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Modeling V2G spot market trading: The impact of charging tariffs on economic viability

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ABSTRACT

The increasing demand for electricity due to the diffusion of electric vehicles (EV) poses challenges to the electricity system. Vehicle-to-grid (V2G) technology is recognized as a promising approach for reducing grid stress and aligning charging demand with volatile renewable energy sources (RES), thereby fully exploiting the decarbonization potential of EVs. However, significant challenges continue to impede the successful market uptake of V2G technology, with fiscal policies for charging and discharging EVs being a notable barrier. In Germany and other European Union countries, the V2G tax scheme levies substantial taxes, fees, and surcharges on electricity purchases, while only the wholesale price is obtained for electricity sales. Hence, a significant price spread is necessary for profitable trading. Using the agent-based electricity market model PowerACE, we simulate four scenarios, demonstrating the tax regime's impact on the electricity markets and V2G revenues. Furthermore, we mirror the electricity market prices with users' willingness to pay for a V2G charging tariff. Our research underscores the pivotal role of taxes, fees, and surcharges as essential tools for policymakers to encourage V2G market adoption while maintaining its economic viability. Current legislation falls short of EV owners' financial expectations for V2G participation. A more favorable tax regime, however, could boost V2G trading, yielding profits in line with owner expectations and leading to lower wholesale market prices as well as reducing the necessity for stationary battery storage investments. With the increasing prevalence of EVs, the shift in V2G's role from a price-taker to a price-maker poses long-term profitability risks. Based on the simulation results, we recommend implementing favorable tax regimes, which could mitigate these challenges, facilitating effective V2G integration.

1. Introduction

As part of the Paris Agreement on Climate Cange, the participating nations have agreed to reduce greenhouse gas emissions (United Nations, 2015). To achieve these emission targets, the substitution of fossil fuels by carbon-free energy carriers is necessary among all sectors. As a result, the share of renewable energy sources (RES) in electricity generation has increased significantly in recent years (IEA, 2021). Additionally, the electrification of the transportation sector is another means to reach climate goals. However, this leads to increased electricity demand, whereby effects on the electricity system cannot be neglected as the diffusion of electric vehicles (EVs) proceeds.

This is especially true for uncontrolled charging of electric vehicles. Aggregated EV load curves show, that EVs are charged primarily in the morning and evening during hours with already high electricity demand (Babrowski et al., 2014; Hanemann et al., 2017; Qian et al., 2011; Harris and Webber, 2014). To fully realize EVs' decarbonization potential, charging needs to be linked with volatile RES (Kamiya et al., 2019; Jochem et al., 2015; Ensslen et al., 2018). Unidirectional controlled charging (UCC) exploits these potentials by shifting the time of the charging process with a unidirectional power flow from the wallbox to the EV (Spencer et al., 2021). Multiple studies (Ensslen et al., 2018; Kühnbach et al., 2020, 2021; Kannan and Hirschberg, 2016; Mullan et al., 2011; Ramos Muñoz et al., 2016; Gemassmer et al., 2021; Yin et al., 2021; Illing and Warweg, 2016; Shafiullah and Al-Awami, 2015; Liebl, 2017) analyzed different effects of UCC, for example, the impacts on the grid (Mullan et al., 2011; Ramos Muñoz et al., 2016; Gemassmer et al., 2021; Yin et al., 2021; Liebl, 2017) or the economic viability (Ensslen et al., 2018; Kühnbach et al., 2020, 2021; Illing and Warweg, 2016). Extending beyond UCC, bidirectional controlled charging allows EVs to feed back electricity to the grid, enhancing their role as electricity storage units and unlocking additional flexibility potentials (Spencer et al., 2021; Szinai et al., 2020). In this paper, we focus on the

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Nomenclature

Variables

$e_{t,x}$	Charged energy for hour t and charging event x [MWh]
$r_{t,x}$	Discharged energy for hour t and charging event x [MWh]
$soc_{t,x}$	Battery state of charge in hour t and charging event x [kWh]
$c_t^{\text{chargingPen}}$	Charged energy for hour t that gets taken back from one iteration to the next, gets penalized in the objective function [MWh]
$c_t^{\text{dischargingPen}}$	Discharged energy for hour t that gets taken back from one iteration to the next, gets penalized in the objective function [MWh]

Sets and Indices

$t \in T$	Time steps
$x \in X$	Charging events
$i \in I$	Iterations
$t_x^{\text{connected}} \in T_x^{connected}$	Time steps the EV is plugged in for charging event x
$t_x^{\text{connected,first}} \in T_x^{connected,\ first}$	Time step the EV gets plugged in for charging event x

Parameters

$p_{i,t}^{\text{forecast}}$	Price forecast for hour t in iteration i [€/MWh]
Q_x^{flex}	Shiftable energy demand of charging event x [kWh]
Q_x^{fix}	Non-shiftable demand for charging event x that must be charged as soon as possible until soc_{min} is reached [kWh]
$P_x^{\max}$	Maximum charging/discharging power [kW]
$d_{t,x}$	Plug-in duration for hour t and charging event x [h]
η_c	Charging efficiency [-]
η_d	Discharging efficiency [-]
$soc_{\min}$	Minimum battery state of charge [kWh]
$soc_{\max}$	Maximum battery state of charge [kWh]
$soc_{\text{start},x}$	Battery state of charge when EV gets plugged in for charging event x [kWh]
$E_x^{\max}$	Theoretically maximum possible charging amount for charging event x [kWh]
$R_x^{\max}$	Theoretically maximum possible discharging amount for charging event x [kWh]
γ	Relaxation coefficient [-]
ϑ	Penalty parameter [€/MWh]
$c^{TFS,buy}$	Taxes, fees, surcharges when buying electricity
$c^{TFS,sell}$	Taxes, fees, surcharges when selling electricity
$c_{electricity,household}$	Total household electricity expenditure
$c_{electricity,mobility}$	Cost of electricity for mobility purposes
$c_{electricty,V2G}$	Expenditure on electricity for V2G operations
$r_{electricty,V2G}$	Revenue generated from V2G electricity sales

vehicle-to-grid (V2G) application of bidirectional controlled charging (BCC), emphasizing the role of EVs as integral storage assets within the electricity system (Kempton et al., 2001; Lund and Kempton, 2008; Kempton and Letendre; Brooks, 2002).

While numerous studies have analyzed the economic potential of V2G, specifically within reserve or spot markets (Kern et al., 2020; Child et al., 2018; Rodríguez et al., 2019; Heilmann and Friedl, 2021; Müller et al., 2022), the methods of investigation have varied in depth and focus. A wide range of research on the economic viability of V2G trading on electricity spot markets relies on relatively simplistic methodologies, such as cost-benefit analyses grounded in historical price data (Gough et al., 2017; Illing and Warweg, 2015). Although these approaches can provide valuable insights, they often overlook the evolving market landscape. Meanwhile, a less frequently explored avenue of research delves deeper, using electricity market models to understand the potential consequences of V2G trading (Kern and Kigle, 2022; Hanemann and Bruckner, 2018; Gunkel et al., 2019). Capitalizing on short-lived price variations in spot markets for V2G trading[1]—a strategy commonly referred to as 'arbitrage'—remains a focal point across these studies, and is central to this paper (Kühnbach et al., 2020, 2021; Kern et al., 2020).

The viability and profitability of V2G relies on various factors. Primarily, the costs for operation and initial investment play a crucial role, but the generated market revenues are just as essential. These cost and revenue streams significantly influence the potential benefits of V2G (Heilmann and Friedl, 2021; Lanz et al., 2022). On the bright side, advancements in battery technology (Schmuch et al., 2018) and the decreasing prices of essential hardware, such as the wallbox (Pfab et al., 2023), forecast a reduction in initial and operational costs of V2G in the upcoming years.

However, while the previous aspects are important, the evolution of profitable V2G business models largely depends on the revenue streams from electricity markets. Thereby, the cost of charging depends not only on wholesale prices, but also on various taxes, fees and surcharges (TFS). Here, two challenges exist side by side. First, taxes, fees and charges have a significant share of the electricity price, especially in Germany. For example, in 2022, the electricity tariff of a typical European household was composed of ~60% for energy, ~22% for distribution and transmission, ~7% for taxes, and ~11% VAT (European Union Agency, 2022, p. 4). In Germany, the share of taxes is even more significant, as is the share of fees for distribution and transmission, making up over 60% of the household electricity price. Another issue is that according to §3 Nr. 25 EnWG EVs are considered end consumers. This classification is also true for most European countries (Burger et al., 2022; Hildermeier et al., 2023), e.g. Denmark, and France (Gschwendtner et al., 2021). The presence of these tariff-related TFS means that a wider wholesale price margin is necessary in order for spot market trading to be profitable. Electricity tariffs can either enhance or undermine the economic benefits of V2G depending on their structure and levels. Fluctuations in these tariffs can lead to variations in profit margins for V2G operators, thus making it essential for stakeholders to keep a keen eye on tariff dynamics. As electricity costs and trading revenues are foundational for V2G participation, the symbiotic relationship between TFS and V2G market viability is evident (Huang et al., 2021; Huber et al., 2019; Parsons et al., 2014).

Moreover, many studies use predominantly optimization-oriented electricity market models that focus on system cost savings and often ignore the complexity of real user behavior (Huckebrink and Bertsch, 2021). Addressing this gap, our work uses a bottom-up modeling approach to analyze the market effects of V2G using the established agent-based model (ABM) PowerACE of the European electricity market. The advantage of ABM lies in its ability to model market participants at their individual decision level, which allows for the analysis of imperfect real-world behavior. By extending the ABM model, this research paper

[1] There are different ways for EVs to participate in electricity markets and to generate revenue, among others, through energy trading or by providing ancillary services. For a comprehensive review, see (Heilmann and Friedl, 2021).

delves into the intricate dynamics of spot market trading, emphasizing the profound implications of TFS on V2G trading from a combined user and market perspective. Hence, the contributions to the research field are threefold:

(1) The development of a novel load-scheduling approach for dispatching V2G capable EVs in agent-based electricity market models.
(2) Evaluation of the economic viability of V2G within future electricity markets and tariffs, and illustration of how tax structures influence V2G revenues.
(3) Alignment of economic market potential with users' willingness to pay under a V2G pricing scheme.

This research paper is organized as follows: We begin by introducing the methodology, which encompasses the PowerACE modeling framework and the newly developed V2G model extension. This is followed by a presentation of the simulation results. Within this section, we first outline the research design for the case study conducted and then delve into a detailed discussion of the key findings. In the subsequent section, we engage in a comprehensive discussion of these findings. We conclude the paper by deriving policy recommendations in the final section.

2. Methodology

2.1. Agent-based electricity market modeling framework

The electricity market model PowerACE is an agent-based model for the investigation of European electricity markets. The primary objective of PowerACE is to provide a tool for conducting long-term analysis of the European day-ahead market, although rudimentary representations of other electricity market segments, such as the control reserve markets, have also been incorporated. The model simulates all 8760 h over a long-term time horizon until up to the year 2040. PowerACE has been employed in various research studies, including the examination of cross-border effects (Bublitz, 2019), capacity remuneration mechanisms (Zimmermann et al., 2021), or EV uptake market effects (Ensslen et al., 2018).

As shown in Fig. 1, a central role in PowerACE is taken by various agents representing different European electricity market participants, e.g., utility companies, grid operators, consumers and regulators. Each agent has an internal decision-making logic that allows it to choose appropriate actions, e.g., bidding strategies. The agents interact dynamically with its environment. On each simulated day, the agents under consideration bring their demand and supply to the market by placing bids according to their bidding strategy. The day-ahead market outcome is calculated using a welfare-maximizing market clearing algorithm that considers all bids submitted and the available transmission capacity. Furthermore, once a year, the agents can decide about potential investments in new generation capacity. A more detailed description of the individual modules of PowerACE can be found in (Fraunholz, 2021).

2.2. Dispatch of V2G with load-scheduling algorithm

In our simulation of the day-ahead wholesale electricity markets, we postulated the existence of a singular EV flexibility agent confined to the respective market area. Consequently, the energy volume allocated by the charging manager is identical to the combined energy demand of the EV fleet. Before bringing the flexibilities to the day-ahead market, the agent estimates the load-shift potential of the EV fleet analogous to (Ensslen et al., 2018), using the following information: (1) The time of arrival $t_x^{arrival}$, (2) the corresponding state of charge when an EV arrives at a charging location $soc_x^{arrival}$, (3) the time $t_x^{departure}$ when an EV is supposed to depart, (4) the corresponding state of charge when an EV departes at a charging location $soc_x^{departure}$, (5) possible minimum range requests soc_x^{MR} and (6) the available charging power $P_x^{\max}$. By treating the minimum range requirement as a precondition for load-shifting activities, it is possible to distinguish between two types of charging energy: energy that must be charged directly to fulfill range requirements Q_x^{fix} and energy that can be charged flexibly for load-shifting purposes Q_x^{flex}. The minimum range requirements have been assessed empirically in a previous study (Baumgartner et al., 2022).

Following identifying the load-shifting potential, the flexibility agent aims to market the flexibility of EVs on the day-ahead market. Specifically, the agent's objective is to schedule the charged and discharged energy for the upcoming day while minimizing the aggregated charging costs for all charging events and adhering to constraints related to charging power, battery state of charge (SOC), and net energy demand. In order to achieve cost-optimal scheduling for EVs, a price forecast is required. This forecast is obtained through a linear regression approach, which considers the demand for electricity (excluding EVs), renewable energy generation, exchange flows from other market areas and power plant availability. As the number of EVs is expected to increase, the aggregated EV fleet cannot be considered a price taker for future energy system scenarios. In the case of decentralized control of large EV fleets, uncoordinated reactions to price signals can lead to so-called avalanche effects (Ensslen et al., 2018), resulting in significant price reactions. To take this into account, the EV flexibility agent schedules the charging energy in multiple heuristic iterations, as visualized in Fig. 2. In each iteration, only a pre-determined share of the total energy demand for the EV fleet is enabled for scheduling.Prior to every consecutive iteration, a new price forecast is calculated that incorporates the charging and discharging energy scheduled in the previous iteration. Using this iterative approach, the influence of the charging and discharging behavior of the EV fleet on the market clearing price can be considered. When determining the number of iterations for the heuristic, it is crucial to balance the distribution of the smallest feasible amount of energy per iteration with the consideration of computing time. Distributing excessively large amounts of energy in each iteration could lead to an inadequate accounting for the resultant price effects.

In each iteration, a linear optimization problem is formulated and solved to determine the optimal charging operation. The key variables and equations of the model are presented below. The objective function (Equation (1) comprises two terms. The first term represents the net charging costs, which are calculated based on the charged or discharged energy per hour and the forecasted price, including TFS. The second term is a penalty term designed to restrict the transport load manager from redistributing charging or discharging energy that has already been scheduled in previous iterations.

$$\min \sum_{t=1}^{T} \sum_{x=1}^{X} (p_{i,t}^{\text{forecast}} + c^{TFS,buy}) e_{t,x} - (p_{i,t}^{\text{forecast}} - c^{TFS,sell}) r_{t,x} + \vartheta \sum_{t=1}^{T} \left(c_t^{\text{ChargingPen}} + c_t^{\text{DischargingPen}} \right) \tag{1}$$

Equations (2)–(7) describe variable bounds, the relation between charging/discharging power and the SOC. The SOC is introduced as a new variable to ensure the battery is never charged or discharged above or below technically possible levels.

$$0 \leq e_{t,x} \leq P_x^{max} \cdot d_{t,x} \quad \forall t \in T, x \in X \tag{2}$$

$$0 \leq r_{t,x} \leq P_x^{max} \cdot d_{t,x} \quad \forall t \in T, x \in X \tag{3}$$

$$soc_{\min} \leq soc_{t,x} \leq soc_{\max} \quad \forall t \in T_x^{connected}, x \in X \tag{4}$$

$$e_{t,x} + r_{t,x} \leq P_x^{\max} \cdot d_{t,x} \quad \forall t \in T, x \in X \tag{5}$$

$$soc_{t,x} = soc_{t-1,x} + \eta_c \cdot e_{t,x} - \frac{1}{\eta_d} \cdot r_{t,x} \quad \forall t \in t_x^{\text{connected}}, x \in X \tag{6}$$

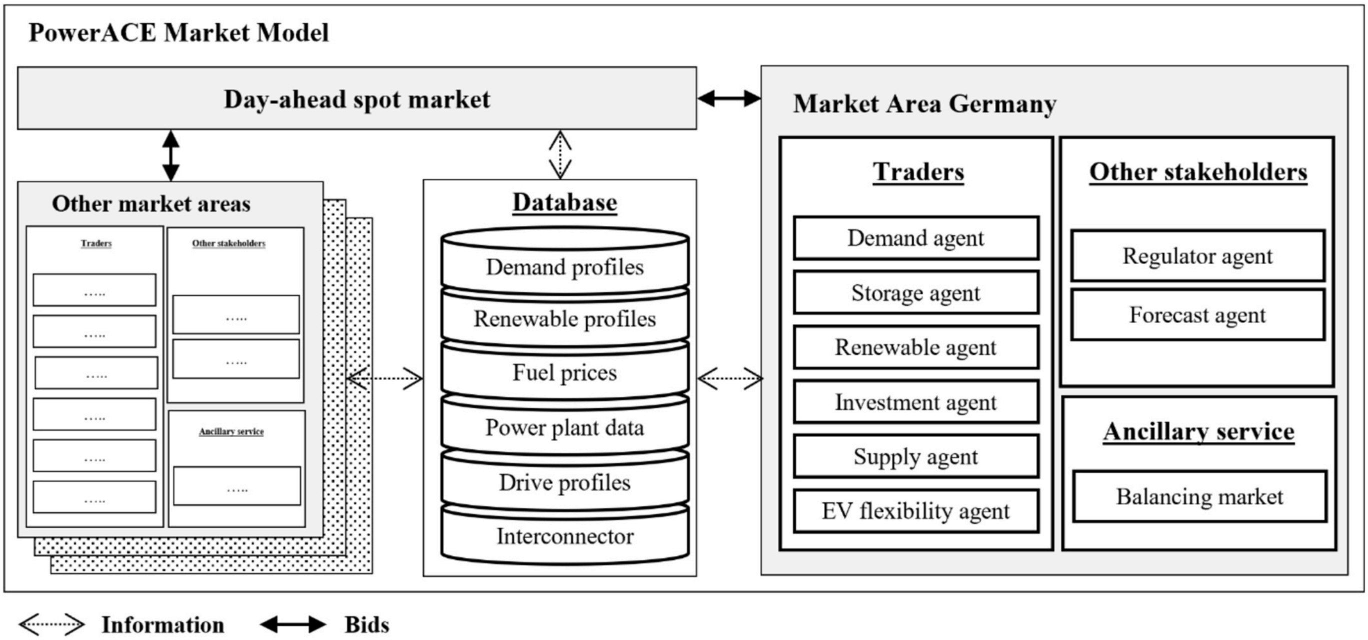

Fig. 1. Structure of the agend-based simulation model PowerACE.

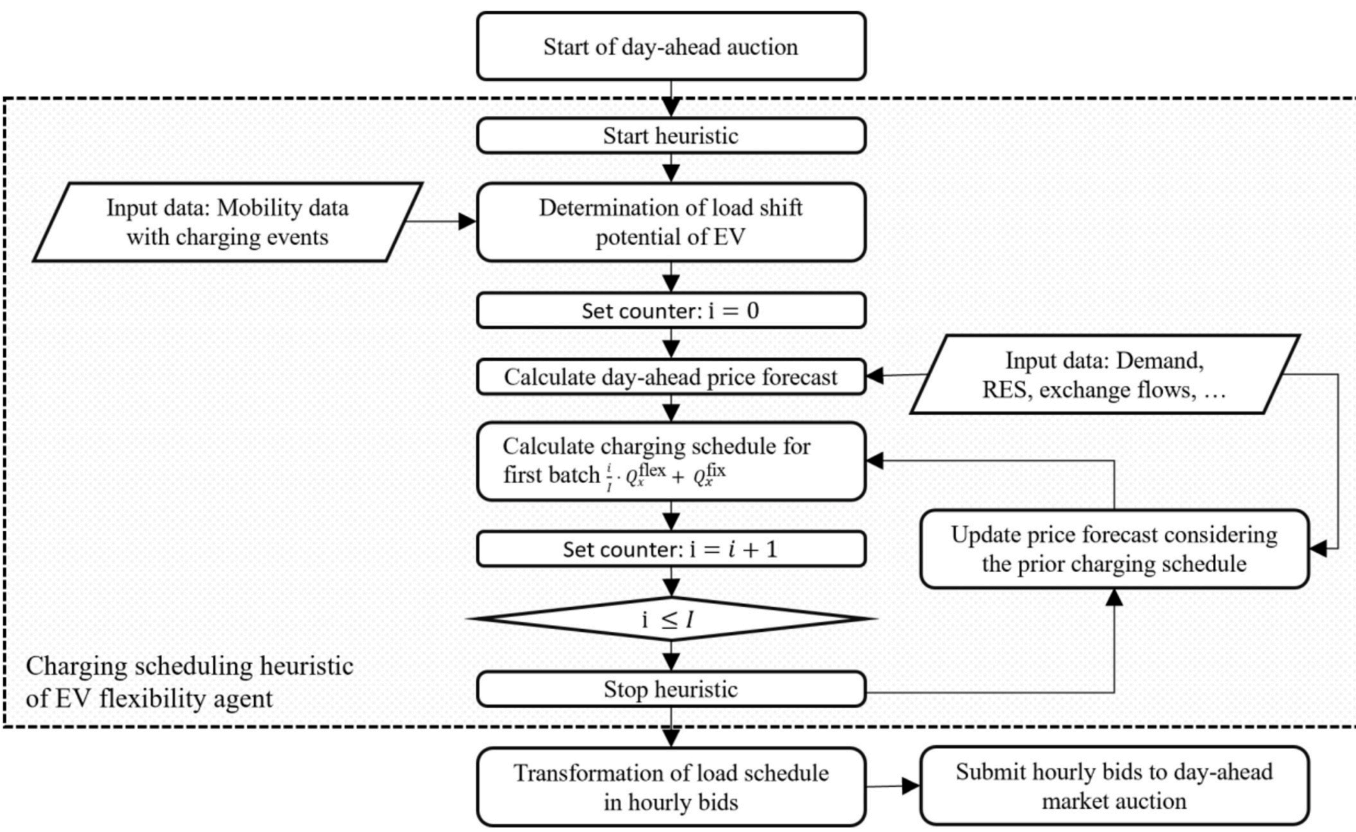

Fig. 2. Flowchart of the load scheduling algorithm of the EV flexibility agent.

$$soc_{t,x} = soc_{start,x} + \eta_c \cdot e_{t,x} - \frac{1}{\eta_d} \cdot r_{t,x} \quad \forall t \in t_x^{\text{connected,first}}, x \in X \tag{7}$$

The constraints regarding the heuristic iterations are described by Equations (8)–(13). Equation (8) ensures that in each iteration the specified fraction of the total net energy demand for each charging event is charged. Equation (9) and (10) prevent the redistribution of already planned charging and discharging energy, improving convergence speed of the approach. These constraints are relaxed by the parameter γ to prevent rare but possible infeasibilities in later iterations. Equations (11) and (12) limit the total charging and discharging amounts per iteration.

$$\sum_{t=1}^{T} \left(\eta_c e_{t,x,i} - \frac{r_{t,x,i}}{\eta_d} \right) = \frac{i}{I} \cdot Q_x^{\text{flex}} + Q_x^{\text{fix}} \quad \forall x \in X, i \in I \tag{8}$$

$$\sum_{x=1}^{X} e_{t,x,i} \geq \gamma \cdot \sum_{x=1}^{X} e_{t,x,i-1} \quad \forall t \in T, i \in I \tag{9}$$

$$\sum_{x=1}^{X} r_{t,x,i} \geq \gamma \cdot \sum_{x=1}^{X} r_{t,x,i-1} \quad \forall t \in T, i \in I \tag{10}$$

$$\sum_{t=1}^{T} e_{t,x,i} \leq \frac{i}{I} \cdot \left(E_x^{\max} - Q_x^{\text{fix}}\right) + Q_x^{\text{fix}} \quad \forall x \in X, i \in I \tag{11}$$

$$\sum_{t=1}^{T} r_{t,x,i} \leq \frac{i}{I} \cdot \frac{R_x^{\max} - \left(Q_x^{\text{flex}} + Q_x^{\text{fix}}\right)}{2} \cdot \eta_d \quad \forall x \in X, i \in I \tag{12}$$

Equations (13) and (14) define the charged and discharged energy that gets rescheduled from one iteration to the next $c_t^{\text{ChargingPen}}$ and $c_t^{\text{DischargingPen}}$. These energy amounts are penalized in the objective function. Equations (15)–(18) describe the linearization of Equations (13) and (14).

$$c_{t,i}^{\text{chargingPen}} = \max\left(0, \sum_{x=1}^{X} e_{t,x,i-1} - \sum_{x=1}^{X} e_{t,x,i}\right) \quad \forall t \in T, i \in I \tag{13}$$

$$c_{t,i}^{\text{dischargingPen}} = \max\left(0, \sum_{x=1}^{X} r_{t,x,i-1} - \sum_{x=1}^{X} r_{t,x,i}\right) \quad \forall t \in T, i \in I \tag{14}$$

$$c_{t,i}^{\text{chargingPen}} \geq 0 \quad \forall t \in T, i \in I \tag{15}$$

$$c_{t,i}^{\text{dischargingPen}} \geq 0 \quad \forall t \in T, i \in I \tag{16}$$

$$c_{t,i}^{\text{chargingPen}} \geq \max\left(0, \sum_{x=1}^{X} e_{t,x,i-1} - \sum_{x=1}^{X} e_{t,x,i}\right) \quad \forall t \in T, i \in I \tag{17}$$

$$c_{t,i}^{\text{dischargingPen}} \geq \max\left(0, \sum_{x=1}^{X} r_{t,x,i-1} - \sum_{x=1}^{X} r_{t,x,i}\right) \quad \forall t \in T, i \in I \tag{18}$$

In future scenarios that assume a high share of EVs and, therefore, very high aggregated battery capacities lead to large amounts of charging or discharging amounts in a single iteration in relation to the entire electricity market size. To counteract the resulting high influence on prices in the forecast and a fluctuation between minimum or maximum dispatch results due to the intra-iteration price-taking assumption, we introduced Equations (19)–(21), which limit the amounts of energy scheduled for each hour in an iteration.

$$\sum_{x=1}^{X} e_{t,x,i} \leq \frac{1}{I} \sum_{x=1}^{X} P_x^{\max} \cdot t_{t,x} + Q_x^{\text{fix}} \quad \forall t \in T, i = 0 \tag{19}$$

$$\sum_{x=1}^{X} e_{t,x,i} - \sum_{x=1}^{X} e_{t,x,i-1} \leq \frac{1}{I} \sum_{x=1}^{X} P_x^{\max} \cdot d_{t,x} \quad \forall t \in T, i \in |i \neq 0 \tag{20}$$

$$\sum_{x=1}^{X} r_{t,x,i} - \sum_{x=1}^{X} r_{t,x,i-1} \leq \frac{1}{I} \sum_{x=1}^{X} P_x^{\max} \cdot d_{t,x} \; \forall t \in T, i \in I \; |i \neq 0 \tag{21}$$

In summary, this paper introduces a novel methodology that employs a heuristic algorithm to optimize the charging and discharging cycles of V2G systems for enhanced profitability. Integrated into an agent-based electricity market model such as PowerACE, this approach facilitates the analyses of V2G's role among diverse market participants and under varying electricity price tariff structures. Due to the generic design of the heuristic, it can be applied to analyze the economic potential of V2G in multiple regulatory and geographic contexts.

3. Results

Before the results are presented in the subsequent section, it is important to highlight the dynamic nature of agent-based market simulations. Using PowerACE, scenarios where various types of agents interact with each other are solved. Agents make decisions concerning dispatch and investment based on expected profits, shaping the generation unit composition and the corresponding market dynamics. Therefore, while interpreting the simulation results, it is crucial to understand that the observed effects should not be interpreted in an isolated way, but are the outcome of the intricate interplay of dispatch and investment decisions of multiple agents under various scenarios.

3.1. Research design

Central to the research design of this paper is the application of the PowerACE model. The model was used to simulate the day-ahead market for 8760 h of a year until 2040. Every timestep of the simulation has evolving framework conditions such as, investments, decommissionings, power plant availability, RES feed-in, exchange flows. PowerACE requires various exogenous data inputs, thatare mainly based on the TYNPD2022 Distributed Energy scenario developed by ENTSO-E (ENTSOG & ENTSO-E, 2022). This scenario aims at a 55 % GHG emission reduction by 2030 and net zero by 2050, while maximizing the RES production and minimizing necessary energy imports to Europe.

The primary data format used is time series data with an hourly resolution to delineate the market framework and the corresponding policies of the market simulation. To accommodate potential cross-border impacts, our simulation incorporated eleven European market areas. As the analysis of tariff effects in question is focused on the German market, the EV flexibility agent was incorporated into the German market area, while in other market areas, EVs were implicitly modeled as part of aggregated demand time series data. An overview of the used data sources and resolution can be found in Table 1.

To evaluate V2G-specific effects on the day-ahead wholesale electricity markets, we assumed the presence of a single aggregator that markets the flexibilities of the entire German EV fleet (see Table 2). The development of the EV fleet size is modeled using a bass-diffusion model, using the approach presented by (Ensslen et al., 2018). The parameters of the bass diffusion model were estimated based on historical data on EV sales and the assumption of 10 million EVs by 2030. We further assume that every EV has a battery capacity of 50 kWh and has access to an 11 kW wallbox at home and at work. To reflect user range requirements, EVs are charged to a minimum state of charge soc_x^{MR} of 18 kWh before utilizing load-shift potentials. This capacity reflects a minimum range of roughly 120 km (Baumgartner et al., 2022). The driving profiles for EVs have been calculated using the method from (infas, 2008). Reducing the computational complexity of the EV flexibility agent, the charging profiles available at the micro level were clustered into a macro level of 200 weighted driving profiles representing

Table 1
Overview of main data and sources used for simulation.

Input data type	Resolution	Data source
Conventional power plants	Plant/utility level	Based on (Global Platts, 2016); adapted by own assumptions, e.g., regarding the nuclear and coal phase-out
Renewable feed-in	Hourly load curves	ENTSOE (ENTSOG & ENTSO-E, 2022)
Demand	Hourly load curves	ENTSOE (ENTSOG & ENTSO-E, 2022)
Interconnector capacity	Yearly/market area level	ENTSOE (ENTSOG & ENTSO-E, 2022)
Fuel and carbon prices	Yearly Prices	ENTSOE (ENTSOG & ENTSO-E, 2022)

Table 2
EV-specific parameterization and assumptions.

Parameter	Assumed Value
Charging location	Home and Work
EV battery capacity	50 kWh
Charging efficiency	92 %
Discharging efficiency	92 %
Minimum range before load-shifting	120 km (Baumgartner et al., 2022)

different mobility patterns in the large-scale market simulation, using the methodology presented in the (Ensslen et al., 2018). The journey profiles are updated at the beginning of each simulation year. The profiles are selected analogous to the method developed in (Ensslen et al., 2018), whereby the number of profiles added is proportional to the EV fleet growth. The daily energy demand of the simulated German EV fleet ranges between 5.4 MWh (2022) and 189.6 MWh (2040). Depending on the mobility profiles applied in the underlying year, the proportion that has to be charged directly is between 5 % and 8 %.

The electricity tariff composition for a typical European household stood as follows: approximately 60% for energy, about 22% for distribution and transmission, roughly 11% for VAT, and around 7% for other taxes (European Union Agency, 2022, p. 9). Germany presents an anomaly in this landscape. The country's tariff structure differs significantly from the weighted average tariff components prevalent in the majority of Europe. In Germany, there is a more considerable share dedicated to taxes and the fees associated with distribution and transmission. Our investigation is closely aligned with the German electricity household tariff structure, considering its unique components. With this context, our study aims to examine the effects of various electricity price tariffs on the electricity system in general and the economic model of EVs in particular. Recognizing that the economic viability of V2G operations is deeply entwined with the legislative milieu surrounding taxes, fees, and surcharges, we investigate the following four scenarios:

- *HouseholdTariff*: This scenario mirrors the conventional household electricity pricing model where the tariff encompasses the costs for electricity provision on wholesale markets, taxes, distribution and transmission fees, and other surcharges. EVs are, according to the German Energy Industry Act (§3 Nr. 25 EnWG) classified as end consumers and not storage assets, implying that temporarily storing electricity in an EV's battery is taxed according to this household tariff. The current V2G legislation in Germany aligns with this model, although it does not recognize the capability of EVs to discharge.
- *HomestorageTariff*: This scenario utilizes an electricity tariff similar to home storage systems. Such a tariff design could potentially serve as a benchmark for V2G-capable EVs. Notably, home storage systems enjoy exemptions from certain electricity TFS, as exemplified by the Geman Electricity Duty Act (§ 5 Abs. 4 StromStG). Electricity tariffs for this model also incorporate various surcharges to boost the growth of Renewable Energy Sources (RES). However, storage systems are majorly exempted from these surcharges, with an exception detailed in the the Electricity Grid User Charge Ordinance (§ 19 Abs. 2 StromNEV) Additionally, they benefit from the absence of grid and measurement fees as specified by the Germany Energy Industry Act (EnWG § 118 Abs. 6) . The exemptions within this tariff are primarily applicable to the electricity charging process.
- *PumpstorageTariff*: This scenario's electricity tariff is designed for large storage assets like pumped hydro power plants. The specifics of this tariff would likely vary from household or home storage tariffs, focusing on the unique requirements and conditions associated with large-scale energy storage.
- *MinimumTFSTariff*: Envisioning a scenario with minimal taxes, fees, and charges, this tariff imposes a minor levy to oversee the load and unload behaviors of the agent within the model. Such a structure prevents unrealistic trading behaviors that might emerge from the slightest price variations being used for trading.

A detailed description of the used electricity tariff components can be found in Table 3. In the context of the German energy market, TFS only applies in the case of the purchase of electricity, while no such TFS is levied on the sale of electricity. Therefore, the data presented in the table refers to the model parameter $c^{TFS,buy}$ while the model parameter $c^{TFS,sell}$ is set to zero across all scenarios examined in this paper.

3.2. Price development

Spot market pricing for wholesale energy, as illustrated in Fig. 3, is an important metric for assessing the impact of investments in generation capacity. These prices do not include the costs of RES, CRMs, or other fees.

The average German wholesale electricity market price, displayed in the left graph of Fig. 3, is characterized by an increasing trend leading up to 2031, followed by a downward trajectory. The average electricity price throughout this period is estimated to be 100 €/MWh. The first notable peak occurred in 2024, which was primarily related to the energy crisis, evoked through the Russian war against Ukraine, which had a large impact on energy carrier prices like gas. Because of the interrelated structure of the energy markets, this resulted in an increase in electricity prices. After the situation in the energy markets eases in the following years, prices decrease to a level of 60 €/MWh in 2025. Due to the increasing demand caused by the electrification of industrial, heat and transport applications as well as the decommissioning of fossil power plants, including nuclear and coal. This combination led to a temporary imbalance of supply and demand, pushing prices upward, reaching a maximum of roughly 140 €/MWh in 2031. Post-2031, a continuous decline in prices can be observed, due to the large-scale emergence of new generation capacities in the market, particularly gas turbines, as well as the expansion of RES capacity, which bids on the wholesale market with zero as price. Additionally, the introduction of flexibility from V2G and battery storage leads to a decrease in the overall price levels.

While all scenarios generally mirror broader market trends, subtle distinctions emerge when examined more closely. In the initial years leading up to 2030, the variance between the scenarios is minimal. This

Table 3
Electricity tariff components applying to a German household.

Cost components[a]	Regular household tariff	Home storage tariff	Pump storage tariff	Minimal TFS tariff
	[€/MWh]	[€/MWh]	[€/MWh]	[€/MWh]
Sales tax	53.74	53.74	0.00	0.00
Electricity tax	20.05	0.00	0.00	0.00
Sum taxes	**73.79**	**53.74**	**0.00**	**0.00**
Offshore surcharge	5.91	0.00	0.00	0.00
Electricity grid surcharge[b]	4.17	4.17	4.17	4.17
CHP-surcharge	3.60	0.00	0.00	0.00
Sum surcharges	**13.68**	**4.17**	**4.17**	**4.17**
Grid and measurement fee	92.50	0.00	0.00	0.00
Concession fee	16.60	16.60	0.00	0.00
Sum transmission fees	**109.10**	**16.60**	**0.00**	**0.00**
Sum of sales cost and margin	**10.00**	**10.00**	**10.00**	**0.00**
Total TFS	**206.57**	**84.51**	**14.17**	**4.17**

[a] Based on (BDEW Bundesverband der Energie-und Wasserwirtschaft e.V., 2023; Bayernwerk Netz et al.; Bayernwerk et al.).
[b] §19 StromNEV.

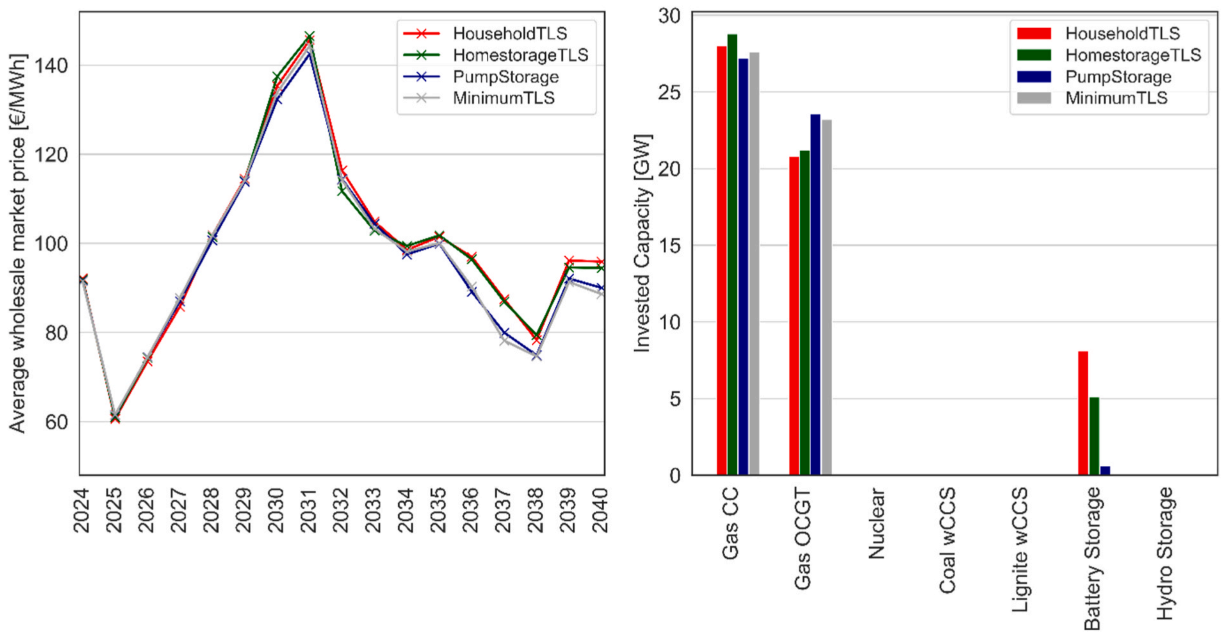

Fig. 3. Average wholesale market price (left) and capacity expansion until 2040 in Germany (right).

can be attributed to the restrained fleet size and the still nascent influence of V2G market dynamics. However, a discernible shift can be observed after the electricity price increase in 2031. Post this juncture, the *HouseholdTariff* and *HomeStorageTariff* scenarios tread a fairly analogous path, whereas the scenario incorporating the minimum TFS tariff demonstrates a pronounced difference, exhibiting wholesale prices that are roughly 5 €/MWh lower. The underlying cause for this divergence is the augmented trading potential facilitated by V2G. This, in turn, fosters a more seamless market assimilation of RES, negating the need for potential curtailment.

The right graph of Fig. 3 showcases the capacity expansion across various scenarios. The simulation identified combined cycle gas turbines (CCGT), open cycle gas turbines (OCGT), as well as stationary battery storage as viable investment options. Across all scenarios, significant capacity expansions of around 50–60 GW of new capacity are being built until 2040. CCGTs largely replace, due to high efficiency, base-load power plants like the retired nuclear and coal units, with investments in CCGT consistently ranging between 27 and 28 GW across all scenarios. OCGTs, on the other hand, primarily function as peaker power plants, operating predominantly during low RES production times. The investments in OCGT range across all scenarios between 21 GW and 23 GW. Notably, large-scale stationary battery storage emerges only in the *HouseholdTariff* and *HomeStorageTariff* scenarios. The absence of significant investments in stationary battery storage in the *PumpstorageTariff* and *MinimumTFSTariff* scenario suggests that the increased trading of EVs, triggered by the low TFS, reduces the need for stationary battery storage investments by as much as 8 GW.

3.3. Charging costs

Fig. 4 provides an illustrative representation detailing the anticipated charging costs for various EV adopters from 2024 to 2040. Within this depiction, it is evident that charging costs are influenced by both the chosen electricity tariff and the driving habits of EV users.

The cost dynamics can be formulated through Equation (22), highlighting that a household's overall expenses for EV charging is a combination of direct electricity costs for driving and the potential gains or losses from V2G trading.

$$c_{electricity,household} = c_{electricty,mobility} + \left(c_{electricty,V2G} + r_{electricty,V2G} \right) \tag{22}$$

Mobility demand profiles with large annual distances are characterized by the highest charging costs. Such profiles naturally lead to higher electricity consumption. Moreover, their limited availability for V2G trading often leads to lower V2G profits.

The *HouseholdTariff* scenario exhibits the highest electricity costs, ranging between 0 € and 3400 €. These costs primarily depend on the driving profile and the year being examined. Elevated costs in this scenario result in limited V2G trading. Over time, however, we see a drop in these costs, making the scenario more competitive. This decrease aligns with a broader decline in wholesale electricity prices. Interestingly, despite a general price increase up to 2031, in this scenario, high charging costs can be avoided.

In contrast, the *MinimumTFSTariff* scenario presents the lowest annual electricity costs, ranging between −500 € and 500 € annually. Its cost advantage is particularly evident in the early stages of the analyzed period, with higher V2G revenues around the year 2025. This benefit starts to fade as more EVs enter the market, leading to higher competition. As more EVs and consequently more flexibility compete in the same market, price peaks are being supplied by more significant bid volumes, negatively affecting V2G profits.

The *HomestorageTariff* and *PumpstorageTariff* scenarios lie between the previously described scenarios in terms of charging costs. Initially, the *PumpstorageTariff*, having fewer TFS, has lower annual charging costs than the *HomestorageTariff* scenario. However, this dynamic changes over time, and around 2030, the *HomestorageTariff*, in which V2G saturation effects are less pronounced due to higher TFS, becomes more cost-effective.

4. Discussion

Our research has examined the role of electricity tariff components such as taxes, fees, and other charges on the economic feasibility and associated market effects of V2G. In the following discussion, we will critically discuss the results obtained in the case study, focusing first on V2G revenues that will be lower in the future market environment with high EV shares. We will then address the paradigm shift of EVs transitioning from price takers to price makers, the consequent complexities in formulating bidding strategies, and the increased trading risks. Additionally, we will explore the variability in profitability among EV owners and the influence of vehicle type and driving profiles. Lastly, we

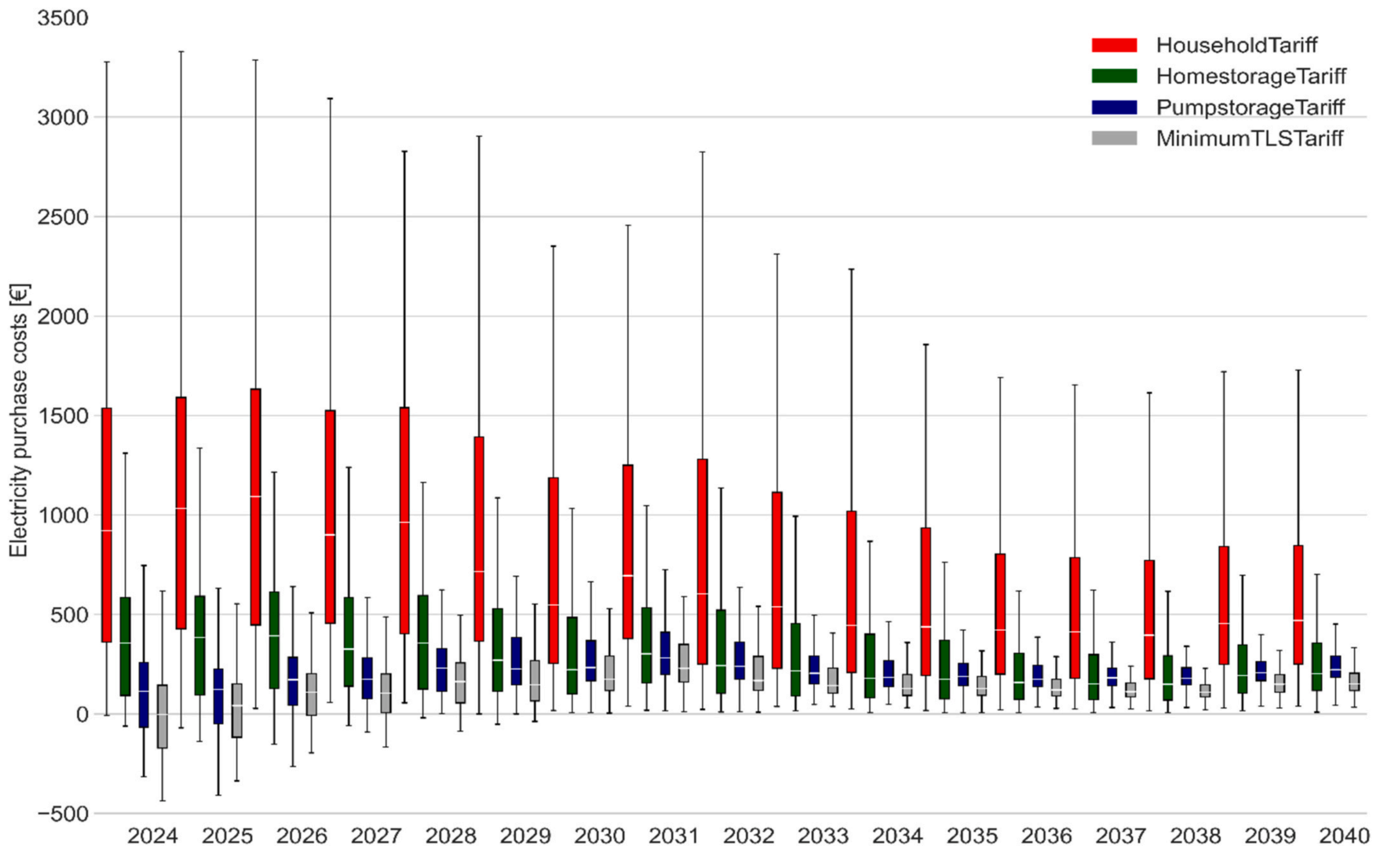

Fig. 4. Electricity purchase costs for different households and scenarios.

will discuss potential future regulatory challenges that could obstruct the market uptake of V2G and propose plausible solutions.

4.1. Revenues and profitability analysis

The results of the electricity market simulation (Section 3.3) show that the profits generated by V2G decrease over the years. One reason for this decline is the expansion of RES generation with low variable costs, leading to more hours of low or negative residual demand and negatively impacting the profitability of V2G. The model assumes that RES generators bid electricity at prices of 0 €/MWh. The increased periods of RES oversupply, which may occur for many consecutive hours in the future, and the resulting limited trading opportunities contribute to lower overall V2G profitability. While storage technologies with a short time horizon, such as electric vehicles or stationary battery storage systems, may not be able to absorb sufficient amounts of electricity during extended periods of RES oversupply, long-term storage options, and interconnectors may provide a solution. These longer-term facilities have the potential to offset the oversupply of renewable energy by creating the necessary demand. In this way, supply of renewable energy can be synchronized with demand more frequently and increase the price level.

4.2. Paradigm shift in the market

As the number of EVs participating in V2G increases, a paradigm shift from price-taker to price-maker can be observed in the market simulation results. In the early stages of EV market diffusion, selected EVs with favorable mobility patterns participate in spot market trading, making their impact on prices minimal. Thus, they take a price-taker role, conforming to existing market prices due to their limited presence. However, as the market evolves and the EV fleet expands, this dynamic changes. When numerous decentralized flexible assets, like EVs, with similar marginal cost structures respond collectively to the same price signal before market clearing, this collective response can significantly influence the wholesale price after market clearing. Therefore, with market maturity, EVs transition from simply being market participants to having a noteworthy impact on market prices. Due to the assumption that all EVs participate in V2G and are centrally branded, the effect could be amplified in the simulation and occur earlier than in reality.

The paradigm shift from price-taker to price-maker increases the complexity regarding the formulation of bidding strategies for V2G. EVs must factor in other EVs' behaviors when developing their bidding strategies. However, other vehicles' behavior is based on similar variable cost structures and similar observations of the market environment. Consequently, such a market environment gives rise to significant price risk due to avalanche effects, in which many market participants react to the same or similar price signals. Avalanche effects were also observed in previous studies. (Kühnbach et al., 2021; Flath et al., 2014; Roscoe and Ault, 2010; Gottwalt et al., 2011; Ramchurn et al., 2011; Dallinger and Wietschel, 2012).

Moreover, in a competitive market, other storage assets like stationary battery systems might hold competitive advantages over V2G due to lower variable costs. Thus, the variable costs of a storage unit consist largely of the battery aging resulting from the charging of the storage unit. It is only profitable for a storage unit to participate in electricity trading when the revenue from the trading exceeds the variable costs due to battery aging (Heilmann and Friedl, 2021). Excessive use of an EV's battery due to V2G could accelerate its aging and potentially limit the vehicle's range (Huber et al., 2019; Sovacool et al., 2017). This factor could dampen an owner's willingness to participate in V2G services. Battery replacement, often associated with substantial expenses, usually signifies a total economic loss for contemporary vehicles. Hence, battery aging is crucial in formulating future V2G services (Maigha and Crow, 2018; Sufyan et al., 2020). Consequently, limiting battery aging must be pushed alongside profit maximization when developing trading strategies for V2G.

To this end, the question of who will bear the price risk in the future needs to be further discussed. If the price risk lies with the aggregator, then the aggregator will charge a premium for this, which reduces the payoff and, thus, the V2G participation incentive of the EV owner. Suppose the price risk is borne by the EV owner, who has limited information about the functioning and development of the electricity market. In that case, the EV owner may be exposed to significant volatility in V2G revenues, which potentially reduces the willingness to participate in V2G. Presumably, the price risk is more reasonably allocated to the aggregator because of better market knowledge. Still, it must be ensured that the risk premium is set at a level that provides sufficient incentive for the EV owner to participate in V2G. One market design option addressing this concept is put into practice in the UK. The Market-wide Half Hourly Settlement (MHHS) sends accurate signals to suppliers about the cost of serving their customers throughout each day. This incentivizes suppliers to develop and offer new tariffs and products that encourage more flexible energy use and help consumers lower their bills (Ofgem & Department for Business, Energy and Industrial Strategy, 2023).

4.3. Comparing user expectations and V2G charging costs across varied electricity tariff designs

Having outlined potential barriers and risks to a successful introduction of V2G, this section points out the associated regulatory challenges in creating V2G tariff designs and expands on the EV user's perspective. Likewise, to potential price risks, taxation affects V2G services and tariff conditions that can be offered to EV owners. These conditions are displayed in the V2G charging tariff. As such, the tariff constitutes the interface between the aggregator and the EV owner. Thus, the electricity tariff plays a crucial role in providing flexibility but also in creating a willingness to engage with V2G processes. Previous studies have thus evaluated whether and under which conditions users would be willing to participate in V2G [e.g. (Huang et al., 2021; Baumgartner et al., 2022; Geske and Schumann, 2018; Wong et al., 2023)]. Among others, financial benefits have been shown to be a primary motivator for user participation in V2G (Geske and Schumann, 2018; van Heuveln et al., 2021; Mehdizadeh et al., 2023). Hence, electricity tariff design can foster the attractiveness of providing flexibility by offering monetary compensation. In turn, the EV owner may be incentivized to plug in the vehicle to provide flexibility and to adopt the charging behavior (Emodi et al., 2022). Remitting discharging prices from TFS could thus have a significant impact on households' willingness to provide flexibility to the electricity market.

To provide a comprehensive understanding of the landscape of tariff conditions across different tax regimes and users' financial compensation expectations, we compare in Fig. 5 the electricity costs per 100 km for a V2G charging tariff at the adopter level for the year 2022 (Baumgartner et al., 2022). This is based on the four scenarios detailed in Section 3.1. We juxtapose this with EV owners willingness to pay (WTP), a concept that gauges the maximum amount a consumer is prepared to expend for a product or service. We adopt the WTP from a previous study (Baumgartner et al., 2022), where the authors asked the respondents to state their WTP for a V2G charging tariff compared to a reference price of 5.20 €/100 km. The comparison between users' WTP and the normalized charging costs helps in discerning whether the market conditions are appealing to potential EV users.

When observing the results, it is evident that charging costs for *MinimumTFSTariff*, *PumpstorageTariff*, and *HomestorageTariff* fall beneath users' upper threshold of WTP. However, the *HouseholdTariff* scenario exceeds what users deem acceptable for a V2G charging tariff. The results suggest that, under the assumption that cost is the primary driver for V2G adoption, most households would be inclined to embrace V2G under a discounted charging tariff with decreased TFS. Additionally, Fig. 5 reveals that a significant portion of the simulated households could trim down their charging costs with V2G revenues. A small subset of these households would experience negative charging costs, meaning they earn more in revenue than they expend for charging, allowing them to neutralize their charging expenditures completely. It is noteworthy to mention that while our findings suggest V2G revenues are on the modest side compared to conclusions from prior research (Kern et al., 2020; Heilmann and Friedl, 2021), from the user's viewpoint, these costs remain within tolerable boundaries, especially when exempted from TFS.

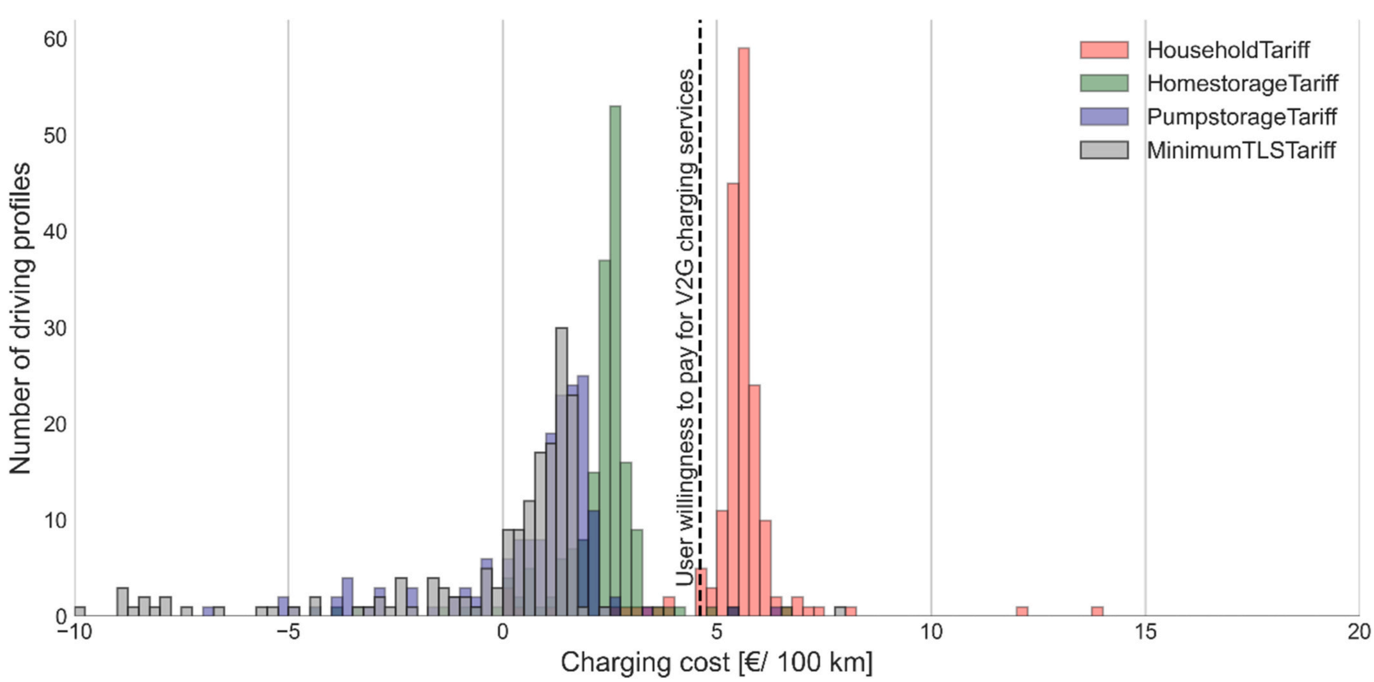

Fig. 5. Normalized charging costs and user willingness to pay.

The results also display the potentially significant impact that different tax regimes would have on the acceptability of V2G charging. According to the prevailing German legislation, EVs are legally classified as consumers. As a result, when EVs purchase electricity, they are obligated to pay TFS, which accounts for over 60% of the retail price. This effectively introduces a form of double taxation. When EVs discharge and sell their stored electricity to an end consumer via V2G, the end consumer is again levied with TFS. However, EVs are only compensated at the wholesale electricity price during this transaction, receiving no refunds for the previously paid TFS. In essence, the TFS, to some extent, is charged twice without any provisions for reimbursement in the V2G process. This systemic flaw has been highlighted by several research works (Heilmann and Friedl, 2021; Lanz et al., 2022; Gschwendtner et al., 2021). The current political discussion, therefore, centers around reduced grid charges as a means to compensate for providing flexibility. The authors in (Dreisbusch et al., 2020) showed in this context, that in particular, reduced grid charges would positively influence users' choice for charging tariffs with flexible charging capacity. Yet, our results indicate that reducing grid charges would most likely only have marginal impacts on electricity purchase costs and, consequently, would not sufficiently incite users to participate in a V2G charging tariff. If V2G market uptake is to be fostered, the tariff design needs to be designed in a way that offers a viable business case for EV adopters.

In this paper, the electricity price tariff was applied uniformly to both the electricity charged for mobility and that intended for trading. Conceptually, regulators might be inclined to designate an electricity tariff with reduced TFS exclusively for energy that is earmarked for V2G trading or ancillary services. A nuance to consider is that certain TFS components, like VAT, are proportionally related to the electricity wholesale market price. This relative nature of some TFS components introduces a complexity. Specifically, when an asset, like an EV, serves dual purposes (both as a mode of transport and storage), challenges arise. When energy is procured at different price points across different hours, and subsequently some of it is used for mobility while the remainder is discharged for V2G, it becomes essential to determine to which segment of the purchased energy, and consequently at which wholesale price, the reduction of relative TFS should be attributed.

The regulatory framework, as we outlined it in terms of the *HouseholdTariff*, also applies to most European countries (Burger et al., 2022; Hildermeier et al., 2023). Double taxation for charging and discharging of batteries is an issue in several European countries, among others Denmark, France and Germany (Gschwendtner et al., 2021). As this situation necessitates large price differentials to secure a profitable energy trade, the question of how to legally define V2G[2] has implications for the current tax regime with direct monetary consequences for the flexibility provider and the aggregator. Reducing or removing TFS could create an environment where smaller electricity price spreads are sufficient for profitability, which may also decrease price risks. The European Union addresses this issue in the revisions of the Energy Taxation Directive (ETD) (Platform for electromobility, 2022) and the Renewable Energy Directive (RED III) Buzek, 2023. By comparing electricity costs for charging and discharging of EVs under different tariff designs with users' willingness to pay for a V2G charging tariff, we highlight market conditions that would be acceptable to EV users. As Fig. 5 suggests, removing the electricity price from taxes, fees and surcharges would significantly impact whether households are willing to provide flexibility to the electricity market. Looking beyond the European legislation, the U.S. government supports retail electricity customers with at least one grid-integrated EV by reimbursing for the discharged energy at the same rate that the customer pays to charge the battery via the Vehicle-to-Grid Energy Credit (Del. Code tit. 26 § 1001 and § 1014). Additionally, taxpayers can benefit from further funding for bidirectional charging equipment for EVs (Campisi and Bailie, 2022), which is not negligible, considering the high investments for V2G. Initiatives such as the abovementioned could potentially boost the large-scale integration of EVs into the energy market and the expansion of V2G technology.

4.4. Limitations

Our study primarily builds on scenario data from the European Transmission System Operators framework (ENTSOG & ENTSO-E, 2022). Although TYNDP provides a wide range of different information, there were cases where it did not fully meet the requirements of our paper. In such cases, we made educated assumptions. Our assumptions have been backed up with historical data, where possible, to derive future estimates (e.g., RES feed-in or demand time series). Some data are unavailable for each year until the end of the simulation, so the required values are interpolated or extrapolated. While predictions based on current technologies are within an acceptable tolerance, the unpredictability of future developments presents a natural challenge, and technology options that we did not consider might be viable in the future. We further restrict the simulation of RES generation to an average weather year, not considering additional weather scenarios. The domestic electricity network has been neglected, except for interconnection capacities between market areas based on the assumption of ENTSOE (ENTSOG & ENTSO-E, 2022), which implicitly considers a sufficient domestic network expansion. Furthermore, while the PowerACE simulation model is tailored to the day-ahead spot market, it's worth acknowledging that electricity trading encompasses multiple markets, including intraday markets that could present additional viable trading opportunities for V2G. Notably, prices on intraday markets tend to be marginally higher. Although our simulation primarily relies on perfect foresight input data (such as RES generation, household demand, industrial demand, and EV availability), thus reducing the necessity of intraday markets, these higher prices could potentially offer more profitable trading possibilities. Consequently, economic benefits when considering both day-ahead and intraday markets together could be slightly elevated despite our current model's focus on the day-ahead market alone.

With regard to EVs in Germany, we have made two main assumptions: First, that all EVs are part of the V2G trade, and second, that EVs are always plugged in at home or at work. However, real-world behavior might not perfectly match these assumptions, which means that our projections about the economic benefits of V2G include some uncertainty and might represent an upper bound. The optimistic estimation of the V2G availability might cause the paradigm shift from price-taker to price-maker to occur later in reality than in our model.

Another limitation of our research model is the assumption that a singular central aggregator is responsible for marketing the flexibility of EVs participating in V2G services. This simplification may only partially capture the complexities of a real-world setting, where multiple aggregators will likely be involved in managing and marketing the flexibility of V2G-capable EVs. This heterogeneous landscape of aggregators could introduce variables not accounted for in our model, such as competition among aggregators, variances in tariff structures, and potentially divergent operational strategies.

The price forecast employed in our study, although effective in capturing broad market trends, is not devoid of inaccuracies and errors. These errors can result in suboptimal scheduling decisions, leading to misplaced trades and potential financial losses in V2G operations. It is essential to note that in a real-world scenario, many price forecasts would be accessible, and different market participants would likely employ various forecasting models. Using diverse price forecasts could level out individual errors to some extent, thereby enhancing the reliability and robustness of trading strategies. The inclusion of a broader

[2] According to the German Energy Industry Act (§3 Nr. 25 EnWG) storage units are defined as end consumers. Thus, current German and European legislation has not yet recognized their capacity to discharge.

range of trading strategies could potentially moderate the price impact of V2G, as it would lead to a more diverse response to price signals. Market participants might adjust their strategies to accommodate the increasingly competitive market environment shaped by V2G. However, it's important to note that while a dampened price effect is conceivable, it should also be acknowledged that price forecasts in reality often depend on fairly consistent market information. Therefore, significant disparities in price forecasts are unlikely.

Consequently, the interpretation of our study's findings must be contextualized within these limitations, particularly when projecting the practical application of V2G systems under complex and dynamic market conditions. It is critical to emphasize that the actualization of our reported findings hinges significantly on the rate of EV adoption and the amount of vehicles participating in electricity markets. While our limitations introduce a degree of uncertainty regarding the extent of the V2G market impacts identified, it is pertinent to highlight that our study goes beyond mere simulation results. We have rigorously elucidated and justified the underlying mechanisms driving the reported effects in our discussion section and bolstered our conclusions with relevant literature sources.

4.5. Future research

Future research directions should include a comprehensive analysis of V2G alongside alternative strategies such as controlled charging (CC), incorporating additional flexibility potentials from both industrial and domestic sectors. A detailed examination of the price effects caused by the shift of EVs from price-takers to price-makers is crucial. This could involve using a reverse engineering approach to identify the necessary price spreads for a sustainable V2G business case. Further research is also needed in understanding battery aging, integrating EV battery-friendly charging strategies, and modeling user behavior in greater detail. Particular focus should be on the plug-in behavior of EV users, which could substantially limit the real-world flexibility potential of V2G systems.

5. Conclusion and policy implication

This work demonstrates regulators' profound influence on shaping V2G market dynamics through TFS-related electricity tariff design. TFS emerges as a central control mechanism that can be used to steer V2G toward system-enhancing trajectories.

Expanding on this foundational understanding and focusing explicitly on the German market, the study reveals a current lack of economic viability for V2G among EV users. This lack of economic viability is mainly due to the structure of TFS, which constitutes a substantial portion of electricity costs for German consumers. Given that TFS often makes up a smaller share of electricity costs in other countries, it is reasonable to assume that V2G could be more economically attractive in different national contexts.

To address the high initial costs of V2G equipment and uncertainties about battery degradation, we recommend the adoption of specialized tariffs, akin to those for pump storage, to make V2G participation more appealing. Simplifying the tax and settlement processes for V2G transactions is also crucial to encourage wider adoption by making the financial benefits more transparent and accessible.

Moreover, our analyses reveal that integrating vehicle-to-grid tariffs within the electricity market, specifically through PumpStorageTFS and MinimumTFS, can yield significant systemic advantages. This integration benefits users considerably, fostering an environment where V2G can thrive under such tariffs. Adopting these tariff structures can lower wholesale electricity prices and diminish the necessity for investments in alternative storage technologies. By aligning V2G operations with these tariffs, we unlock enhanced flexibility and efficiency within the energy system. This alignment not only incentivizes the adoption of V2G but also positions it as a competitive contender alongside established storage solutions, thereby promoting a more sustainable and economically viable energy landscape. However, ensuring non-discriminatory market access for all storage technologies is paramount. Current regulations, particularly evident in the German market, categorize storage systems as end consumers, inadvertently hindering their integration and full potential within the energy sector. Advocating for a regulatory framework that treats V2G and other storage technologies equitably is crucial. Such a framework would level the playing field, eliminating biases towards specific technologies and encouraging merit-based competition. This equitable approach is essential for identifying and nurturing the most promising storage solutions. While tariffs based on pumped storage have proven their worth. One possible proposal would be to classify V2G similarly to tariffs derived from pumped storage. This could generate significant systemic benefits, as shown in this paper.

Our study further uncovers that if tariffs are applied uniformly to all EV users participating in V2G, EV users can benefit economically in two ways: by receiving discounted energy for mobility and by earning profits through V2G. If a V2G charging tariff is to be applied only to energy procured for trading, the previously discussed issue of allocating the discounted TFS to the charged energy must be resolved.

From a systemic viewpoint, our simulations point to some critical implications. Increased participation in V2G could negate the need for additional investments in stationary storage infrastructure. Furthermore, heightened V2G activity is correlated with reduced market prices in the medium to long term. This offers compelling evidence for regulators to consider supporting V2G operations through competitive TFS structure, as it benefits individual users and contributes to systemic efficiency and stability.

Lastly, with regard to the long-term trajectory of V2G economic viability, the research indicates a potential decline due to extended periods of renewable energy oversupply. Thus, the financial incentives to participate in V2G may become smaller over time, and EV users are exposed to price risk due to more volatile markets. In addition, as the number of EVs with V2G capabilities increases, V2G participants move from price takers to price makers. This could complicate their integration into the energy-only market. Such a shift could require more complex bidding strategies, potentially making V2G participation more difficult. A viable solution in the long term could be provided by adding capacity mechanisms, where users are rewarded for holding flexible power. This adjustment could relieve these challenges while creating price stability and reducing risks.

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CRediT authorship contribution statement

Tim Signer: Data curation, Formal analysis, Methodology, Software, Validation, Visualization, Writing – original draft. **Nora Baumgartner:** Conceptualization, Investigation, Methodology, Validation, Writing – original draft. **Manuel Ruppert:** Conceptualization, Methodology, Project administration, Supervision, Validation, Writing – review & editing, Funding acquisition. **Thorben Sandmeier:** Formal analysis, Methodology, Software, Writing – original draft. **Wolf Fichtner:** Funding acquisition, Project administration, Supervision.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used Grammarly and ChatGPT in order to avoid grammatical and spelling errors. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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

The authors do not have permission to share data.

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