future developments when assessing environmental impacts of emerging technologies [56]. As outlined in [57], this includes considering changes in the foreground, e.g., technological specifications, and in the background system, e.g., changes in the system the technology is embedded in, such as the global economy. The applied model ISAaR incorporates assumptions on future developments of investigated power generation technologies (e.g., sizes of wind turbines). Through a technology matching between the technologies used in ISAaR in 2030 and the respective process in the Life Cycle Inventory (LCI), the method considers changes in the foreground system. Furthermore, [43] apply the modeling results on the power generation per technology (use phase) from ISAaR. Developments affecting the background require an adjustment of the entire LCI. As outlined in [57], several frameworks for generating prospective LCI databases (pLCI) have been developed, including the most recent framework 'premise'. Premise allows a systematic modification of the Ecoinvent LCI database by integrating developments from a chosen scenario of an Integrated Assessment Model (IAM) (details on premise in [58]). For consistency with the climate ambitions followed in ISAaR, the climate policy scenario from the IAM 'REMIND' [59] is applied, with medium challenges to mitigation and adaptation by following the Shared Socioeconomic Pathway 2 (SSP2) outlined in [60]. After a technology matching between the created pLCI databases and the ISAaR, we quantify GHG-emission factors as the GWP per kWh of electricity generated per technology type in $kgCO_2e$ using the LCA framework 'Brightway' [61]. These factors serve as an input for the last step, i.e. the multiplication of the emission factors per technology with the share of the respective electricity generation per hour as an output from ISAaR. Analogous to the historical emission factors, the resulting time series represent hourly lifecycle-based emissions of the German energy system for the year 2030.

3.5. Evaluation

The fifth step comprises the evaluation of cost savings, additional costs, profits, and emissions of the charged and discharged electricity linked to the use cases. For this purpose, the optimized charging strategies for each use case and year resulting from the simulations are translated into operational cost savings. These savings are combined with additional costs per year and EV to display and discuss current and future profitability prospects. For an environmental evaluation, we present and discuss the operational GHG emissions per EV and year for each case.

4. Results

To analyze the results of our work, we first introduce the most important input data for today and 2030, which resemble the scenarios to be simulated. Second, we present additional costs for smart charging and bidirectional charging. Third, we analyze all relevant results.

4.1. Scenarios and input data

As a result of the scenario process, Table 2 summarizes the input data of the developed scenarios, including the cases/ sensitivities used in the analyses in Section 4.3. The values in Table 2 summarize the cases and sensitivities to be simulated and analyzed, including a short description of the respective input data. The values in Table 2 refer to average values of all profiles (200 individual simulations). As a result of the scenario process, we refrain from varying too many parameters, having already done so in previous works [6,18]. Instead, we focus on sensitivities that are feasible variations from the base cases. For spot market trading, the focus lies on sequential market trading (see Section 3.3.2). In addition to the displayed cases, Appendix C.1 shows some extra simulations we conducted to determine robust input settings.

4.2. Additional costs

As a result of the cost calculations, we present differential costs of smart charging to direct charging and bidirectional charging to direct charging. Table 3 shows these additional costs for today and 2030. For smart charging, significant additional costs arise for unfavorable circumstances, with initial additional costs as high as 1700 € in the MAX case today (plus additional annual metering costs). The purchase of a smart EVSE can be substantially more costly than the purchase of an uncontrollable EVSE. Rather costly additional hardware may also become necessary. Installation costs can increase considerably due to additional cabling and internet connection. For 2030, EVSE purchase costs decrease, in particular for the MAX case. All other costs remain essentially the same.

For bidirectional charging, additional costs for EVSE installation, metering equipment and additional hardware are identical to those for smart charging. However, the additional costs of purchasing a bidirectional EVSE are substantially higher, as an additional inverter from DC to AC is needed for discharging the EV's battery (we consider a DC EVSE for bidirectional charging). These additional EVSE purchase costs result in a total maximum of 5200 € of initial additional costs today. As a strong cost degression for bidirectional EVSEs is anticipated, these additional costs decrease considerably for 2030, resulting in initial additional costs of about 2300 € in the MAX case 2030.

To sum up, the respective use cases must yield substantial annual cost savings for users of smart and bidirectional charging to justify an investment. These findings are consistent with the results in [30]. In Appendix B.2, we list the absolute costs of all three charging strategies and provide further details.

4.3. Savings, emissions and profitablity

Based on the use case simulations in *eFlame*, we first present the electricity charged and discharged, the cost savings, and - in combination with calculated hourly emission factors - operational GHG emissions per year for the base cases 2021 and 2030. Second, we analyze the different sensitivities of all three use cases. Third, in combination with the additional costs presented before, profitability prospects of the different charging strategies and use cases are analyzed in dependence on the year of purchase. All results are specific per EV.

4.3.1. Analyses of base cases

In this section, we analyze the base cases 2021 and 2030 in detail. Fig. 5 and Fig. 6 present averaged simulation results of **sequential spot market trading** for all three charging strategies distinguished by components that demand or supply electricity. No household is included in the simulations, as only an EV is needed to perform the use case. The top of Fig. 5 shows that due to the implemented variable charging efficiency

Table 2
Simulated scenarios and respective sensitivities including selection of most relevant input data.

Scenario	Cases/ sensitivities	use cases	Relevant parameters & input
today	base case 2021	spot market trading (1), PV self-consumption optimization (2), PV self-consumption optimization + spot market trading (continuous intraday market) (3)	60 kWh battery capacity, 11 kW (dis) charging power* 85% nominal roundtrip efficiency** 7 kW_{peak} PV system* prices of 2021 (constant or spot market electricity prices, fixed PV renumeration rate, TLGF exemption)** ~ 3000 kWh/a electricity consumption of household (without EV), ~ 7200 kWh PV electricity generation, ~ 12,000 km annual mileage*** 6 h/d charging hours limit* Others: see tables in Appendix B.1
	prices 2022	(1), (2), (3)	As base case, expect for: prices of 2022 (constant or spot market electricity prices, fixed PV renumeration rate, TLGF exemption)**
	non-commuters 2021	(1), (2), (3)	As base case, expect for: ~ 9000 km annual mileage***
	no charging hours (CH) limit 2021	(1), (2), (3)	As base case, expect for: no charging hours limit
	reduced TLGF (increased exemption) 2021	(1), (3)	As base case, expect for: TLGF reduced for EV discharging into the public grid, exemption as for commercial stationary battery storages**
future	base case 2030	(1), (2), (3)	60 kWh battery capacity, 11 kW (dis) charging power* 89% nominal roundtrip efficiency** 7 kW_{peak} PV system* prices of 2030 (constant or spot market electricity prices, fixed PV renumeration rate, TLGF exemption)** ~ 3000 kWh/a electricity consumption of household (without EV), ~ 7200 kWh PV electricity generation, ~ 12,000 km annual mileage*** 12 h/d charging hours limit* Others: see tables in Appendix B.1
	non-commuters 2030	(1), (2), (3)	As base case, expect for: ~ 9000 km annual mileage***
	increased TLGF (reduced exemption) 2030	(1), (3)	As base case, expect for: TLGF increased for EV discharging into the public grid, exemption rule as today**

* Based on specifications of the unIT-e^2 project [3].
** For more details see Appendix B.1 (supplementary material).

*** Output of the household profile generator [36], see Appendix B.1.

smart charging has a slightly higher electricity consumption than direct charging. Since for a few times the EV is charged at powers lower than nominal power, the average charging efficiency for smart charging is slightly lower than for direct charging. The additional electricity consumption for bidirectional charging is mainly due to arbitrage trading. In 2021, the trading translates into an additional consumption of 25% and 11 additional EFCs per EV and year. In 2030, the consumption is 8.5 times higher than for direct charging (315 additional EFCs), which indicates a lot more trading.

Concerning electricity costs (bottom of Fig. 5), a cost reduction of 14% is obtained for smart charging in both years despite the slightly increased electricity consumption. In 2030, the charging costs are almost halved by shifting the charging process to periods with low spot market prices. For bidirectional charging, where selling electricity generates additional revenue, net electricity costs are reduced in both

Table 3
Additional costs of smart and bidirectional charging in respect to direct charging.

		Today			2030		
		MIN	MID	MAX	MIN	MID	MAX
smart charging	EVSE purchase	150 €	525 €	900 €	100 €	300 €	500 €
	EVSE installation	100 €	350 €	350 €	100 €	350 €	350 €
	Metering equipment	0 €/a	30 €/a	30 €/a	0 €/a	30 €/a	30 €/a
	Additional hardware	100 €	450 €	450 €	0 €	100 €	450 €
bidirectional charging	EVSE purchase	2700 €	3550 €	4400 €	950 €	1225 €	1500 €
	EVSE installation	100 €	350 €	350 €	100 €	350 €	350 €
	Metering equipment	0 €/a	30 €/a	30 €/a	0 €/a	30 €/a	30 €/a
	Additional hardware	100 €	450 €	450 €	0 €	100 €	450 €

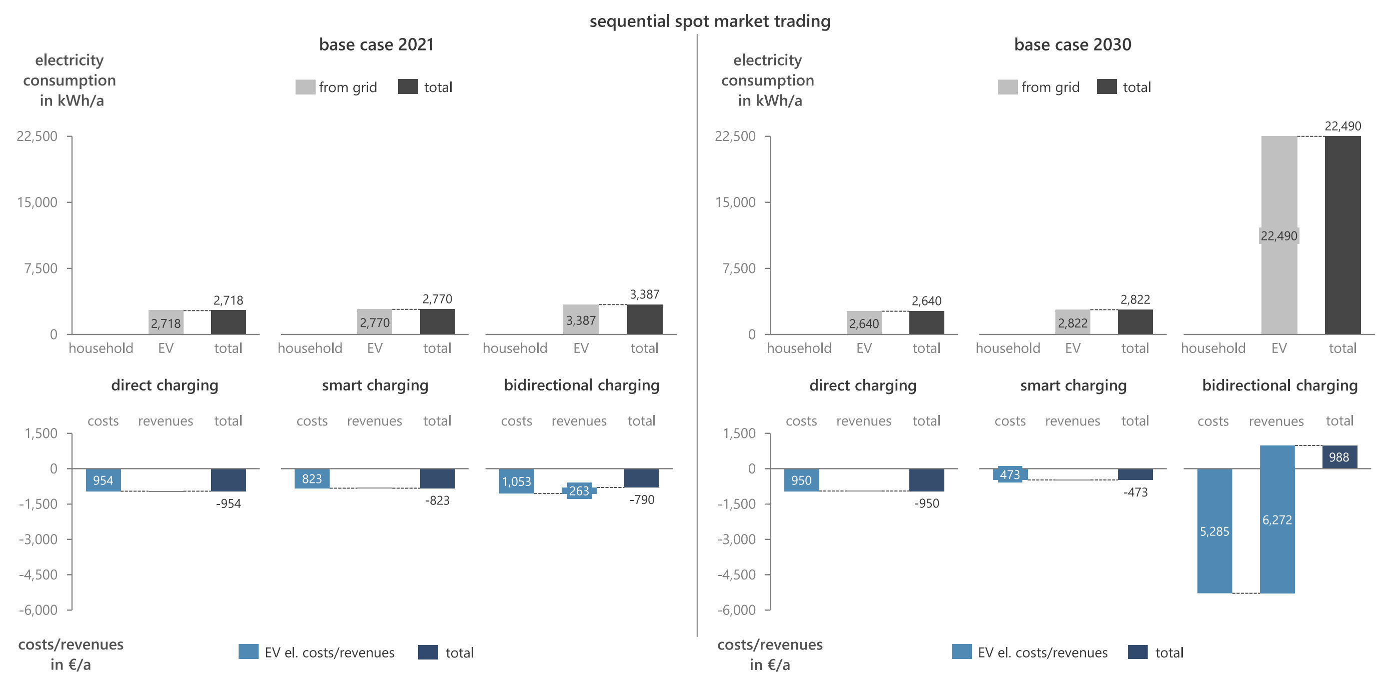

Fig. 5. Consumed electricity and electricity costs/ revenues for sequential spot market trading base cases in 2021 (left) and 2030 (right) differentiated by charging strategy (average of 200 individual simulation results).

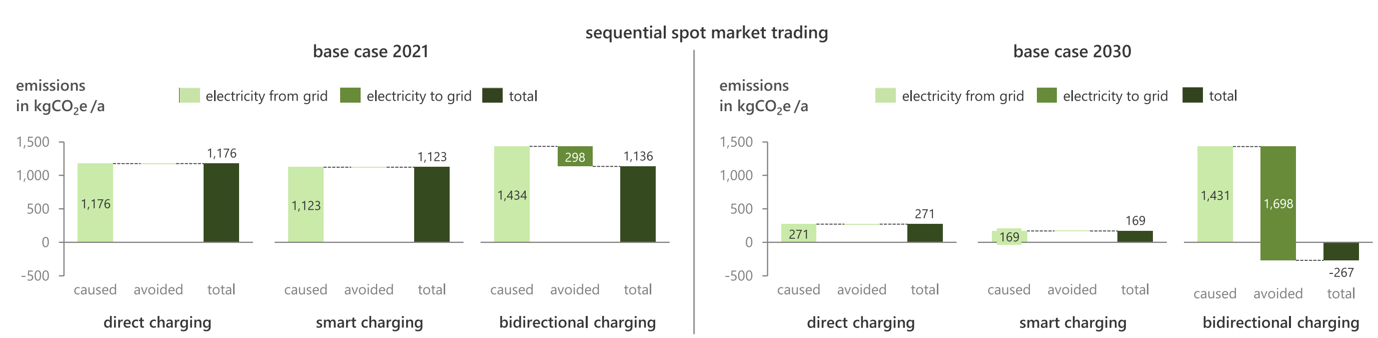

Fig. 6. GHG emissions for sequential spot market trading base cases in 2021 (left) and 2030 (right) differentiated by charging strategy (average of 200 individual simulation results).

years. In 2021, only 30 €/EVa more are saved in comparison to smart charging (17% reduction to direct charging). In 2030, discharging electricity into the public grid generates more revenue than the total electricity costs of charging. Thus, not only are costs saved but net revenues are generated. The added value to smart charging is >1300 €/EVa.

Referring to the left of Fig. 6, operational GHG emissions in 2021 do not vary significantly for the different charging strategies. Slight reductions in net emissions can be observed for both smart charging and bidirectional charging in comparison to direct charging. In 2030, emissions for direct charging and smart charging are significantly reduced in comparison to 2021 due to generally lower emissions in electricity generation. For bidirectional charging, the large amount of discharged electricity into the public grid results in net emission reductions. In this case, bidirectional charging not only generates net revenues but also net emission reductions.

In Fig. 7 and Fig. 8, we present averaged simulation results of **PV self-consumption optimization** for the base cases 2021 and 2030. In addition to the previous figures, household electricity consumption and on-site generated PV electricity are included. For direct charging, a share of PV generation is consumed by household and EV at times when generation and consumption overlap. This share increases for smart charging, as the EV charging times are shifted to periods of PV generation whenever possible. As a result, the self-consumption rate nearly doubled in both years. The EV electricity consumption increases for smart charging by 10% in 2021 and 8% in 2030 due to a reduced average charging efficiency (for exact values, see Appendix C.1). For bidirectional charging, the EV consumption increases by 14% in 2021 and 12% in 2030 resulting in a slightly higher self-consumption rate. This is not only due to efficiency losses for charging and discharging (especially since the average discharging efficiency is lower than the nominal efficiency) but also caused by an increase in charging to later discharge into the household (blue bars in the top plot, this amount of electricity is not included in the EV so that it is not accounted for twice). The amount of bidirectional charging translates into 4 additional EFCs in 2021 and 3 additional EFCs in 2030.

Concerning costs and revenues for this case, the net electricity costs consist of electricity consumption costs and PV electricity revenues (bottom of Fig. 7). For both years, smart charging enables considerable cost savings (24% and 27%), as it is financially beneficial to use the self-generated PV electricity on-site. Applying bidirectional charging further reduces the net electricity costs (28% and 31% compared to direct charging). The added value in comparison to smart charging is relatively low for both years, as the temporary storage of electricity for bidirectional charging is subject to considerable losses. To additionally present the variation of the results of all 200 individual simulations, we visualized the range of resulting electricity costs for all three charging strategies in Appendix C.2.

When considering GHG emissions of the different years and charging strategies (Fig. 8), the resulting net emissions do not vary significantly. For 2021, smart charging increases net emissions by 12% instead of reducing emissions. Less self-generated PV electricity is fed into the public grid at times of high average electricity emissions while average charging losses are increased. Bidirectional charging slightly decreases net emissions, as the grid electricity demand is reduced substantially, which counters the effect described for smart charging. Notably, net emissions of 2030 exceed net emissions of 2021, as negative emissions from feeding self-generated PV electricity into the public grid do not have the same displacement effect in 2030 as in 2021.

The base cases of the third use case, **PV self-consumption optimization and spot market trading**, are presented in Fig. 9 and Fig. 10. Concerning the top of Fig. 9, the electricity consumption of smart charging compared to direct charging is only marginally increased in 2021 (plus 5%) and identical in 2030. The EV is often charged at nominal power or close to nominal power. For bidirectional charging in 2021, EV consumption is increased by 80% provided by self-generated PV electricity to a large extent, resulting in a PV self-consumption rate of 53%. Apart from the mentioned increased losses due to storing electricity, the displayed increase is due to additional trading on the continuous intraday market (ID1 prices). In addition to the displayed electricity supplied from the EV to meet part of the household demand, 1326 kWh/a are fed from the EV into the public grid to generate revenues. In total, the bidirectional activities result in 32 additional EFCs. In 2030, not only the amount of electricity from the EV to the household is increased, but also the electricity fed from the EV into the public grid leaps (10,927 kWh/a), which translates into a total consumption increase of 500% and 209 additional EFCs.

Regarding costs (bottom of Fig. 9), smart charging results in significant cost savings (36% in 2021 and 40% in 2030). Not only are the financial benefits of using PV electricity on-site exploited, but electricity

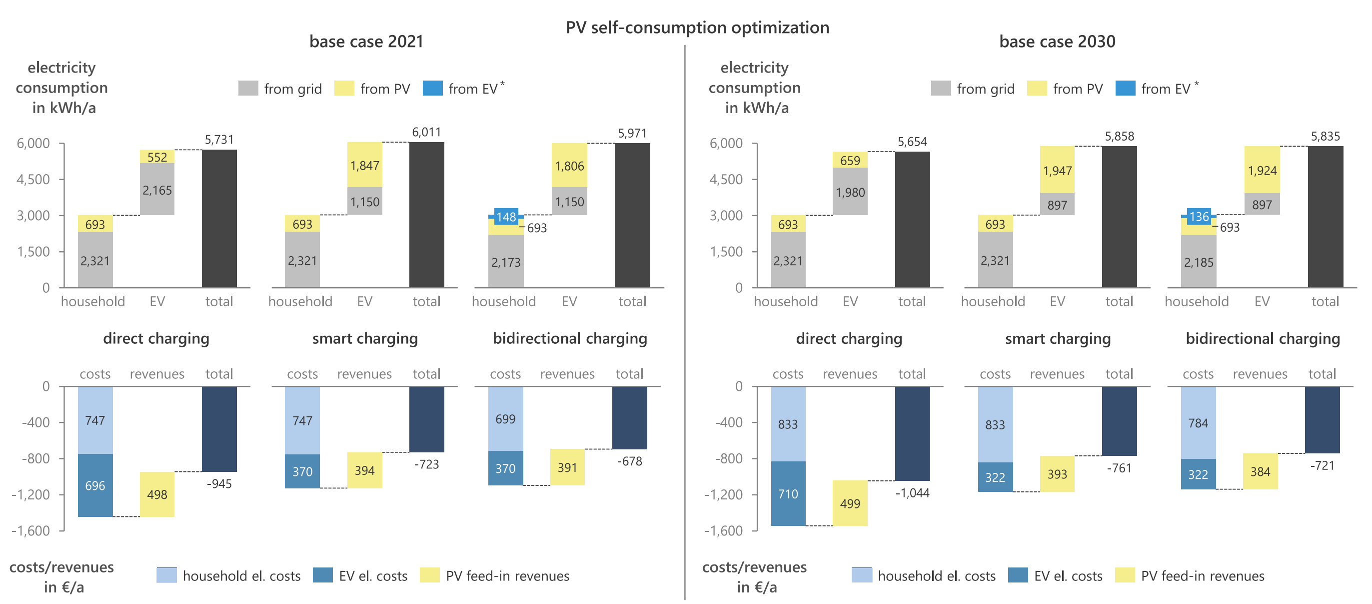

Fig. 7. Consumed electricity and electricity costs/ revenues for PV self-consumption optimization base cases in 2021 (left) and 2030 (right) differentiated by charging strategy (average of 200 individual simulation results).

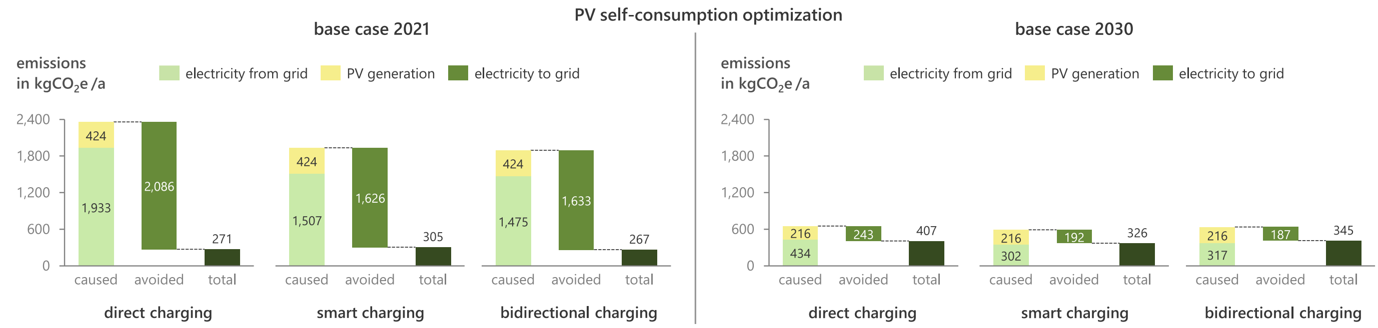

Fig. 8. GHG emissions for PV self-consumption optimization base cases in 2021 (left) and 2030 (right) differentiated by charging strategy (average of 200 individual simulation results).

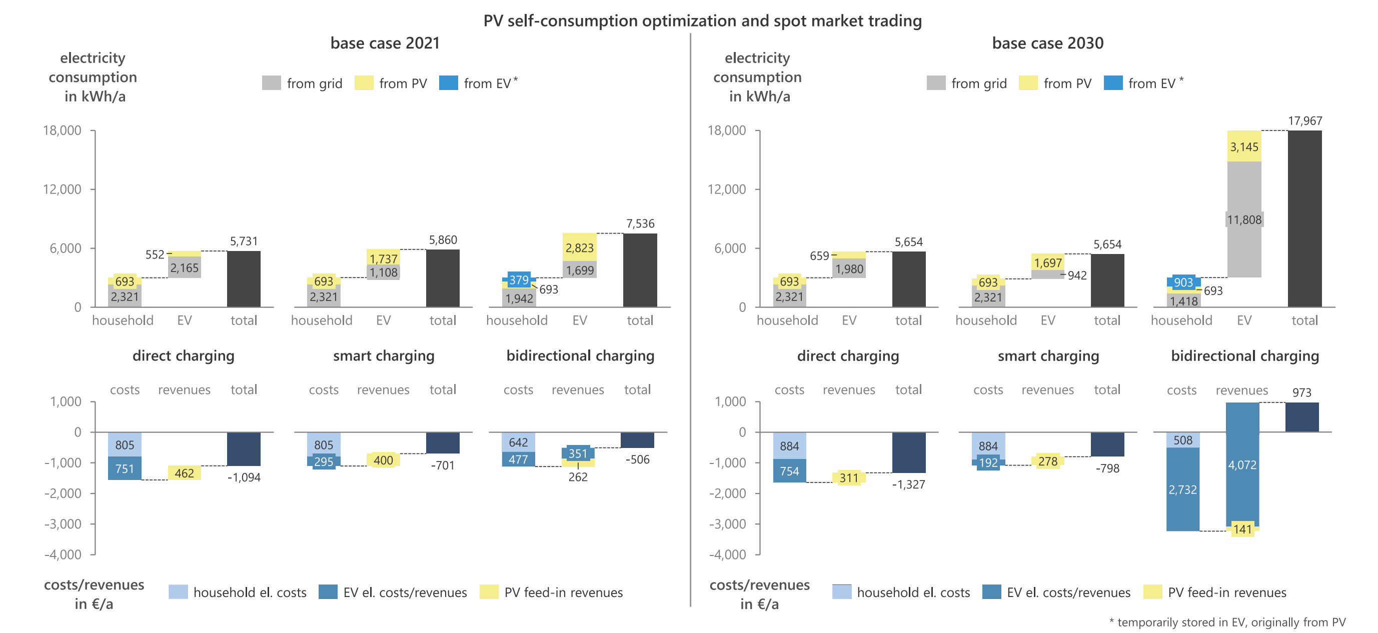

Fig. 9. Consumed electricity and electricity costs/ revenues for combined PV self-consumption optimization and spot market trading base cases in 2021 (left) and 2030 (right) differentiated by charging strategy (average of 200 individual simulation results).

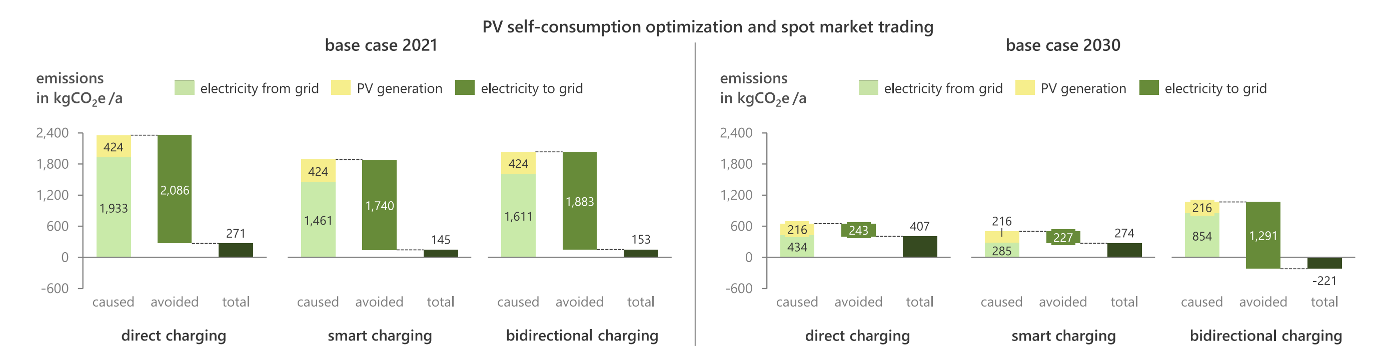

Fig. 10. GHG emissions for combined PV self-consumption optimization and spot market trading base cases in 2021 (left) and 2030 (right) differentiated by charging strategy (average of 200 individual simulation results).

for EV charging from the public grid is also drawn at times when electricity is cheaper than average prices. For bidirectional charging, the cost-benefit of additional arbitrage trading becomes apparent. In 2021, additional trading revenues result in additional cost savings of 200 €/EVa in comparison to smart charging (minus 54% compared to direct charging). In 2030, the large amount of trading yields revenues that are higher than the overall electricity costs resulting in positive net revenues. In contrast to sequential spot market trading, not only the EV electricity costs are offset here, but also those of the household. The additional benefit in comparison to smart charging is higher than 1700 €/EVa (minus 173% compared to direct charging).

Reductions in net GHG emissions for the use case are relatively high (see Fig. 10). Smart charging in 2021 nearly halves the net GHG emissions in comparison to direct charging. The reasons for this are that, on the one hand, the average efficiency is higher than that of PV self-consumption optimization. On the other hand, the times of electricity consumption for charging from the public grid are lower in emissions than for the other use cases. For bidirectional charging, emissions are reduced in comparison to direct charging by 44%, yet are slightly higher than for smart charging, as more losses occur due to the temporary storage of electricity. In 2030, smart charging again reduces GHG emissions, but not as much as in 2021, since electricity emissions in the public grid are generally lower at all times, and the described reduction effects are thus reduced. For bidirectional charging, the large amount of electricity, which is fed back into the grid as a result of arbitrage trading, displaces other emission-related electricity generation and results in net emission reductions (reduction of 154% in comparison to direct charging).

4.3.2. *Analyses of sensitivities*

In addition to the detailed base case analyses, simulation results of all cases/sensitivities listed in Table 2 (see Section 4.1), are presented in Fig. 11. In contrast to previous figures, we directly display cost savings and emission reductions of smart and bidirectional charging with regard to direct charging.

For **sequential spot market trading**, cost savings for smart charging sensitivities in 2021 and 2030 remain in the same order of magnitude as in the base case 2021 and 2030. For non-commuters, savings are lessened in comparison to the corresponding base cases, as less electricity is needed for charging, and the potential of shifting charging processes to times of cheaper electricity prices is reduced. For the sensitivity 'prices 2022', smart charging cost savings increase significantly in comparison to the base case 2021 due to more volatile spot market prices during this year. Concerning bidirectional charging in 2021 and 2022, results show that the reduction of TLGF on electricity fed back into the grid, eliminating the CH limit, and the volatile prices in 2022 lead to increased cost savings. In the cases of 'TLGF reduced 2021' and 'prices 2022', significantly more trading than in the base case takes place, which is why the amount of additional EFCs rises substantially. In 2030, non-commuters generate considerably more revenues than in the base case 2030, as more suitable price spreads can be used due to higher EV availability. In contrast to the non-commuters 2021 sensitivity, non-commuters are not as restricted by the CH limit. The increase in TLGF on electricity fed back from the EV into the grid yields lower cost savings than for the base case 2030. Cost savings remain high while the amount of additional EFCs is substantially reduced.

The emission reductions for smart charging correlate to a certain degree to the cost savings, such that increased cost savings indicate

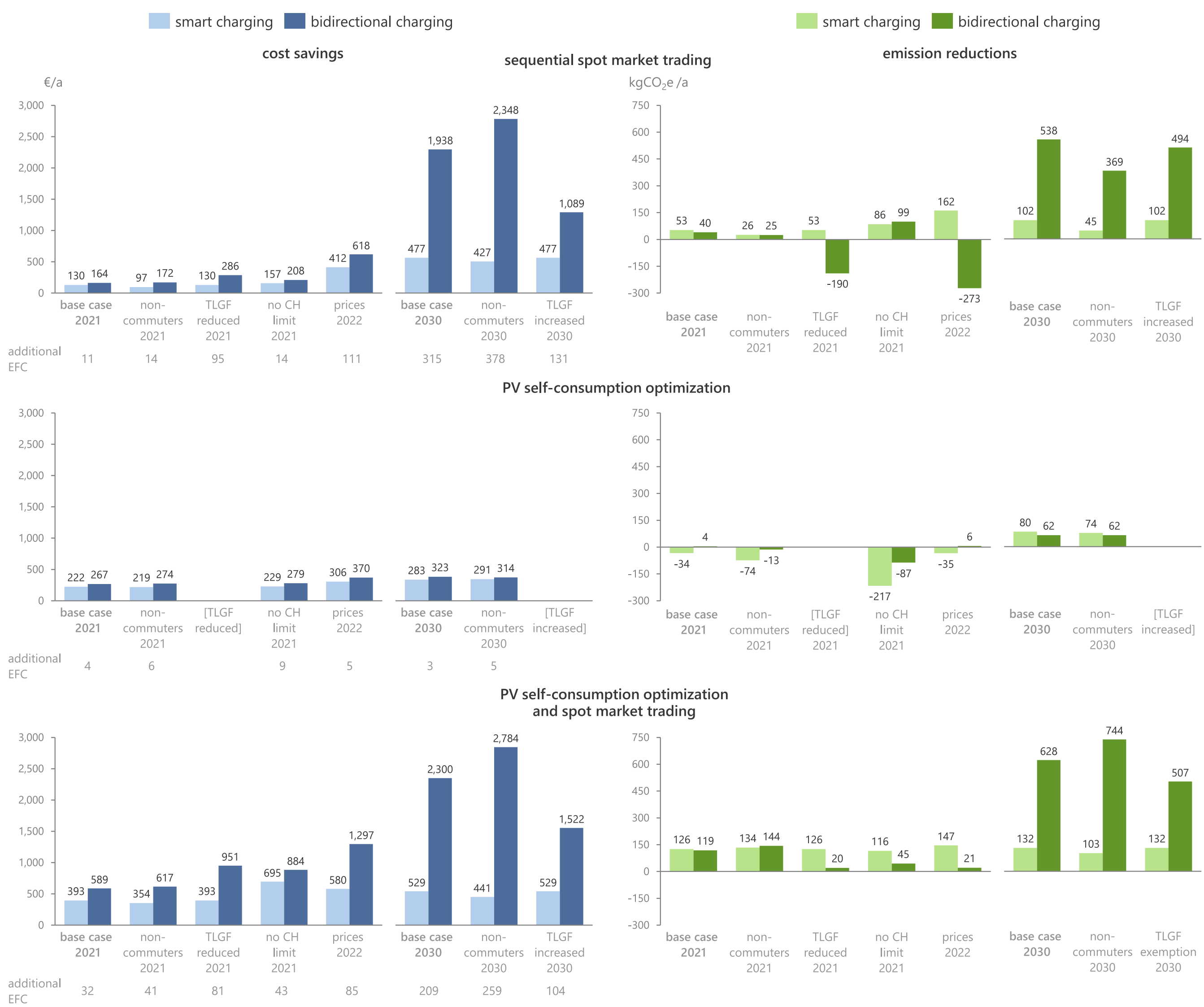

Fig. 11. Electricity cost savings and GHG emission reductions of main sensitivities for smart and bidirectional charging in comparison to direct charging for all three use cases (average of 100 to 200 individual simulation results).

reduced GHG emissions. For the sensitivities 'no CH limit 2021', 'prices 2022', and 'TLGF increased 2030' as well as for the base case 2030, the highest emission reductions are obtained. An ambivalent pattern is presented concerning emission reductions for bidirectional charging. For some sensitivities, emissions are reduced to a similar extent as for smart charging. For the sensitivities 'TLGF reduced 2021' and 'prices 2022', GHG emissions are increased instead of decreased. One reason for this increase is that in total, charging and discharging losses accumulate for the large amount of arbitrage trading in these two cases. The second reason is that for some of the trading activities, which take place in addition to the base case, electricity from coal power plants with high GHG intensity is charged. Later in times of discharging, electricity from natural gas with a comparatively lower emission factor is substituted. For all cases in 2030, emission reductions are generally high and substantially higher for bidirectional charging than for smart charging, as more negative emissions result from the highly increased spot market trading. Due to the gradual phase-out of coal-fired power plants in Germany, the previously mentioned effect is not as severe for this future year.

Concerning the use case **PV self-consumption optimization**, Fig. 11 shows that cost savings are relatively constant regardless of restrictions or years considered for smart charging and for bidirectional charging. The high increase in cost savings in 2030 observed in spot market trading is not reflected here. Notably, there is no significant financial advantage for bidirectional charging compared to smart charging in any of the cases. The consistently low number of additional EFCs also confirms the comparatively modest bidirectional activity for this use case.

With regard to the GHG emissions, the consistency observed for cost savings is not given. For today, GHG emissions of smart charging are not reduced but increased in comparison to direct charging for all sensitivities. The reason for this is the same as for the base case 2021 (see Fig. 8). Most noteworthy is the significantly negative emission reduction for the sensitivity 'no CH limit 2021'. In this case, the average charging efficiency is lowest for all cases/ sensitivities of this use case, and the most self-generated PV power is used for charging at different times, neither of which is beneficial with regard to overall emissions. In 2030, smart charging reduces emissions in both cases, as efficiencies increase and as the electricity mix of the public grid generally consists of lower emissions. For bidirectional charging in 2021, emissions are marginally reduced for two cases and moderately increased for two other cases. The increases in emissions are due to similar causes as for smart charging, namely increased losses as a result of low average efficiencies and certain times of charging and discharging that are particularly unfavorable for reducing emissions. For bidirectional charging in 2030, emissions are reduced but to a lesser extent than for smart charging mainly due to storage losses for bidirectional charging.

The third use case, **PV self-consumption optimization and spot market trading**, displays the generally highest cost savings of all use cases. Smart charging results in high savings across all cases with similar characteristics to sequential spot market trading. The cost savings for the sensitivity 'no CH limit 2021' are considerably higher than for the base case 2021 due to the increased time flexibility for the charging process. For bidirectional charging, the increase in cost savings in comparison to the other use cases is even higher than for smart charging. All sensitivities for today yield higher savings than the base case 2021. Especially in the sensitivities 'TLGF reduced 2021' and 'prices 2022', a lot more arbitrage trading is conducted than in the base case indicated by the number of additional EFCs. In 2030, the very high cost savings (net revenues) exceed the high savings of sequential spot market trading in 2030, despite the number of additional EFCs being approximately one-third lower for all cases. In terms of emission reduction, the results also exceed those of the other use cases.

In contrast to the other use cases, both smart charging and bidirectional charging reduce GHG emissions for all cases/ sensitivities. The reduction for smart charging is quite consistent at a relatively high reduction level. For bidirectional charging today, the reduction is relatively low for those sensitivities which yield an increase in emissions for the other use cases. For bidirectional charging in 2030, emission reductions are generally high and, in particular, significantly higher than for smart charging. This is mainly due to the effect of relatively high negative GHG emissions for discharging into the public grid, as already observed for sequential spot market trading. The use case PV self-consumption optimization and spot market trading demonstrates the most beneficial results for both charging strategies in almost all aspects.

4.3.3. Analyses of profitability

To determine the prospects of profitability for the simulated use cases, we combine the averaged cost savings with the calculated additional costs of the respective charging strategy. In Fig. 12, we present the profitability results for bidirectional charging in comparison to direct charging of both base cases 2021 and 2030 over time. As a simplification, simulated cost savings/ revenues of the base year are assumed to remain constant in real financial terms. They are thus discounted for subsequent years using a real interest rate of 1.3% resulting from the average German inflation rate of the past 20 years (1.7%) and a nominal interest rate of 3% [30]. Regarding additional costs, all costs that arise during purchase and installation are real prices for the base year (see Table 3). Only metering equipment costs are incurred annually and are discounted with regard to the respective base year. The line resulting from the cumulative difference between cost savings/revenues and additional costs represents the expected profits and is illustrated in blue. As a comparison, we also depicted the profit line for the respective smart charging case as a dotted blue line. A similar analysis of GHG emission reductions over time is presented in Appendix C.3.

The left side of Fig. 12 shows that the profit line for bidirectional charging does not cross the X-axis within the first 15 years for two of the three use cases. For sequential spot market trading and PV self-consumption optimization, bidirectional charging is not profitable when starting the use case today, requiring a return on investment after 15 years at the latest. For these cases, the annual cost savings are insufficient to compensate for high initial costs. For PV self-consumption optimization and spot market trading, the comparatively high annual cost savings for bidirectional charging lead to positive profits in the ninth year after purchase in the base year 2021. The left side of Fig. 12 also implies that smart charging is profitable for all three use cases in year 15 at the latest and generally becomes profitable earlier than the bidirectional charging counterpart for the base year 2021.

With regard to the right side of Fig. 12, bidirectional charging is profitable for a purchase in 2030 for all use cases. For sequential spot market trading and PV self-consumption optimization and spot market trading, cost savings/ revenues of the first year already exceed the sum of initial additional costs, such that high profits can be expected for both use cases from the first year onwards. In comparison, smart charging becomes profitable in the second year. The gradient of the profit line for smart charging is lower than for bidirectional charging, which means that the profits in these cases will always be lower than for bidirectional charging. For PV self-consumption optimization, the annual cost savings/ revenues of bidirectional charging are substantially lower than for the other use cases. The main reason why bidirectional charging becomes profitable in the seventh year after purchase is the reduced initial additional costs in 2030. Still, bidirectional charging remains less profitable than smart charging over the displayed 16-year time horizon for this case.

5. Discussion

The discussion is divided into two sections. First, we discuss the main influences and implications of cost savings and profits, taking into account the amount of energy charged and discharged. Second, we discuss the impact of smart charging and bidirectional charging on operational GHG emissions for the three use cases.

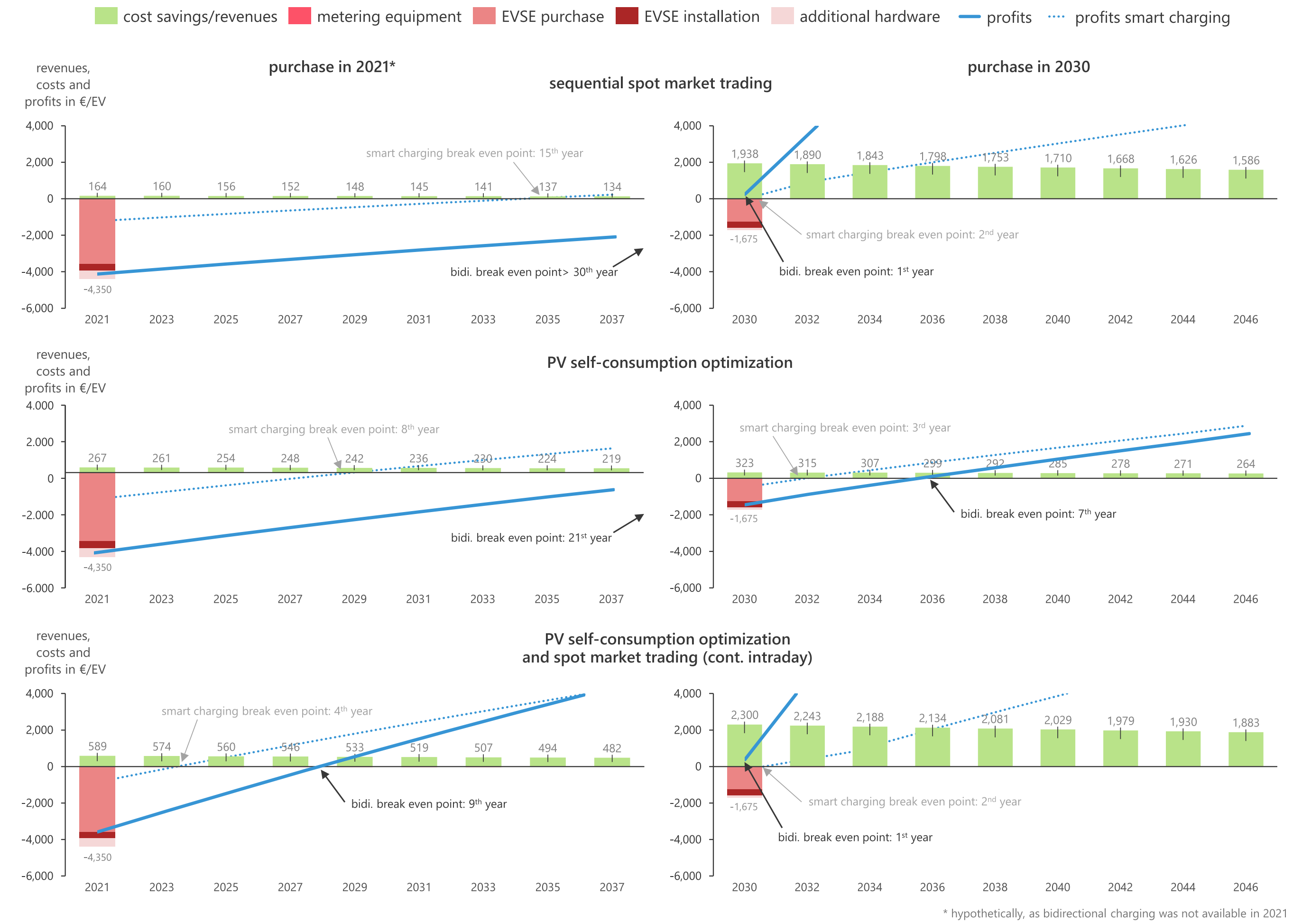

Fig. 12. Additional costs, cost savings/ revenues (average of 200 individual simulation results) and resulting profits (all real prices) for bidirectional charging (direct charging as a reference), profits for smart charging as benchmark (dashed line).

5.1. Influences on profitability

Concerning the analyzed use cases, smart charging is profitable in almost all cases today (except for non-commuter sequential spot market trading in 2021) and in all cases in 2030. For bidirectional charging, the use case combination PV self-consumption optimization and spot market trading is the only one that offers a realistic prospect of profitability today, as its base case 2021 and all sensitivities today are profitable. This use case combination combines the benefits of PV self-consumption with the advantages of spot market trading without the need for extensive trading in most cases (often moderate additional EFCs). In contrast, the use case sequential spot market trading today comprises much additional trading (many additional EFCs), but is still only profitable for the extreme prices of 2022 and not for the cases of 2021. Similarly, the use case PV self-consumption optimization is only profitable for 2022 and not for any case of 2021 (few additional EFCs). For bidirectional charging in 2030, all use cases become profitable in all cases/ sensitivities. High additional costs constitute a major influence on profits for smart charging and especially for bidirectional charging. Purchase costs of the more complex EVSE make up 40% of all initial additional costs for smart charging and >80% for bidirectional charging. As we expect these costs, in contrast to some of the other cost components, to be reduced in the future due to further technological advancements and scaling effects (see assumptions for 2030), the development of EVSE purchase costs is a crucial factor for the profitability of smart charging and bidirectional charging in particular.

Regarding annually reduced electricity costs by applying the investigated use cases, cost savings for smart charging vary, depending on the sensitivity, today between 100 €/EVa and 700 €/EVa, and in 2030 between 280 €/EVa and 530 €/EVa. These extensive ranges suggest several important influencing factors. For bidirectional charging, the cost saving range is significantly larger, i.e. today from 160 €/EVa to 1300 €/EVa and in 2030 from 320 €/EVa to 2780 €/EVa. Bidirectional charging is even more sensitive to the investigated influencing factors.

One essential factor is the electricity price characteristic, i.e. the volatility of spot market prices and the price level. The extreme spot market prices in 2022 and the likewise highly volatile spot market prices in 2030 (see Table B.1 in Appendix B.1) enable increased saving potentials for all cases where these prices are used. If constant electricity prices are applied (PV self-consumption optimization), cost savings increase in 2022 and 2030. The constant household electricity price is higher in 2022 and 2030 than in 2021, while the PV renumeration rate remains almost the same. Reducing the electricity demand from the public grid lowers the total electricity costs to a greater extent in years with high constant electricity prices. If variable electricity prices are applied, the main benefit of smart charging is that significantly lower prices than the average price are used for charging in the available time window. Since for bidirectional charging, not only low prices can be exploited but also the entire price spreads on the markets, the volatility of spot market prices has a much greater influence on the cost savings than for smart charging. Hence, cost savings in 2022 and 2030 prices highly increase in both use cases with variable prices.

With regard to the volatile spot market prices of price forecasting for 2030, it is worth mentioning that cannibalizing effects due to a high number of flexible assets in the system are taken into account to some extent, as the day ahead forecast for 2030 considers the impact of a large number of EVs in the energy system (see Section 3.3.4 and Appendix B.1). The forecasted ID1 price spreads of the continuous intraday market for 2030 are less volatile than intraday auction prices, while in historical prices ID1 prices are usually more volatile. The applied modeling method is based on the residual load deviations, that depict typical characteristics of intraday prices with respect to the day ahead price. Volatility due to other factors, like short-term changes in renewable and load forecast, is not described.

As the high cost savings for variable prices and bidirectional charging are the result of many arbitrage trading activities, the number of additional EFCs per year is very high in those cases (85 at least and 378 at maximum, which translates into 134,000 km additional mileage in one year). High numbers of additional EFCs might be a reason for concern when it comes to cyclical battery aging. For all cases today with additional EFCs per year above approximately 20, cyclic aging can already have a relevant effect on the battery capacity, and at least for some EV manufacturers, warranty conditions might be affected, if such amounts of additional EFCs are carried out over several years [4]. All cases of PV self-consumption optimization and some important cases of sequential spot market trading are not critical in terms of cyclical aging, while most cases of the use case PV self-consumption optimization and spot market trading show particularly critical additional EFCs today. The most extreme cases regarding additional EFCs occur in the 2030 scenario. Conclusively assessing the extent to which such additional EFCs will affect battery aging in 2030 is, however, beyond the scope of this paper and generally difficult to predict due to potential technological advancements. To account for aging to some extent, an additional sensitivity, battery aging, is presented in Appendix C.1, where each additional EFC is assigned opportunity costs. The results indicate that even with less arbitrage trading due to those opportunity costs, high cost savings can be achieved as the most suitable, i.e. the highest, price spreads are still exploited. Restricting the additional EFCs per year would have a similar effect.

A comparable influence as restricting additional EFCs is exerted by the limitation of charging and discharging hours per day (CH limit) with the difference that this limit also affects smart charging, as the comparison of the base cases 2021 with the sensitivity 'no CH limit 2021' shows. The CH limit of the base case reduces the length of smart and bidirectional charging, such that only the times with the lowest electricity prices or respectively with the largest price spreads are exploited. Consequently, charging and discharging efficiency are on average higher for the base case 2021 than for the sensitivity 'no CH limit 2021'. Limiting CH not only increases the lifespan of EV and EVSE electronics but also reduces charging and discharging losses. Nevertheless, higher cost savings are obtainable without a CH limit for all cases.

For the use cases that involve spot market trading, the charging and discharging efficiencies are close to the nominal values, as charging and discharging are carried out at maximum power whenever possible to best take advantage of favorable prices or price spreads. However, low efficiencies occur, especially for PV self-consumption optimization. For charging, the EV charges with low power and with high losses when the self-generated PV power output is low. For discharging, the household's electricity demand sets the discharging power and consequently the discharging losses. As the household's demand is, on average, lower than the generated PV power, average discharging efficiencies are lower than charging efficiencies for this use case. Below a minimum economically viable efficiency, charging and discharging become economically unattractive. This minimum is mainly determined by the amount of constant losses while charging/ discharging, aside from the gradient of the linear loss functions (see Section 3.4.1). Whether charging or discharging takes place at a certain point in time depends on the amount of constant losses as well as on the available PV power or the household's electricity demand,respectively. The amount of bidirectional charging is reduced in 2030 in comparison to 2021 for PV self-consumption optimization (less additional EFCs), even though the CH limit is loosened, the PV system size is relatively large, and non-commuters make up half of the users. We deduce that the times of sufficiently high PV power to charge and high household demand to discharge are limited for the investigated profiles. This is the case even though the set limit of 200 W today and 125 W in 2030 (see Appendix B.1, Table B.3) is relatively low, as reflected by experts from the unIT-e^2 project [3]. For higher constant losses, even less charging and discharging would occur for the use cases with household demand and PV systems, and thus the self-consumption rate would be lessened. For this reason, some domestic users install an additional stationary battery storage, which can charge and discharge at low power without high losses.

As expected, the assumed changes to the current TLGF regulation in the sensitivities 'TLGF reduced 2021' and 'TLGF increased 2030' result in arbitrage trading becoming more attractive for the 2021 sensitivity (120 €/EVa to 360 €/EVa more) and less attractive for the 2030 sensitivity (780 €/EVa to 850 €/EVa less) than in the respective base case. An exemption of parts of the TLGF on electricity fed back from the EV into the public grid is a very effective regulatory means to enable or limit arbitrage trading by bidirectional charging.

Concerning users' driving behavior as an influencing factor, cost savings of non-commuters for smart charging in absolute numbers are lower than the average savings of the base cases. Despite of a higher EV availability, we show that the lower annual mileage of non-commuting users has less potential to shift charging processes during the day. Yet, if comparing the ratio of cost savings of non-commuters to the reference electricity costs of direct charging, the relative cost savings are higher than the average for all users. Hence, the figures in Section 4.3 are partly misleading, and, relatively speaking, non-commuters show considerable saving potentials and generally good profitability prospects for smart charging. Concerning bidirectional charging, cost savings increase for non-commuters both in 2021 and 2030, as the higher EV availability facilitates more bidirectional activities (more additional EFCs), and the lower mileage is no limitation due to the possibility of discharging.

5.2. Influences on operational GHG emissions

In 2021 and 2022, operational emissions are only consistently reduced for the use case combination of PV self-consumption optimization and spot market trading. For the other two use cases, operational emissions increase for some sensitivities in 2021 and 2022. The influences on annual operational GHG emissions, which are responsible for these inconsistent findings of smart charging and bidirectional charging for the various use cases and sensitivities, are complex and in some situations ambiguous. For example, use cases involving variable electricity prices, i.e. market trading, achieve annual emission reductions in the majority of considered cases. This is primarily caused by the correlation between spot market prices and the GHG intensity of the generated electricity that is fed into the public grid. Generally speaking, market prices on the German spot markets are usually low in case of high renewable energies availability compared to hours with generation from fossil-based sources. However, carbon pricing is not always the most decisive factor in setting the market price today. Coal-based electricity in Germany is often cheaper than the less GHG-intense electricity from natural gas at present [62]. As a result, a correlation between market prices and emission intensity is not always evident for times at which the EV is available for charging. This is reflected in the finding that emission reductions for use cases involving today's spot market trading are rather moderate.

Especially for cases of bidirectional charging, the correlation between prices and emissions comes into effect twice due to discharging. Emission reductions, however, are very low in some cases and even become negative in others, i.e. leading to a total increase in emissions. For today, we deduce that the more arbitrage trading takes place, indicated by the amount of additional EFCs, the lower the emission reductions, if no additional influence affects the GHG emissions. The sensitivity ‘no CH limit 2021’ of the use case sequential spot market trading represents an anomaly in this respect. Here, the additional trading compared to the base case 2021 takes place at times that continue to reduce emissions. This is explained by the increased EV availability for charging and discharging enabled by the elimination of the CH limit. For the future scenario 2030, the correlation between market prices and GHG emissions is substantially stronger due increased carbon pricing along with the expansion of renewable-based electricity. Hence, emission reductions for use cases involving market trading are substantially increased for cases/ sensitivities in 2030. The stronger prices-emissions-correlation has an additional positive effect on bidirectional charging compared to smart charging due to the additional discharging.

Furthermore, varying average charging and discharging efficiencies impact the operational GHG emissions. This is particularly important for the use case of PV self-consumption optimization. Since constant electricity prices are applied, the mentioned positive effect of variable prices on operational GHG emissions has no impact. At the same time, charging and discharging efficiencies for PV self-consumption optimization are, on average, the lowest compared to the other use cases. Another reason for increased emissions in cases of PV self-consumption optimization is the reduction of self-generated PV electricity fed into the public grid. In contrast to uncontrolled direct charging, the majority of electricity from PV is used for self-consumption in the cases of smart charging rather than for feeding into the public grid. Since this includes hours with highly fossil-based electricity generation, the negative emissions through electricity feed-in into the public grid are higher in case of direct charging. We conclude that PV self-consumption optimization is no suitable strategy to actively reduce operational GHG emissions. The described negative effect of increasing one’s self-consumption rate on overall GHG emissions also occurs for use case combination (PV self-consumption optimization and spot market trading). The superimposition of the positive influences of variable electricity prices and increased efficiencies reduces or even counteracts the effect.

To bring the assessed changes in annual GHG emissions for smart charging and bidirectional charging into perspective with the overall changes in emissions, we refer to Appendix C.3, where total emission reductions of the base case 2021 over time are exemplarily presented for all three use cases in comparison to direct charging. Similar to the presented financial break-even per use case, we compare the annual GHG emission reductions to the initial lifecycle-based footprint of additionally required components of charging infrastructure as determined in [63]. For both smart and bidirectional charging, annual GHG emission reductions are only high enough in some cases to compensate these additional environmental impacts. As an estimate, smart charging use cases must reduce GHG emissions by around 20 $kgCO_2e$ per year and EV to counteract additional emissions from the charging infrastructure within 15 years. For bidirectional charging, around 90 $kgCO_2e$ per year and EV GHG emission reductions are necessary for a overall reduction after 15 years. For the future scenario 2030, additional emissions are expected to decrease due to reduced production emissions. At the same time, operational GHG emissions increase, especially for bidirectional charging. We conclude that substantial total GHG emission reductions are quite possible for the considered use cases in 2030, whereas under the conditions today increases in total emissions are likely. Notably, in this assessment we consider neither cyclical battery aging as a consequence of the large number of additional EFCs in some cases nor battery aging over time, which might negatively influence the total emission balance per use case.

6. Conclusions

Given the right circumstances, the presented use cases can benefit users and other stakeholders. As smart charging is profitable for almost all cases analyzed today and in 2030, we conclude that this charging strategy is financially advantageous for many EV users already today. In contrast, our findings for today show that bidirectional charging is only profitable for the use case combination of PV self-consumption optimization and spot market trading, but becomes profitable for all use cases in 2030. Technical limitations and parameters greatly influence on bidirectional charging to generate sufficient cost savings, and external factors such as spot market prices or regulation are crucial. Bidirectional charging, even if becoming available to users soon, is not beneficial for all users, but only generates financial benefits for users at a later time.

Regarding emissions from a user’s perspective, smart charging and bidirectional charging do not reduce operational GHG emissions in all cases. For today, operational GHG emissions are increased in some cases when applying smart or bidirectional charging. When including emissions caused by additionally required hardware for charging, even fewer cases are environmentally beneficial today. For 2030, reduced operational GHG emissions can be expected for the majority of use case configurations. Other key findings of our work can be summarized as follows:

- Cost savings for smart charging in 2021 are between 100 €/EVa and 700 €/EVa, and in 2030 between 280 €/EVa and 530 €/EVa, whereas for bidirectional charging savings range in 2021 from 160 €/EVa to 950 €/EVa and in 2030 from 310 €/EVa to 2780 €/EVa.
- A generally high electricity price level and particularly volatile spot market prices have a positive effect on the cost savings of smart charging and bidirectional charging, but also result in a very large number of additional EFCs and thus in increased battery aging in some cases, even if charging and discharging hours are limited.
- Restricting EV charging and discharging hours reduces possible cost savings, but not to an extent, that would render all cases unprofitable, which makes a CH limit a viable option for extending the lifespan of components.
- Concerning different use behaviors, non-commuters gain fewer absolute yet higher relative cost savings from smart charging than average users, while cost savings from bidirectional charging are generally higher.
- If bidirectional spot market trading shall be incentivized by regulation, exempting the electricity that is charged into the EV from the public grid and later fed back into the grid from parts of the TLGF is an effective option.
- Additional EVSE purchase costs dominate the overall additional costs for smart charging and especially for bidirectional charging. Reducing such purchase costs of bidirectional EVSE is a key lever to achieve profitability of bidirectional charging.
- For today, annual operational emission reductions are, in many cases, not high enough to counterbalance high additional emissions of production and operation.
- Low average charging/ discharging efficiencies and unfavorable shifts of charging/ discharging processes are the main causes for increased rather than reduced annual operational GHG emissions in several cases today (except for the use case PV self-consumption optimization and spot market trading).
- The significant reduction of annual operational GHG emissions in many cases in 2030, especially for bidirectional charging, is mainly due to the altered electricity generation for the German electricity markets (substantially more renewable generation, some remaining fossil-based generation).

As an outlook, the optimization model eFlame is undergoing continuous development. As our findings reveal that the considered use case combination provides great benefits, both in terms of cost savings and emission reductions, further multi-use applications should be implemented and investigated. Depending on how critical cyclical battery aging is considered to be, we advise pricing or restricting additional EFCs in the model. We also recommend further development of the cyclic battery aging module as part of eFlame. With regard to the price forecast 2030, an alternative approach to be applied in future research might be the sequential modeling of the ID1 index from the intraday auction prices, instead of modeling both, auction and continuous prices, from day ahead prices. Taking market cannibalizing effects into account would be a highly valuable model development, especially with respect to modeling intraday characteristics. As pooling by an aggregator is ignored in eFlame, considering pooling restrictions (e.g. risk mitigation against unavailability of EVs) could also be a possible future development. To model charging and discharging losses in even more detail, further sensitivities with higher constant losses that better reflect the current technological realities and sensitivities with a small-scale domestic stationary battery storage for cases with household demand and PV system should be conducted. Regarding the high additional purchasing costs of bidirectional charging, an AC EVSE in combination with an on-board charger could be considered as a more cost effective concept. Yet, at least in Germany, bidirectional AC EVSE are only expected to be widely available in the medium to long term due to challenges in IT communication.

GHG emissions depend on the system boundaries of emission balancing. Some use cases, such as PV self-consumption optimization, are attractive from a user's perspective but do not necessarily reduce GHG emissions from a systemic perspective. When further including systemic repercussions, smart and bidirectional charging might have a greater effect on overall GHG emissions, as outlined in [43]. Future research should focus on how new use cases can result in an overall decrease in GHG emissions and thus contribute to climate neutrality. From a lifecycle-based perspective, this requires a decrease both in operational emissions such as mobility behavior (modal shift), including car sharing solutions in combination with smart and bidirectional charging, as well as in production-based impacts, including vehicle sizes and production processes.

Nomenclature

Abbreviations

EV	electric vehicle
PV	photovoltaic
AC	alternating current
DC	direct current
GCP	grid connection point
EVSE	electric vehicle supply equipment
DA	day ahead auction
IA	intraday auction
CI	continuous intraday
GHG	greenhouse gas
MILP	mixed-integer linear programming
SOC	state of charge
EFC	equivalent full cycle
TLGF	taxes, levies, and grid fees

Parameters

m^{charge}	gradient of charging losses (no unit)
$m^{\mathrm{discharge}}$	gradient of discharging losses (no unit)
n^{charge}	minimum charging losses (in kW)
$n^{\mathrm{discharge}}$	minimum discharging losses (in kW)
$\eta^{\mathrm{EV,charge}}$	nominal charging efficiency of EV (in %)
$\eta^{\mathrm{EV,discharge}}$	nominal discharging efficiency of EV (in %)
$\mathrm{CH}_{max,\mathrm{day}}$	maximum daily (dis)charging hours (in h)
$c_t^{\mathrm{el,buy}}$	price, at which electricity is bought (in €/kWh)
$c_t^{\mathrm{el,sell}}$	price, at which electricity is sold (in €/kWh)
$P_t^{\mathrm{h,el}}$	electric load of household (in kW)
P_t^{PV}	PV power generation (in kW)
$P_t^{\mathrm{EV,drive}}$	EV consumption while driving (in kW)
$P^{\mathrm{GCP},max}$	maximum power at GCP (in kW)
$P^{\mathrm{EV,charge},max}$	maximum charging power (in kW)
$P^{\mathrm{EV,discharge},max}$	maximum discharging power (in kW)
SOC^{safe}	minimum safety SOC when connected (in %)
SOC^{dep}	minimum SOC at departure (in %)
$E^{\mathrm{EV},max}$	EV battery energy capacity (in kWh)
t	timestep (no unit)
T	total timesteps of optimization horizon (no unit)

Binary variables

$b_t^{\mathrm{grid,in}}$	binary variable if energy is drawn from the grid (no unit)
$b_t^{\mathrm{grid,out}}$	binary variable if energy is supplied to the grid (no unit)
b_t^{charge}	binary variable if EV is charging (no unit)
$b_t^{\mathrm{discharge}}$	binary variable if EV is discharging (no unit)
b_t^{EV}	binary variable if EV is connected (no unit)

Decision variables

$P_t^{\mathrm{grid,in}}$	power from grid (in kW)
$P_t^{\mathrm{grid,out}}$	power to grid (in kW)
E_t^{EV}	energy level of EV battery (in kWh)
$E_t^{\mathrm{EV,dep}}$	energy level of EV battery at departure (in kWh)
$P_t^{\mathrm{EV,charge,pub}}$	public charging power (in kW)
$P_t^{\mathrm{EV,charge}}$	charging power of EV (in kW)
$P_t^{\mathrm{EV,discharge}}$	discharging power of EV (in kW)
$P_t^{\mathrm{EV,discharge,2g}}$	discharging power of EV into the public grid (in kW)
$P_t^{\mathrm{EV,loss,charge}}$	charging losses of EV and EVSE (in kW)
$P_t^{\mathrm{EV,loss,discharge}}$	discharging losses of EV and EVSE (in kW)
P_t^{curt}	curtailment of PV generation (in kW)

Funding

The presented work is part of the research project unIT-e^2, which deals with many important aspects of smart and bidirectional charging in Germany, by the FfE (Forschungsgesellschaft für Energiewirtschaft mbH) and is funded by the Bundesminsterium für Wirtschaft und Klimaschutz (BMWK) under the funding code 01MV21UN01.

CRediT authorship contribution statement

Patrick Vollmuth: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Daniela Wohlschlager:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation. **Louisa Wasmeier:** Writing – review & editing, Validation, Methodology, Formal analysis. **Timo Kern:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare no conflict of interest. The funders had no role in the design of the study, in collection, analyses, or interpretation of data, in the writing, or in the decision to publish the results.

Data availability

Data will be made available on request.

Acknowledgements

The authors would like to thank Florian Biedenbach and Valentin Preis for technical support regarding the eFlame model, Kirstin Ganz for her contribution in generating user profiles and valuable discussions, Leon Berger for his assistance in editing simulation results, and Kristin Wagner for processing additional costs.

Appendix A. Appendix

A.1. Relevant constraints of the optimization model

The most relevant constraints of the model *eFlame* are explained here. Eq. A.1 presents the power balance at the GCP, where $P_t^{\mathrm{h,el}}$ is the electric load of the household, P_t^{PV} is the self-generated PV power (only relevant for PV self-consumption optimization), P_t^{curt} is curtailed PV power (only relevant for PV self-consumption optimization), $P_t^{\mathrm{EV,charge}}$ is the power charged into the EV and $P_t^{\mathrm{EV,discharge}}$ is the power discharged from the EV. In Eq. A.2, the energy balance for the EV battery is formulated to guarantee energy conservation. Here, the energy level of the EV battery between two time steps ($E_t^{\mathrm{EV}} - E_{t-1}^{\mathrm{EV}}$) equals the charged and discharged energy. Charging and discharging losses are included by introducing $P_t^{\mathrm{EV,loss,charge}}$ and $P_t^{\mathrm{EV,loss,discharge}}$ (more details in Section 3.3.1). The energy level can be additionally reduced by the energy consumption for driving ($P_t^{\mathrm{EV,drive}}$) and increased by public charging ($P_t^{\mathrm{EV,charge,pub}}$). A generally applied constraint is the non-negativity constraint for all decision variables, presented in Eq. A.3 for the representative variable P_t^{decision}.

$$P_t^{\mathrm{grid,in}} - P_t^{\mathrm{grid,out}} = P_t^{\mathrm{h,el}} - P_t^{\mathrm{PV}} + P_t^{\mathrm{curt}} + P_t^{\mathrm{EV,charge}} - P_t^{\mathrm{EV,discharge}} \tag{A.1}$$

$$E_t^{\mathrm{EV}} - E_{t-1}^{\mathrm{EV}} = \left[\left(P_t^{\mathrm{EV,charge}} - P_t^{\mathrm{EV,loss,charge}}\right) - \left(P_t^{\mathrm{EV,discharge}} - P_t^{\mathrm{EV,loss,discharge}}\right)\right] \bullet \Delta t$$

$$- P_t^{\mathrm{EV,drive}} \bullet \Delta t + P_t^{\mathrm{EV,charge,pub}} \bullet \Delta t \tag{A.2}$$

$$P_t^{\mathrm{decision}} \geq 0 \forall t \in T \tag{A.3}$$

Eqs. A.4 and A.5 prevent energy from being drawn and supplied simultaneously at the GCP. To do so, $b_t^{\mathrm{grid,in}}$ and $b_t^{\mathrm{grid,out}}$ are introduced. These binary variables are either zero or one. The sum of both is a maximum of one, such that either $b_t^{\mathrm{grid,in}}$ or $b_t^{\mathrm{grid,out}}$ or both are zero (Eq. A.6). Similarly, Eqs. A.7 and A.8 prevents that the EV is charged and discharged at the same time by introducing b_t^{charge} and $b_t^{\mathrm{discharge}}$, which function in the same way as $b_t^{\mathrm{grid,in}}$ and $b_t^{\mathrm{grid,out}}$. In addition, Eqs. A.7 and A.8 guarantee that the EV can only be charged or discharged if connected to the charging point through the binary variable b_t^{EV}. This variable is one, when the EV is located at the household, that is when the EV can be charged or discharged. For all time steps, where the EV is not located at the household, b_t^{EV} becomes zero. b_t^{EV} is determined by the individual driving profiles, which are input time series. This usage of binary variables result in a MILP.

$$b_t^{\mathrm{grid,in}} \bullet P^{\mathrm{GCP},max} \geq P_t^{\mathrm{grid,in}} \tag{A.4}$$

$$b_t^{\mathrm{grid,out}} \bullet P^{\mathrm{GCP},max} \geq P_t^{\mathrm{grid,out}} \tag{A.5}$$

$$b_t^{\mathrm{grid,in}} + b_t^{\mathrm{grid,out}} \leq 1 \tag{A.6}$$

$$b_t^{\mathrm{EV}} \bullet b_t^{\mathrm{charge}} \bullet P^{\mathrm{EV,charge},max} \geq P_t^{\mathrm{EV,charge}} \tag{A.7}$$

$$b_t^{\mathrm{EV}} \bullet b_t^{\mathrm{discharge}} \bullet P^{\mathrm{EV,discharge},max} \geq P_t^{\mathrm{EV,discharge}} \forall t \in T \tag{A.8}$$

Two additional constraints are concerned with the EV's SOC. Here, SOC^{safe} represents the minimum amount of energy, that must be in the EV's battery at all times when connected to the EVSE at home. Eq. A.9 ensures this safety SOC, where $E^{\mathrm{EV},max}$ is the EV's battery maximum capacity, such that the energy level cannot fall below SOC^{safe} when discharging the EV. For the scheduled departure, it is furthermore important that a sufficient amount of energy is stored within the EV's battery for user convenience. We hence implement Eq. A.10, where SOC^{dep} represents a previously set input parameter which defines the minimum SOC at scheduled departure. The binary variable $b_t^{\mathrm{EV,dep}}$ is one, if *t* is the time of departure, and zero at all other times.

$$E_t^{\mathrm{EV}} \geq SOC^{\mathrm{safe}} \bullet E^{\mathrm{EV},max} \bullet b_t^{\mathrm{EV}} \tag{A.9}$$

$$E_t^{\mathrm{EV}} \geq SOC^{\mathrm{dep}} \bullet E^{\mathrm{EV},max} \bullet b_t^{\mathrm{EV,dep}} \forall t \in T \tag{A.10}$$

A.2. Variable loss functions

Variable losses, as modeled in *eFlame*, are mainly caused by inverter losses of the EVSE, when converting AC power to DC power or vice versa. EVSE efficiency (η) is defined as the ratio of power output to power input, where the power input equals the sum of power output and power losses (Eq. A.11).

$$\eta_t^{\mathrm{EVSE,charge}} = \frac{P_t^{\mathrm{EVSE,charge,out}}}{P_t^{\mathrm{EVSE,charge,in}}} = \frac{P_t^{\mathrm{EVSE,charge,out}}}{P_t^{\mathrm{EVSE,charge,out}} + P_t^{\mathrm{EVSE,loss,charge}}} \tag{A.11}$$

As described in [6], the EVSE charging efficiency can be expressed as a function of the power input, which is the AC charging power. The left graph of Fig. A.1 presents this dependency. The right graph of the figure shows the AC charging losses as a function of AC charging power, where variable EVSE charging losses as well as constant losses are included. The calculation of this curve is also explained in detail in [6]. The dotted red line in the right graph of Fig. A.1 illustrates the linearization of the charging losses in *eFlame*, as described in Section 3.3.1, which enables the computational performance of the model to be greatly increased while maintaining a high level of accuracy. For discharging, identical equations and calculations are used.

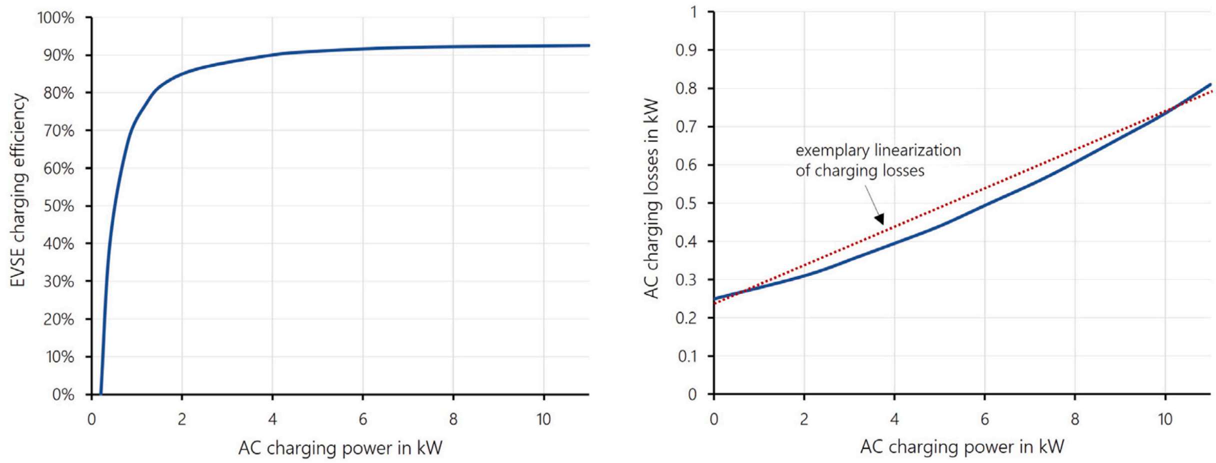

Fig. A.1. EVSE charging efficiency (left) and AC charging losses (right) as a function of AC charging power.

A.3. Exemption from varying taxes, levies, and grid fees (TLGF) for energy fed back into the grid

A particular feature, that is given special attention in the approach presented in this paper, is the implementation of the varying taxes, levies, and grid fees (TLGF) to be paid. As explained in the begin of Section 3.3, the amount of energy, which is charged into the EV from the grid and discharged at a later point in time back into the grid, is exempt from some of the TLGF, that are to be paid for private households.

In *eFlame*, the amount of energy, which is exempt from parts of the TLGF, is the energy discharged from the EV into the grid ($P_t^{\text{grid,out}}$ in the case of single spot market trading and $P_t^{\text{EV,discharge,2g}}$ in the case of use case combination). The different amounts of TLGF to be paid are taken into account by differentiating between the buying and selling prices. Eqs. A.12 and A.13 are used for the implementation of the use case combination. $c_t^{\text{el,buy,levies}}$ represents the full amount of TLGF to be paid when buying electricity. $c_t^{\text{el,sell,levies}}$ accounts for the reduced amount TLGF applicable for discharged energy in the amount of previously charged energy. For the single use case spot market trading, the equations apply analogously to the total energy that is bought and sold. The exemption parts of the TLGF can be varied through the input data according to the year and the scenario.

$$c_t^{\text{el,buy,EV}} = c_t^{\text{el,buy,market}} + c_t^{\text{el,buy,levies}} \tag{A.12}$$

$$c_t^{\text{el,sell,EV}} = c_t^{\text{el,sell,market}} + c_t^{\text{el,sell,levies}} \tag{A.13}$$

Appendix B. Appendix

B.1. Details regarding relevant input data

As an extension of the input data discussed in Section 4.1, a more detailed explanation of relevant data is given here. For time-variable spot market prices in 2021 and 2022, we use historical data from the different markets [49]. For 2030, the day ahead prices are based on [1], where the impact of bidirectional EVs towards a future European energy system is modeled in the energy system model ISAaR, and corresponding intraday prices are modeled as described in Section 3.3.4. The price forecast is shown for an exemplary time period in January in Fig. B.1.

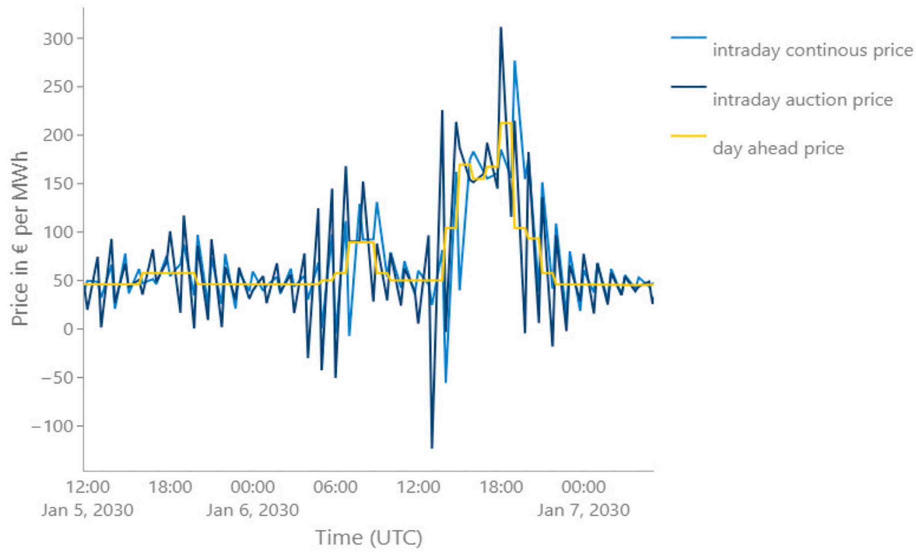

Fig. B.1. Price forecasts for day ahead prices, intraday auction prices and the ID1 index from 02.01.2030 till 05.01.2030.

Table B.1 shows statistical key figures, i.e. the average daily mean deviation, the average daily standard deviation, and the number of prices below zero, for the historical prices of the years 2021, 2022 and the reference time period of 2023, as well as for the price forecasts for 2023. While the average daily mean deviation lies above the prices of 2021 and 2023 (reference time period), it is below the prices of 2022 for all three prices considered. This may be attributed to the high absolute price level of 2022. The standard deviation of the forecasted prices is higher than the historical standard deviations for day ahead and intraday prices indicating a higher volatility. Especially, the standard deviation of the intraday auction shows a comparatively high level compared to the historical prices and, for 2030 clearly lies above the standard deviation of continuous intraday prices, while in historical prices the opposite is the case. This shows an overestimation of the intraday auction's price spreads in comparison to continuous intraday trading, which occurs due to modeling intraday prices solely based on the historical relation of hourly to quarter-hourly price and residual load deviations, which was already described in Section 3.3.4. This higher price spreads can also be seen in the number of prices below zero, where the intraday auction shows a higher number of prices below zero than the continuous intraday trade. Day ahead prices are not falling below zero due to the boundary conditions in [1]. Yet, the high number of day ahead prices close to zero leads to a high number of intraday prices below zero, as the price deviations of intraday prices usually go both directions within one hour.

Referring to Table B.2, PV renumeration rates for 2021 and 2022 are based on [64], where the renumeration rates, which are fixed for 20 years under the German regulatory incentive system, are specified. We assume that the PV systems start to operate at the beginning of the respective year. For 2030, it is assumed that the system is installed at the beginning of the current year 2023 and accordingly receives the fixed PV renumeration rate of 2023 for 20 years [65], as renumeration rates for 2030 are unavailable. The constant household electricity prices for the use case PV self-consumption optimization as well as the values for the different TLGF for 2021 and 2022 are average prices for households for Germany for the respective year derived from [66]. For these years, the exemption from TLGF in the base cases includes the combined heat and power levy (KWK-Umlage), the electricity grid charges ordinance (StromNEV) and the offshore grid levy. The exemption is based on the current regulation in Germany and accounts for 6% to 10% of the total TLGF. For the sensitivity of reduced TLGF (increased TLGF exemption), all remaining TLGF apart from the concession fee are exempted on discharged electricity that was charged into the EV from the grid at an earlier time. This is in accordance with the current German regulation for large-scale stationary battery storages. The increased exemption accounts for 87% to 91% of the total TLGF.

Table B.1
Key figures of historic spot market prices and price forecasts.

Year	average daily mean deviation			average daily standard deviation			number of prices below zero		
	day ahead	intraday auction	continuous intraday	day ahead	intraday auction	continuous intraday	day ahead	intraday auction	continuous intraday
2021	96.84	97.12	97.16	24.47	29.70	33.50	139	1184	1268
2022	235.46	234.53	236.13	57.30	67.21	73.97	70	695	985
2023 (Jan-Sep)	99.53	100.49	103.00	29.58	38.06	50.53	225	2108	2480
2030	127.43	128.50	130.54	60.92	92.14	74.89	0	4202	2945

For 2030, the methodology of [67] is applied to forecast plausible household prices and TLGF of the future. All values displayed in Table B.2 are real prices relating to the base year 2021 based on the average German inflation rate of the past 20 years (1.7%) and a nominal interest rate of 3% [30]. Energy procurement costs are derived from forecasted day ahead market prices using the energy system model ISAaR (see spot market prices of 2030). Real prices of distribution costs are assumed to remain constant due to a general increase in prices. For concession fee, electricity tax, combined heat and power levy, electricity grid charges ordinance, and the offshore grid levy, nominal prices are kept constant. For grid fees, the methodology explained in [67] is applied resulting in fees that are increased by one-third in comparison to 2021. The levy for disconnectable loads is eliminated completely by 2030. The value added tax remains at 19%. The resulting exemption from TLGF in the base case of 2030 is based on the current German regulation for large-scale stationary battery storages assuming that these regulatory exemptions will also apply to EV batteries in the future. The sensitivity of increased TLGF (reduced TLGF exemption) relates to the current regulation for EV.

Table B.2
Applied real prices for different years.

Year	spot market prices	PV renumeration rate	household electricity prices	total TLGF on electricity	exemption from TLGF*	increased/reduced TLGF exemption
2021	historical time series of day ahead, intraday auction	8.16 ct/kWh	32.16 ct/kWh	18.80 ct/kWh	1.09 ct/kWh	17.14 ct/kWh
2022	and continuous intraday (ID1)	6.83 ct/kWh	38.57 ct/kWh	12.73 ct/kWh	1.24 ct/kWh	11.07 ct/kWh
2030	forecasted time series	8.20 ct/kWh	35.88 ct/kWh	15.06 ct/kWh	13.67 ct/kWh	1.60 ct/kWh

* When discharging electricity from the EV into the grid, that was charged into the EV from the grid at an earlier time.

Regarding driving behavior of EV users, we use the FfE driving profile generator [36]. In the generator, mobility data and user activity data is matched to create mobility profiles for a variety of user groups. Most prominently, a distinction is made between users who commute to work during work days and those who do not commute on a regular basis. Taking the distance between two locations, the temperature, and the vehicle category into account, the final driving profiles are obtained, which consist of time of departure and arrival, location of the EV (home, work, other place), the distance of each ride, and the consumption per ride. For the simulations, a representative set of 200 individual profiles is generated consisting of all different user groups, half of which are commuters and half of which are non-commuters. As Fig. B.2 shows, at least 40% of all EVs are available at the charging location (at home) at any point in time. The average EV availability for charging is 80%. For the sub-group of non-commuters, at least 65% of all EVs are available for charging at any time and the average EV availability is 91%.

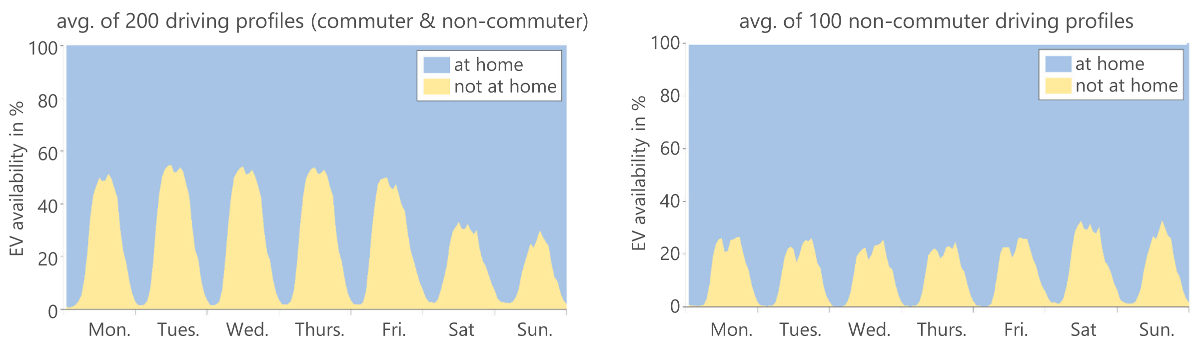

Fig. B.2. Average weekly EV availability at home resulting from the generated representative driving profiles.

If a household is considered for a use case, the FfE household load profile generator is utilized to determine the electricity consumption of each household [36]. In these cases, user activity data are used to generate activity profiles. These activities involve EV driving as well as other activities such as cooking, heating, cleaning and more. Thus, household load profiles can be generated which match the respective driving profiles. The corresponding PV generation profile is calculated based on the PV system size (peak power). For the household load profiles generated in this paper, we chose a medium household size. The resulting household electricity demand over one year varies from 1225 kWh to 7440 kWh, the load varies from 0 up to above 1 kWh. For the subset of 100 non-commuters, annual household consumption ranges from 1605 kWh to 5735 kWh.

Concerning relevant EV and EVSE parameters, Table B.3 summarizes nominal efficiencies and relevant SOCs. The efficiency data is obtained from EVSE manufacturers of the unIT-e^2 project and is identical to the data used in [6]. From today to 2030, nominal efficiencies and losses are increased due to technological improvements. The two relevant battery capacity parameters, SOC^{safe} and SOC^{dep}, are the result of expert discussions with car manufactures and user researchers. For SOC^{safe}, we consider a minimal safety mileage of 100 km to be sufficient for emergency trips with the EV taking the net battery capacity and the average electrical consumption into account. For SOC^{dep}, we use empirical data from the field trials of the BCM project as a basis [68]. The data suggests that most users are willing to depart with a not fully charged EV battery if benefitting from the reduced battery level. An average value of 70% for the medium sized EV used in our simulations is determined to be a realistic SOC at departure.

Table B.3
Applied PV parameters for base case.

Year	nominal charging efficiency (AC-DC)	nominal discharging efficiency (DC-AC)	EV and EVSE constant losses	SOC^{safe}	SOC^{dep}
2021/2022	92.5%	92.0%	200 W	31%	70%
2030	94.5%	94.5%	125 W	31%	70%

B.2. Absolute costs data

To understand how we come to the additional costs presented in Section 4.2, the underlying absolute costs per cost component are presented in Table B.4. Real costs for today and 2030 are displayed differentiated by MIN, MID and MAX and the three charging strategies. The data is obtained through expert assessments of the unIT-e^2 project partners. The data for today is partly based on a review of current purchase costs (EVSE purchase costs for direct charging and smart charging, metering equipment costs and additional hardware costs). For bidirectional EVSE purchase costs, expert assessments of EVSE manufactures of the unIT-e^2 project are used. EVSE installation costs are based on real installation costs in Germany today. Metering equipment costs arise from additionally needed metering devices. Additional hardware, which is needed for smart and bidirectional charging, comprises some sort of controlling or energy management device.

Most of the ranges of absolute prices remain constant over time (EVSE installation, metering equipment, additional hardware). For EVSE purchase, a cost degression is assumed based on the expert evaluation of EVSE manufactures of the unIT-e^2 project. We compared the obtained degression values for bidirectional EVSE costs with other literature and found that our cost values are well in line with the numbers of other studies [69,70].

Table B.4
Absolute costs of direct charging, smart charging and bidirectional charging for today and 2030.

		Today			2030		
		MIN	MID	MAX	MIN	MID	MAX
direct charging	EVSE purchase	300 €	450 €	600 €	250 €	375 €	500 €
	EVSE installation	300 €	800 €	3.000 €	300 €	500 €	3.000 €
	Metering equipment	0 €/a	20 €/a	20 €	0 €/a	20 €/a	20 €/a
	Additional hardware	0 €	0 €	0 €	0 €	0 €	0 €
smart charging	EVSE purchase	450 €	975 €	1.500 €	350 €	675 €	1.000 €
	EVSE installation	400 €	1.150 €	3.350 €	400 €	850 €	3.350 €
	Metering equipment	0 €/a	50 €/a	50 €/a	0 €/a	50 €/a	50 €/a
	Additional hardware	100 €	450 €	450 €	0 €	100 €	450 €
bidirectional charging	EVSE purchase	3.000 €	4.000 €	5.000 €	1.200 €	1.600 €	2.000 €
	EVSE installation	400 €	1.150 €	3.350 €	400 €	850 €	3.350 €
	Metering equipment	0 €/a	50 €/a	50 €/a	0 €/a	50 €/a	50 €/a
	Additional hardware	100 €	450 €	450 €	0 €	100 €	450 €

The range of determined prices sets the MIN and MAX values. The MID value for EVSE purchase is the mean of MIN and MAX values. For EVSE installation, circumstances such as the availability of electricity or internet connection at the site of installation are considered to determine the MID value as well as the additional costs for smart and bidirectional charging (see also [30]). Regarding metering equipment and additional hardware, MID values are considered to be equal to MAX values.

Appendix C. Appendix

C.1. Further simulation results in detail

Table C.1 summarizes relevant key figures of simulation results obtained in the context of this paper. Average values of 200 - and in the case of the non-commuter sensitivity 100 - individual simulations are presented. Some individual values vary greatly from the average, as for example for the charging and discharging efficiencies. The use case of single DA market trading is presented as a reference to the newly implemented sequential spot market trading. Battery aging is not a focus of this paper, but since the model *eFlame* comprises a novel submodule accounting for cyclical battery aging [14], we included the sensitivity battery aging in Table C.1. For the sensitivity, cyclical aging of a lithium-ion Nickel Manganese Cobalt (NMC) battery is modeled by applying the linear aging model, which determines the opportunity costs from degradation for each optimization step such that the capacity losses of each additional EFC are considered as a cost function to account for the aging. As the results in C1 show, cyclical battery aging has some effect on the results. Further simulations can provide additional insights in this regard.

In addition to the simulations displayed in Table C.1, we conducted preparatory simulations to determine the parameter sets and optimization parameters. As for the latter, we decided on an optimization horizon of 96 h with a saved optimization horizon of 24 h for the use case of sequential spot market trading and a saved optimization horizon of 48 h for all other use case.

Table C.1
Additional key figures of simulation results (average of 200 simulations or 100 simulations in the case of non-commuters) of main simulations conducted for this paper.

Use case	case/ sensitivity	smart charging					bidirectional charging					
		cost savings	emission reductions	daily charging hours	charging efficiency	self-consumption rate	cost savings	emission reductions	daily charging hours	charging/ discharging efficiency	self-consumption rate	additional EFC
Single spot market trading (DA)	base case 2021	94 €/a	19 kg/a	0.8	90.5%	–	128 €/a	52 kg/a	0.8	92.5%/ 92.0%	–	1.3
	non-commuter 2021	64 €/a	9 kg/a	0.6	90.0%	–	100 €/a	30 kg/a	0.6	92.5%/ 92.0%	–	1.6
	prices 2022	273 €/a	9 kg/a	0.9	87.3%	–	459 €/a	82 kg/a	1.8	92.5%/ 92.0%	–	36.2
	base case 2030	163 €/a	92 kg/a	1.3	84.7%	–	962 €/a	676 kg/a	4.2	94.5%/ 94.5%	–	115.2
	non-commuter 2030	107 €/a	37 kg/a	0.9	82.6%	–	1087 €/a	474 kg/a	4.9	94.5%/ 94.5%	–	145.9
Sequential spot market trading	base case 2021	130 €/a	53 kg/a	0.8	92.0%	–	164 €/a	40 kg/a	1.0	92.5%/ 92.0%	–	11.4
	non-commuter 2021	97 €/a	26 kg/a	0.7	91.1%	–	143 €/a	25 kg/a	0.9	92.5%/ 92.0%	–	13.6
	TLGF reduced 2021	130 €/a	53 kg/a	0.8	92.0%	–	286 €/a	−190 kg/a	3.6	92.5%/ 92.0%	–	95.0
	no CH limit 2021	157 €/a	86 kg/a	1.6	88.5%	–	208 €/a	99 kg/a	1.1	92.4%/ 92.0%	–	13.6

(continued on next page)

Table C.1 (*continued*)

Use case	case/ sensitivity	smart charging					bidirectional charging					
		cost savings	emission reductions	daily charging hours	charging efficiency	self-consumption rate	cost savings	emission reductions	daily charging hours	charging/ discharging efficiency	self-consumption rate	additional EFC
	prices 2022	412 €/a	162 kg/a	0.8	90.6%	–	618 €/a	−273 kg/a	4.1	92.5%/ 92.0%	–	110.7
	battery aging 2021	130 €/a	53 kg/a	0.8	92.0%	–	147 €/a	46 kg/a	0.9	92.5%/ 92.0%	–	4.4
	base case 2030	477 €/a	102 kg/a	0.8	87.3%	–	1938 €/a	538 kg/a	10.2	94.5%/ 94.5%	–	315.2
	non-commuter 2030	427 €/a	45 kg/a	0.7	85.5%	–	2348 €/a	369 kg/a	11.9	94.5%/ 94.5%	–	378.2
	TLGF increased 2030	477 €/a	102 kg/a	0.8	87.3%	–	1089 €/a	494 kg/a	4.7	94.5%/ 94.5%	–	130.9
PV self-consumption optimization	base case 2021	222 €/a	−34 kg/a	3.1	83.1%	35%	267 €/a	4 kg/a	2.7	89.1%/ 61.3%	36%	4.0
	non-commuter 2021	219 €/a	−74 kg/a	3.3	77.5%	36%	274 €/a	−13 kg/a	3.0	87.4%/ 62.2%	38%	5.7
	no CH limit 2021	229 €/a	−217 kg/a	3.3	74.9%	40%	279 €/a	−87 kg/a	4.6	86.8%/ 48.0%	41%	8.8
	prices 2022	306 €/a	−35 kg/a	3.1	83.1%	36%	370 €/a	6 kg/a	3.1	88.8%/ 64.7%	38%	4.9
	base case 2030	283 €/a	80 kg/a	3.0	87.0%	35%	323 €/a	62 kg/a	2.5	92.4%/ 65.1%	37%	3.5
	non-commuter 2030	291 €/a	74 kg/a	3.1	82.0%	37%	314 €/a	62 kg/a	2.8	91.7%/ 66.9%	39%	5.1
PV self-consumption optimization and spot market trading (CI)	base case 2021	393 €/a	126 kg/a	2.3	87.5%	34%	589 €/a	119 kg/a	4.7	89.3%/ 90.1%	53%	31.5
	non-commuter 2021	354 €/a	134 kg/a	2.3	84.4%	35%	617 €/a	144 kg/a	5.2	88.7%/ 90.5%	62%	40.8
	TLGF reduced 2021	393 €/a	126 kg/a	2.3	87.5%	34%	951 €/a	20 kg/a	5.4	90.8%/ 92.3%	56%	80.6
	no CH limit 2021	695 €/a	116 kg/a	2.3	85.7%	35%	884 €/a	45 kg/a	7.8	88.4%/ 86.0%	64%	42.8
	prices 2022	580 €/a	147 kg/a	1.6	89.1%	30%	1297 €/a	21 kg/a	5.0	91.7%/ 91.9%	47%	84.9
	battery aging 2021	393 €/a	126 kg/a	2.3	87.5%	34%	561 €/a	137 kg/a	4.4	89.2%/ 88.6%	53%	17.1
	base case 2030	529 €/a	132 kg/a	2.4	92.2%	35%	2300 €/a	628 kg/a	11.5	94.4%/ 93.5%	64%	208.6
	non-commuter 2030	441 €/a	103 kg/a	2.4	91.0%	38%	2784 €/a	744 kg/a	11.9	94.2%/ 93.9%	84%	259.1
	TLGF increased 2030	529 €/a	132 kg/a	2.4	92.2%	35%	1522 €/a	507 kg/a	9.8	94.2%/ 92.8%	66%	104.1

C.2. *Exemplary description of range of simulation results*

Fig. C.1 depicts the range of simulation results using the example of the base case 2021 for the use case PV self-consumption optimization (left) and the use case PV self-consumption optimization and spot market trading (right). In each plot, the user groups commuters and non-commuters are differentiated. Each user group area consists of 100 individual simulation results. The area's width to left or right reflect the density of values along the y-axis. The dotted lines represent the 25% and 75% quantiles, the dashed line the median.

As the figure shows, electricity costs vary significantly more for the commuter group than for the non-commuter for both use cases. Non-commuter show generally lower electricity costs and less deviation due to lower milage and more similar user behavior. The shift of the areas for smart and bidirectional charging behaves in a similar way. For both use cases, the density distribution, i.e. the shape of the area, remains largely the same, and the areas move further downwards towards lower electricity costs.

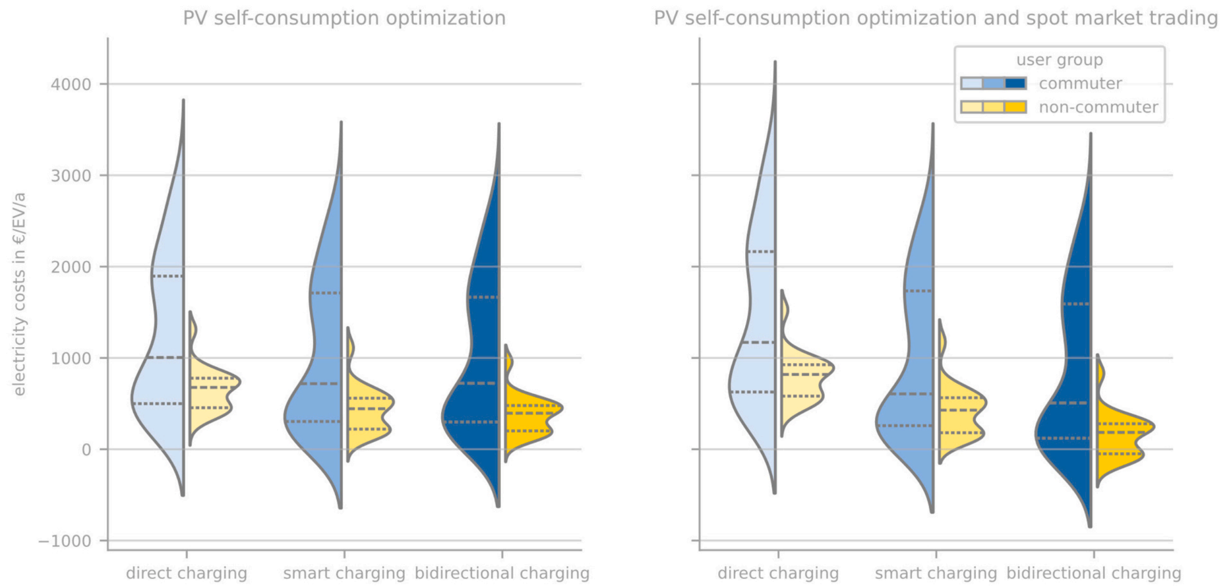

Fig. C.1. Violine plots for base case 2021 of PV self-consumption optimization (left) and PV self-consumption optimization and spot market trading (cont. intraday), each curve showing the distribution of 100 simulations.

C.3. Exemplary display of total emission reductions over time

Analogous to the profit assessment in Fig. 12 (Section 4.3.3), we exemplarily analyze the total emission reductions of the base case 2021 over time, taking not only the annual emission reductions of the respective use case into account, but also considering additional emissions from hardware production and operation for smart charging and bidirectional charging. To do so, emissions of metering equipment and EVSE from [63] are used to determine today's lifecycle emissions of production (at time of purchase) and operation (annually) for direct charging, smart charging and bidirectional charging. Additional cyclical battery aging is not considered. The difference between smart charging and direct charging constitutes the additional emissions for smart charging. The difference between bidirectional charging and direct charging constitutes the additional emissions for bidirectional charging.

The resulting plot is shown in Fig. C.2 for bidirectional charging. For all use cases, the initial additional emissions for bidirectional charging are high in comparison to the annual emission reductions. For the use case sequential spot market trading and the use case PV self-consumption optimization, annual emission reductions are not high enough to compensate for the initial additional emissions over the displayed timespan. In fact, as the positive gradients of the cumulated emissions indicate, the annual emission reductions are not even high enough to compensate for the additional annual emissions for operation. Especially for PV self-consumption optimization, the resulting annual increase of cumulated emissions for bidirectional charging is substantial. Concerning smart charging as a comparison, in the case of sequential spot market trading the additional emissions are offset by emission reductions in the second year. In contrast, for PV self-consumption optimization cumulated emissions of smart charging increase steadily over time, since the charging strategy in this cases does not reduce but increase emissions. For the use case PV self-consumption optimization and spot market trading, annual emission reductions of bidirectional charging are high enough to offset the initial as well as the annual additional emissions in the ninth year after purchase. For smart charging, the emission reductions of the first year are already high enough to balance the initial and annual additional emissions out.

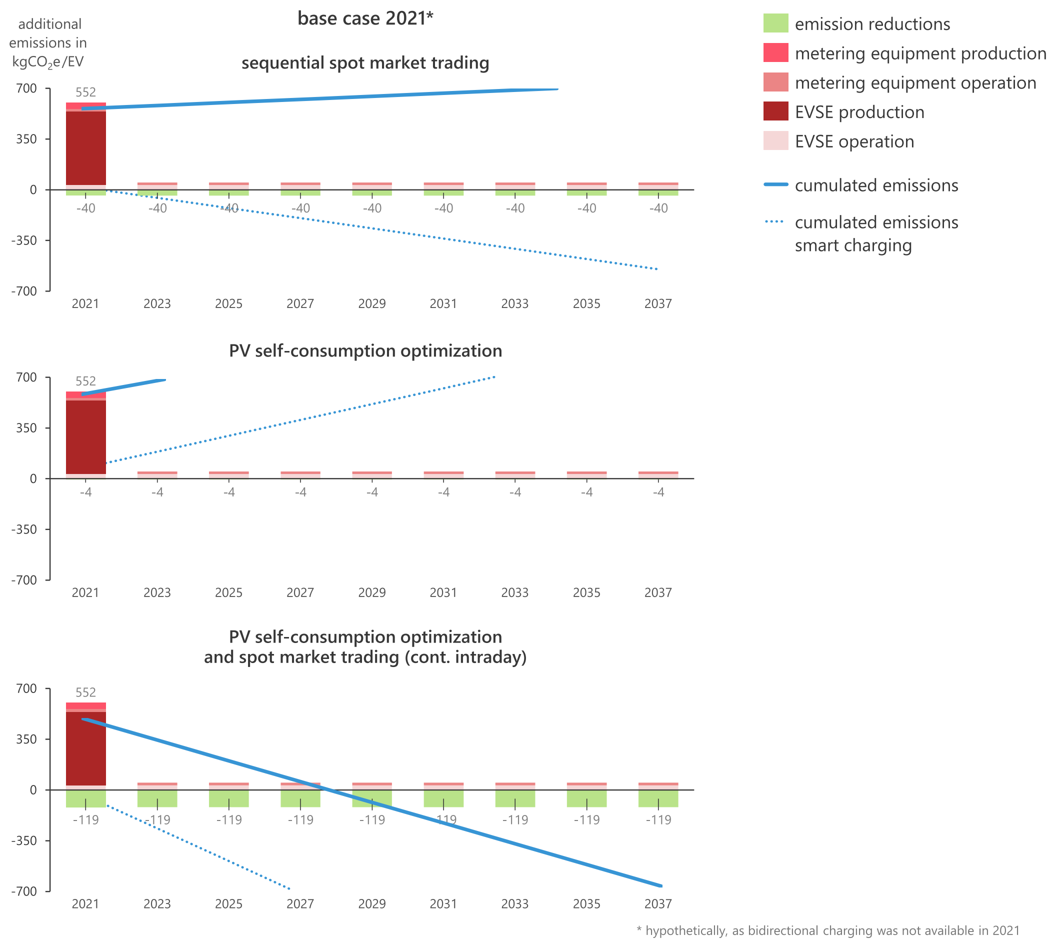

Fig. C.2. Additional emissions, annual emission reductions (average of 200 individual simulation results) and resulting cumulated additional emissions for bidirectional charging (direct charging as a reference), cumulated emissions for smart charging as benchmark (dashed line).

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Publication 4 [Pub4]:
Smart E-Mobility: User Potential in Germany Today and in the Future

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NEIS 2023 **2023**, pp. 273-280

Permanent web link:

Smart e-mobility: user potential in Germany today and in the future - Tagungsbeiträge - VDE VERLAG

Smart e-mobility: user potential in Germany today and in the future

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Abstract

Electric vehicles are an effective mean to decarbonize the transport sector in an effort to address the climate crisis. In this regard, intelligently managing the charging process of electric vehicles enables the purposeful integration of electric mobility. Use cases of such smart charging processes range from local self-optimization (PV-optimized charging, peak shaving) to spot market participation (day ahead or intraday market trading) to system-stabilizing measures (redispatch, balancing services). To contribute to current research, this paper presents a novel approach to determine so-called user potentials, which are the number of vehicles users, who are generally eligible to conduct a respective use case. Two types of user potentials are calculated for a base year (2021) and a future year (2030) for Germany using specific methodologies for ten use cases. The resulting user potentials for 2021 are relatively high in relation to the current number of electric vehicles registered in Germany. The use case day ahead market trading shows the highest user potential with at least 1.7 million applicable electric vehicles users. Optimized PV self-optimization and peak shaving also yield potentials of well above 1 million electric vehicles users. Other use cases, such as all intraday markets or balancing services, display rather small user potentials. For the future year of 2030, user potentials are increased for most cases. The largest increases are obtained for day ahead market trading and PV self-consumption (3.5 and 2.9 million additional users). Potentials of intraday market trading, peak shaving and redispatch remain rather moderate with only slight increases. For balancing services, the user potentials are even slightly decreased.

Keywords – electric vehicle, smart charging, spot market, balancing services, grid support, redispatch, peak shaving

1 Introduction

Electric mobility (e-mobility) facilitates the decarbonization of the transport sector, especially for private vehicles, due to lower operational emissions of electric vehicles (EVs). The smart management of charging - and potential discharging - processes of EVs allows for e-mobility to be implemented purposefully and for specific applications. [1] Such specific applications of smart charging are called 'use cases' in the following.

1.1 Motivation

At present, smart charging use cases are subject to substantial academic research, often with regard to their profitability, their effects on the energy system as well as their convenience for the user [2,3,4,5]. To add value and novelty to current research, this work presents a methodology to capture user potentials for specific smart charging use cases.
We define user potential as the number of possible users, who are generally eligible to conduct the respective use case in a given year. The user potential does thus not depend on the actual number of available EVs, but displays the general relevance of a use case in terms of EV users. The results of applying our methodology can be utilized to analyze, which use cases are of great relevance regarding the number of users today and in the future. These findings can then be linked to other research in smart e-mobility, such as profitability or effects on the energy system.
For this work, we apply the developed methodology to relevant use cases in the context of Germany for a recent year (2021) and a future year (2030). The relevant use cases are determined on the basis of the research in the unIT-e² project, where 29 partners of the energy and automotive industry investigate the integration of smart e-mobility in the German energy system and conduct various field trials with a research focus on matching dynamic market requirements and efficient grid operation [6].

1.2 Scope of use cases

The smart charging use cases, which are relevant in this work, can be classified intro three categories according to different incentive mechanisms:

- location-based use cases, where optimization processes are conducted behind the grid connection point inside the property
- spot-market-oriented use cases, which are based on price signals from energy markets, where charging processes are optimized according to the price characteristic on the respective spot market
- system-oriented use cases with the aim of ensuring stability of the energy system at transmission as well as distribution grid level

Table 1 shortly describes the use cases relevant in this work sorted by category.

Table 1 Relevant use cases for smart e-mobility

Use case	Short description
Location-based use cases	
Optimized photovoltaic (PV) self-consumption	Direct usage of self-generated PV electricity for EV charging to reduce electricity costs and increase self-sufficiency
Peak shaving	Reduction of peak load by shifting EV charging times to lower capacity charges as part of the grid fees if applicable

Spot-market-oriented use cases	
Day ahead market (DA) trading	Charging at times of low hourly prices in the day ahead market to reduce electricity costs
Intraday auction market (IDA) trading	Charging at times of low quarter-hourly prices in the intraday auction to reduce electricity costs
Continuous intraday market hourly (CID 1h) trading	Charging at times of low hourly prices in the continuous intraday market to reduce electricity costs
Continuous intraday market quarter-hourly (CID ¼h) trading	Charging at times of low quarter-hourly prices in the continuous intraday market to reduce electricity costs
System-oriented use cases	
Frequency containment reserve (FCR)	Provision of FCR by increasing or decreasing charging power to earn additional revenues
Automatic frequency restoration reserve (aFRR)	Provision of aFRR by increasing or decreasing charging power to earn additional revenues
Manual frequency restoration reserve (mFRR)	Provision of mFRR by increasing or decreasing charging power to earn additional revenues
Redispatch provision	Provision of redispatch (congestion management in the transmission grid) by increasing or decreasing charging power to earn additional revenues

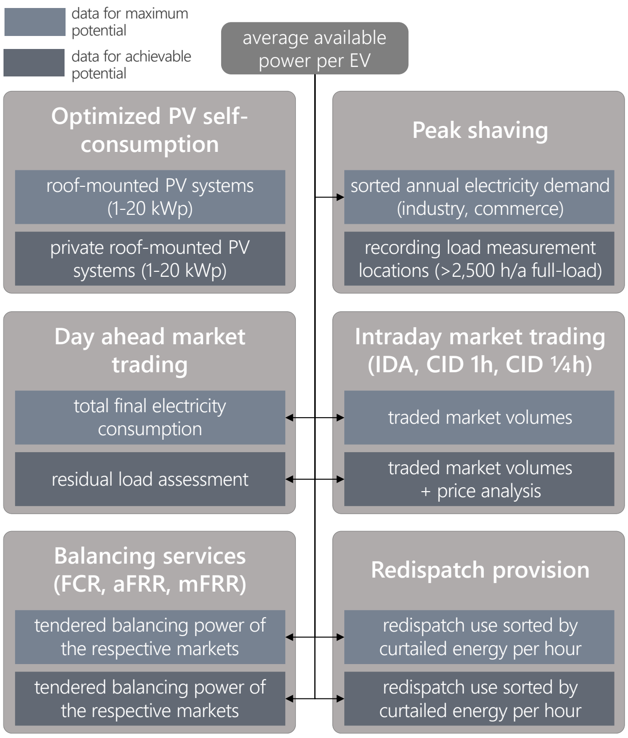

Figure 1 Main data basis for user potentials of the individual use cases and usage of average available power

2 Methodology

In this paper, user potentials are determined for each defined use case (see table 1). As design and incentive mechanism vary for each use case, the actual calculation of user potentials is carried out based on different methodologies and may vary for the two different years (2021 and 2030). An important methodological aspect is the distinction between two different types of user potential:

- the **maximum user potential**, which is an upper, rather theoretical estimate of the total possible number of EV users given the basic constraints of the respective use case
- the **achievable user potential**, which is based on a more realistic assessment for the number of EV users depending on use case specific premises and further user limitations

Some of the user potentials are calculated using the average available power per EV. The average available power (p_{avg}) is the product of maximum charging power, vehicle availability at the charging location, and reliable plug-in probability. Depending on the use cases, the charging location (at home, at work, or both) and thus the vehicle availability may vary. Public charging is not included in our analysis, as smart charging is less likely for such locations. Reliable plug-in probability can change for future years due to learning effects and a higher reliability.

Figure 1 shows the main data sources per use case and displays in which cases the average available power is used. The individual methodologies of calculating both types of user potential are described in the following subsections.

2.1 Optimized PV self-consumption

For optimized PV self-consumption, the number of buildings with a roof-mounted PV system is considered as criterion to determine the user potential. In Germany, PV feed-in tariffs decrease with the increasing system size and larger PV systems are more likely to be directly marketed or included in long-term power purchase agreements (PPAs). For these reasons, we consider buildings with PV systems no larger than 20 kW peak power to be relevant for the use case. PV systems smaller than 1 kW peak power and plug-in systems are excluded due to the small electricity output. Thus, for the maximum potential, data from the German core energy market data register [7] is used to determine the number of buildings with PV systems in the range of 1 – 20 kWp. This number represents the maximum potential for the base year 2021.

For the future year 2030, we utilize the German development goals for installed PV power in 2030 (215 GW) [8]. Half of the additional PV power to be installed is set to be roof-mounted PV systems [9]. Taking the installed PV power of the base year 2021 [10] into account results in 78 GW additionally installed PV power of roof-mounted systems in 2030. By considering the average peak power of all roof-mounted systems in Germany to be constant [7], the total number of additionally installed roof-mounted systems in 2030 is calculated. The share of roof-mounted systems between 1 – 20 kWp in all roof-mounted systems of 2021 is kept constant and multiplied by the total number of additionally installed roof-mounted systems. The resulting number of additionally installed roof-mounted systems in the range of 1 – 20 kWp in addition to the maximum potential of 2021 yields the maximum potential for 2030.

An identical approach is used to calculate the achievable user potential. Based on the core energy market data register [7], all roof-mounted PV systems smaller than 20 kWp and larger than 1 kWp, which are registered for private households, are determined. Thus, the achievable user potential excludes all systems which are used for industrial, commercial or agricultural purposes, or are not specified. The underlying assumption is that private households in particular have an interest in optimizing their own consumption via EVs. Industry, agriculture, and commerce have overlapping interests (for example direct electricity use or peak shaving). For the achievable potential 2030, the same steps are followed as for the maximum potential.

2.2 Peak shaving

The use case peak shaving is attractive for those users which must pay a power-based price component (capacity charge) as part of the grid fees for their electricity usage. In Germany, these are usually users of the commerce sector and the industry sector. The maximum user potential of the use case is based on the German electricity load curves of these two sectors, where the annual power demand is sorted in descending order over the hours of the year [11]. To ensure comparability between the two years, load curves derived from simulations of the sector models of the FfE are used for both 2021 and 2030. As these results are confidential, they are not explicitly stated here. The curves are used to determine the power that can be reduced via peak shaving. To do so, a reasonable number of hours for operating peak shaving per year is defined. Due to the different characteristics of the two sectors, this number of hours differs for industry (1,000 h/a) and commerce (2,500 h/a). The difference between the maximum power during the year and the power that is reached at the respective hours per year in the curves represents the reducible power (see Figure A.1). The sum of the reducible powers of both sectors divided by the average available power per EV for the charging location *at work* yields the maximum number of EVs – that is the maximum potential – for peak shaving of the respective year.

The achievable user potential for peak shaving depends on the number of relevant industrial and commercial businesses and on the number of EVs necessary to achieve a substantial load reduction per business. For the number of businesses, the amount of metering locations, which are subject to a recording load measurement (locations with an annual electricity consumption higher than 100,000 kWh), is taken as a starting point, as these businesses must pay a capacity charge [12]. Since a significantly increased capacity charge is due for businesses with more than 2,500 hours of annual full-load operation, we consider only this share of businesses to be relevant for the achievable potential.

The total number of EVs (n_{EV}) for the respective year, which represents the achievable user potential, is calculated via Equation 1.

$$\mathrm{N}_{EV} = \mathrm{n}_{bus,s} \cdot EV_{bus,s} + \mathrm{n}_{bus,l} \cdot EV_{bus,l} \tag{1}$$

For the number of EVs necessary per business, a distinction is made between small to medium-sized businesses (*bus,s*) and large energy-intensive industrial businesses (*bus,l*). For small to medium-sized businesses today simulation results show that up to six smart charging EVs constitute added value to reduce load peaks [13]. Additional EVs reduce the load peak but not in a cost-effective way. For large industrial businesses, the reasonable amount of EVs is determined by scaling the six EVs, which are suited for small to medium businesses. As a scaling factor, the ratio of the average passenger car fleet size of large businesses (at least 1,000 employees) to small businesses (less than 1,000 employees) is used, resulting in 78 EVs for the base year 2021 [14]. The number of businesses is kept constant. The numbers of EVs are scaled in accordance with the development of electricity consumption. As an increase in electricity consumption of the commerce and industry sector is assumed, the number of EVs increases as well [11,15]. The resulting numbers of EVs are calculated in the same way as for 2021, which yields the achievable potential for 2030.

2.3 Day ahead market trading

For day ahead market trading, different approaches are used to identify maximum and achievable potential. As the day ahead market is the primary source of electricity procurement in Germany and over-the-counter trading is also linked to this market, the total final electricity consumption is used as the basis to determine the maximum potential for EVs to participate in the market. As Equation 2 shows, the maximum number of EVs (n_{EV}) for the respective year is calculated by dividing the average consumed net electric power [16] by the average available power per EV both at work and at home. The underlying premise is that this power has to be purchased directly or indirectly via the day ahead market.

$$\mathrm{n}_{EV} = \frac{E_{el,net}/8760h}{p_{avg}} \tag{2}$$

For both 2021 and 2030, the same equation is used, yet an increase in electricity consumption based on predictions of [17] and the average available power per EV for 2030 are incorporated into the calculations of 2030.

For the achievable user potential, analyses of the German residual load are used. The residual load constitutes the part of the electricity consumption, which remains after subtracting the electricity provided by variable renewable energies (PV and wind power). It can be interpreted as a measure of the demand for flexible consumers and producers. For this paper, we calculated the minimum and the mean residual load per day for various years. Times of minimum residual load represent times of low electricity prices that are suitable for smart charging. Therefore, the difference between daily minimum and mean residual load is considered as the amount of power, that can be applied for smart charging. [10,18] The resulting power applicable for smart charging is divided by the average available power per EV to return the achievable user potential. This approach is carried out for both the base year 2021 and the future year 2030 in the same way.

2.4 Intraday market trading

The user potentials for the three different German intraday markets (IDA, CID 1h, CID ¼h) are quantified in identical ways. For the maximum potentials of 2021, market volumes of 2021 are obtained from the German EPEX electricity exchange [19] and average traded powers are calculated by dividing market volumes by the number of hours per year. Dividing these powers per market by the average available power for locations both at work and at home per EV yields the maximum user potential of the base year 2021 for all three markets. For 2030, predictions of the future market volumes of these spot markets are highly complex, sensitive to many parameters and thus often inaccurate. For these reasons, we use a linear extrapolation based on historical data from recent years (2017 to 2022) to estimate the market volumes for 2030. Using these market volumes and the average available power per EV of 2030, the maximum potentials for 2030 are calculated.

For the achievable potentials, the market volumes of the respective spot markets ($E_{traded,market}$) again constitute the basis of the calculations. As an additional factor, analyses of the markets' prices are taken into account. For this purpose, we determined the daily mean market prices of 2021 for all three markets. Since smart charging shifts charging to times with low electricity prices, the number of times for which the market price was below the daily mean price was identified ($f_{prices,low}$). Thus, to calculate the achievable potential, $f_{prices,low}$ is multiplied with the average traded powers per market and the result is divided by the average available power per EV (p_{avg}) (see Equation 3).

$$\mathrm{n}_{EV} = \frac{E_{traded,market}/8760h \cdot f_{prices,low}}{p_{avg}} \tag{3}$$

For 2030, extrapolated market volumes and the average available power per EV for 2030 are used, but as no feasible future price series exist, the same ratios of low prices are used as for 2021.

2.5 Balancing services

For all three balancing services, similar approaches are used to determine the user potentials. As a basis serves the tendered balancing power of the different balancing markets for Germany, which is available in the annual monitoring report of the German network agency [20]. The user potential is calculated by dividing the tendered balancing power of a market by the average available power per EV for locations both at work and at home. However, differences in the methodology occur for the different balancing markets. For FCR, market participants must be able to provide both positive and negative balancing power in the amount of the offered power. Hence, for each kW offered in the FCR market, two kW of charging power must be reliably available. For the aFRR and mFRR market, either negative or positive balancing power can be offered. Thus, no additional factor is needed for these two use cases.

The difference between maximum and achievable user potential can be established by taking the necessary redundancy for the offered balancing power into account. As it is highly important for the provision of balancing services that the power offered on the market is definitely available, the power of a pool of assets must always be fail-safe under current rules. At present, according to the prequalification conditions, the so-called n-1 rule applies, which states that the redundancy must be equal to the highest power offered by an individual asset [21]. However, given the comparatively low charging power of EVs and the relatively high uncertainty of availability, it can be assumed that these rules will change in the future and that more or different reserve power must be provided. Following several conversations with aggregators and grid operators, an assumption is carried out, as 25% of the pool capacity is assumed for redundancy meaning that a pool of EVs participating in balancing markets must always comprise 25 % more power than can be offered.

Initial considerations resulted in the assumptions that no redundancy is required for estimating the maximum potential, but that it is required for determining the achievable potential. Yet, these assumptions would result in an achievable potential that is higher than the maximum potential. Hence, a distinction between the types of user potential is not possible for the use cases of balancing services, such that achievable equals maximum potential for these cases.

Predicting the future development of tendered balancing power is difficult. No distinct trend can be detected when analyzing past years [20]. Some developments might lead to a decrease in balancing power demand, such as improvements in forecast quality of variable renewables, others to an increase, such as the expansion of variable renewables, and still others have no detectable effect [22]. As estimating the average capacity with a sufficient degree of certainty is impossible, we refrain from forecasting a change in market volumes for balancing services in 2030. Instead, the same numbers of tendered balancing power as in the base year 2021 are chosen for 2030. As the average available power per EV changes for 2030 due to an increased plug-in probability, the resulting user potentials still vary.

2.6 Redispatch provision

The use case redispatch is special as EVs are not included in the current regime of redispatch 2.0 in Germany [23]. Hence, relatively little specifications exist for the use case at the moment. A redispatch market to include flexible small--scale consumers, such as EVs, is not unlikely in the future [23]. As a way to assess user potentials in the absence of a defined future regime, current data of the redispatch demand in Germany are used for both maximum and achievable potential. The German annual monitoring report provides the German redispatch need per hour for the base year 2021 [20].

For the maximum user potential, we imply that redispatch is provided via EVs in the few hours of the year, where the redispatch demand is the highest. The underlying assumption is that during these hours (we suppose 100 h/a) renumeration might be high. Thus, redispatch power needed for 100 h/a is selected from [20]. For the achievable potential, the redispatch power needed for 2,500 h/a is selected. This ensures that EVs are used for redispatch sufficiently often to be able to create a business case. The user potential is calculated by dividing the needed redispatch power by the average available power per EV at both locations, at home and at work.

For the future year of 2030, we scale the redispatch need by using forecasts of redispatch demand. Different predictions exist for the future regarding this demand. If the targets of the German grid development plan are met, sufficient measures will be taken to reduce the need for redispatch very significantly [9]. If few or no such measures are taken, the redispatch demand will rise sharply. An intermediate solution is provided by [24], where the demand increases from 15.3 GWh in 2021 to 20 GWh in 2030. The quotient from the values of 2030 and 2021 is used to scale the redispatch need. Dividing the new redispatch needs by the average available power per EV of 2030 results in the respective user potentials of 2030.

3 Results and discussion

We applied our methodology in the described way and obtained both maximum and achievable user potentials for 2021 and 2030. To start with, table 2 shows the average available power per EV, which is utilized for some of the use cases, for both years and locations. The maximum charging power is 11 kW for both years, since this is the standard resulting from a three-phase 230 V connection with 16 A. The percentages of vehicle availability result from analyzing the FfE-driving-profiles [25]. The reliable plug-in probability is a figure, which describes the probability that a user will start the charging process whenever the EV is at the charging location. The figure for 2021 results from assessing real user data recorded in an EV field trial project [26]. For 2030, an increase is expected due to learning effects of the users and a higher reliability for the operators. Subsequently, the potentials for both years are presented and discussed.

Table 2 Charging and availability parameters

Parameter	**2021**			**2030**		
	At home	**At work**	**both**	**At home**	**At work**	**both**
maximum charging power in kW	11			11		
vehicle availability at the charging location	77 %	18 %	96 %	77 %	18 %	96 %
reliable plug-in probability	60 %			70 %		
average available power per EV in kW	**5,1**	**1,2**	**6,3**	**6,0**	**1,4**	**7,4**

3.1 User potentials today

The resulting user potentials of the base year 2021 are displayed in Figure 2, where the outer circle represents the maximum potential and the inner circle the achievable potential. At this point, it is important to bear in mind that the user potential is not related to the number of registered EVs. In general, apart from the use case of day ahead market trading, the numbers of users eligible for the relevant use cases appear to be relatively small measured by the total number of passenger cars in Germany, which was 48.5 million by the end of 2021 [27]. In relation to the number of EVs in 2021, which was 620,000 cars [28], the user potentials can be interpreted as rather promising meaning that for the base year EV users would be able to perform various different smart charging use cases if all of these would be possible today.

The first use-case-specific finding is that the maximum potential of the use case day ahead market trading exceeds the potentials of the other use cases by far. Up to 9.2 million EV users could be eligible for the use case. However, the difference between the maximum potential and the more realistic achievable potential is huge (7.5 million EV users). This indicates that although theoretically a large number of EV users can engage in day ahead market trading, the markets' price spreads, which are indirectly the basis for the achievable potential, are only sufficiently high for fewer users to operate the use case in a profitable manner. The achievable potential is therefore a much better indicator of the potential for this use case.

For the other spot-market-oriented use cases, the differences between maximum and achievable potential are not as large. All three use cases show relatively small user potentials, with the hourly trading in the continuous intraday market displaying the largest potential and the sum of achievable potentials being 630,000 EV user. Hence, even though intraday markets and especially the quarter-hourly trading in the continuous intraday are considered by many to be financially promising, the number of EV users who can actually participate in the markets is rather limited.

A similar assessment holds true for the use cases of balancing services (FCR, aFRR, and mFRR), where maximum and achievable potential are identical (see section 2.5). The potentials are approximately of the same magnitude as the potentials of the intraday use cases. Taking the FCR market as an example, the number of EV users (220,000 in 2021), which can participate in the market, is not as large as some might expect. Yet, the user potentials of FCR, mFRR, and aFRR can be considered as even more realistic as these of intraday trading, since instead of the average traded power, the real tendered balancing power of the respective market are used for calculation.

For the system-oriented use case of redispatch provision, user potentials are again relatively small and maximum and achievable potential differ by 470,000 EV users, which is 75 % of the maximum potential. These potentials are subject to uncertainty, as they are based on assumptions on which number of hours of annual redispatch need is realistic for an EV user to provide redispatch (see section 2.6). However, as the maximum potential already constitutes a rather optimistic estimate of only 100 hours of redispatch provision per year, it is reasonable to say that no more than 630,000 EV users are to be expected for this use case.

Both location-based use cases present medium to large user potentials, which only day ahead market trading showing greater potentials. For optimized PV self-consumption, maximum and achievable potential do not differ substan-

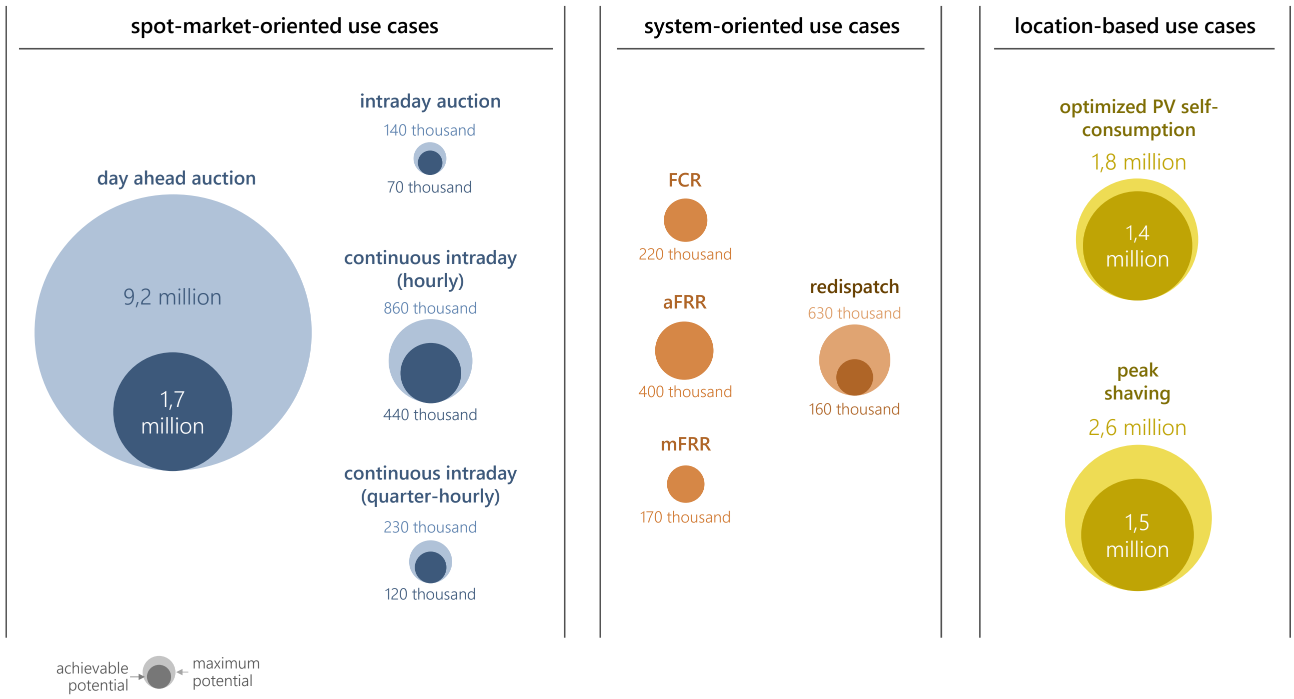

Figure 2 User potentials for smart charging in 2021

tially, since the additional limitation, that explicitly only private households are considered for the achievable potential, does not substantially decrease the user potential. For peak shaving, both the high maximum and achievable potential mainly result from the peak shaving potential of the commerce sector. The rather large difference between the two types of potential (1.1 million EVs) shows the inherent uncertainty of the use case.

3.2 User potentials 2030

For the user potentials of 2030, the main focus of the analysis lies on the predicted developments of the numbers of EV users. Apart from the use cases of balancing services, all user potentials are increased in comparison to the base year 2021 (see Figure 3, where - in addition to maximum and achievable potentials of 2030 – the achievable potentials of 2021 are displayed). Some of the achievable user potentials show a particularly large increase. Even if a direct addition of the user potentials is not permissible, the amount of individual use cases implies that many EVs could participate in smart charging in 2030 taking the target of the German government of 15 million EVs by 2030 as a perspective [29]. Still, some of the individual user potentials are rather small, since the number of expected EVs is increasing but some potentials are not or only slightly.

For the use case of day ahead trading, the maximum number of potential EV users remains almost constant, since the slightly increased average available power per EV for 2030 counteracts the effect of an increased total electricity consumption. The achievable potential shows the largest increase of all displayed achievable potentials with a plus of 3.5 million EV users. This substantial increase is due to an expected rise of residual load volatility or to be more precise the rise of the difference between maximum and mean residual load per day.

As more variable renewable energies are to be installed in 2030, a higher fluctuation in electricity production is simulated resulting in a more volatile day ahead market with increased prices spreads, which in turn increases the potential for smart charging in this market. For the other spot-market-oriented use cases, increased numbers of EV users are determined for both types of potential due to the predicted rise in market volumes. For quarter-hourly continuous intraday trading, both potentials are more than doubled. Still, in absolute figures the user potentials of these markets remain rather small, and the increase of the achievable potentials is not as high as for the day ahead market use case. As mentioned above, the potentials of the use cases of balancing services are the only potentials that are reduced for 2030 and the numbers of EV users remain rather small for all three markets. The reason for the decrease is that, in the absence of alternatives, market volumes are kept constant, whereas the used average available power per EV for 2030, is increasing. As a consequence, the decrease in user potential can be traced back to learning effects of the users and a higher certainty for EV availability, which cause the increase of average available power. Again, it is important to mention that the numbers of EVs presented for FCR, aFRR, and mFRR are very well-founded, as these are based on the tendered powers of the respective markets and not on averaged powers.
Both maximum and achievable user potential of redispatch provision are only slightly increased. Similar to the maximum potential of day ahead market trading, the opposed effects of increased redispatch demand and increased average available power per EV cancel each other out. Since the user potential for redispatch in 2021 is already not as well-founded as for other use cases and any prediction of the redispatch need of the future is subject to many uncertainties, this finding should be interpreted with caution.

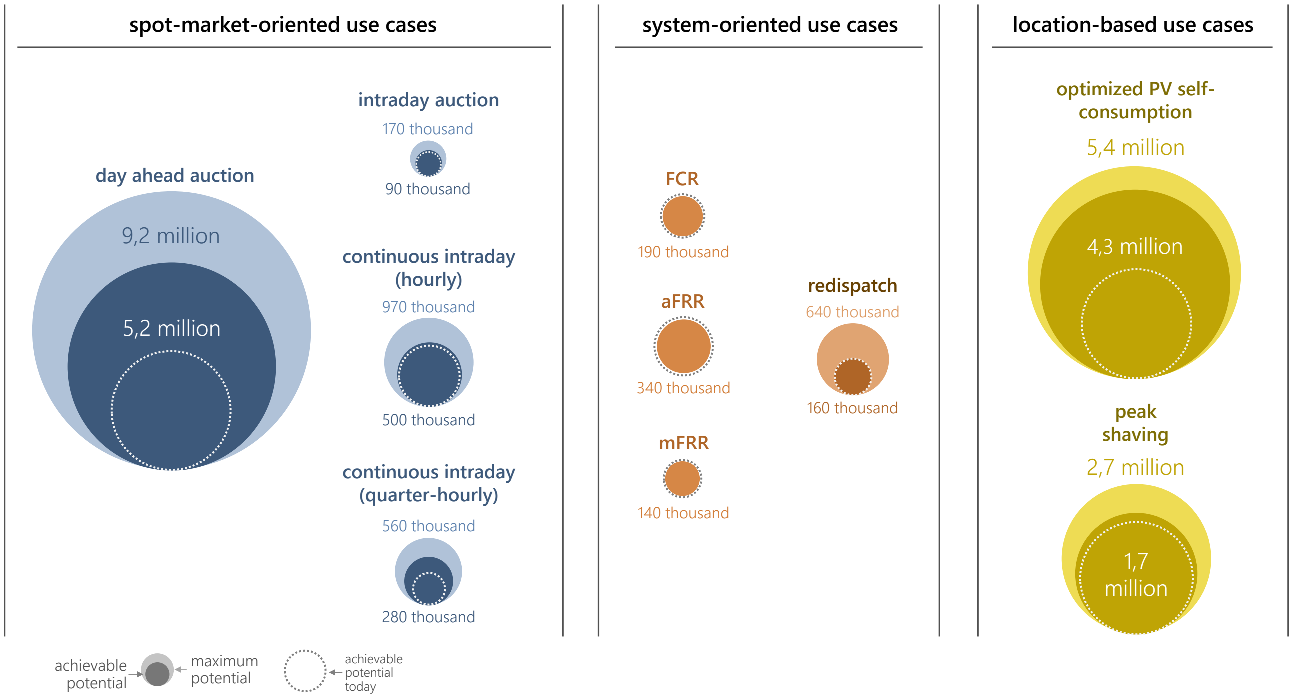

Figure 3 User potentials for smart charging in 2030 (dashed circle show the achievable potentials of 2021)

Nevertheless, it is safe to say that if the redispatch need will not increase drastically by 2030, the user potential would increase just as much.

For the use case of optimized PV self-consumption, an increase in EV users of the same magnitude as for day ahead trading is determined. The maximum potential rises by 3.6 million, which is the largest increase of maximum potential, and the achievable potential by 2.9 million EV users. The large increase for both potentials is caused by the expected rise in roof-mounted PV systems in Germany. The development goals of the government promise new installations of 4.4 million roof-mounted systems in total, if the average installed power remains constant, which in proportion results in the mentioned rise of user potentials.

In the case of peak shaving, both the maximum and the achievable potential are only slightly increased. The increase is due to the general prediction of rising electricity demand and is not attributable to changes in load characteristics or different business approaches.

4 Conclusions

In many respects, smart charging is a meaningful step toward the purposeful integration of e-mobility. Conclusions drawn from assessing user potentials of relevant use cases in this field differ for today and the future development. In relation to the current number of EVs on German streets, the potentials for 2021 are relatively high. Yet, for some use cases, potentials are rather limited. The future potentials of 2030 are increased for most cases. Still, compared to the target of 15 million EVs in Germany in 2030, the rise from 2021 to 2030 is moderate for many use cases.

Most pertinent findings for the base year (2021) are:

- The day ahead market presents a large market with 1.7 million or more potential EV users today.
- The number of EV users, that can realistically participate in the intraday and balancing markets is rather limited (each market less than 1 million users).
- The user potential of redispatch, which as for now cannot be provided by EVs, lies in a small to medium range and is very uncertain in general.
- Both optimized PV self-consumption and peak shaving show substantial numbers of potential EV users, each well over one million users.

For the future development (2030), important findings are:

- Day ahead market trading and PV self-consumption display the largest rise of achievable user potentials (3.5 and 2.9 million additional users).
- The number of EVs applicable for intraday markets remains, even though increased, rather small, where quarter-hourly traded continuous intraday market shows the largest increase in user potential.
- For balancing services, the user potentials are slightly decreased and no significant changes are determined for redispatch and peak shaving.

A noticeable limitation of this work is that user potentials are assessed on a relatively broad basis. With improved data, real vehicle availabilities could, for example, be used to estimate potentials even more precisely. It is unclear, however, how much additional value such an advance methodology would create in real terms. Furthermore, it is important to emphasize that the results have no relation to actual ramp-up rates for EVs or charging infrastructure but were collected completely independently of these figures.

Regarding further development in the field of user potentials, two different ideas come to mind. First, the possibility of bidirectional charging, i.e. the capability of smart discharging of the EV in addition to smart charging, can be included into the analysis. This would mean that for some use cases the methodology needs to be adapted. For FCR, e.g., bidirectional EVs can provide power in both directions, positive and negative. Thus, each kW of balancing power can be provided by one kW of available EV power, instead of two kW in the smart charging case. For other use cases, methodology and potentials would change little or not at all. The number of useable roof-mounted PV systems, for example, is not affected by the ability of discharging the EV. Second, the analysis could be extended by a methodical evaluation of user potentials of combined use cases, since it is likely that use case combinations will play a relevant role in the future of smart e-mobility [30].

Acknowledgement/ Funding

The work was conducted as part the unIT-e² project, which is funded by the German Federal Ministry for Economic Affairs and Climate Action (funding code 01MV21UN01).

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