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Aggregated fuel cell vehicles in electricity markets with high wind penetration

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***Abstract*—In this paper we present an agent-based model of aggregated fuel cell vehicles in a car park participating in the day-ahead market through an aggregator. Price-based vehicle-to-grid (V2G) contracts between drivers and the aggregator define the conditions under which the aggregator may use the cars for V2G. Using price forecasts, the aggregator places V2G offers in the day-ahead market. Whenever prices are expected to be low, the aggregator places bids to buy electricity and operate an electrolyzer, to produce hydrogen. Drivers refill their cars using the hydrogen storage operated by the aggregator. When cars are parked and plugged-in, the aggregator can use them for V2G under the conditions defined in the contract. Under different wind penetration scenarios, the maximum profits in a population of 100 drivers resulted in a range between 15.09 to 671.95 Euro in a year.**

***Index Terms*—fuel cell vehicles, vehicle-to-grid, contracts, electricity markets**

I. Introduction

To cope with future targets for increasing variable renewable energy sources (VRES) in power systems, several institutional changes are needed to facilitate the introduction of flexibility sources like storage, demand-side response and flexible clean generation [1], [2]. Although these sources can be provided by the incumbent actors in the electricity system, it is expected that the participation of prosumers in electricity markets will increase in the future [3]. Prosumer-side flexibility can be aggregated and exploited by traditional retailers, energy service companies, or new players in the electricity sector that take an aggregator role. Moreover, the electrification of other sectors like transportation and heating can provide opportunities for cross-sector synergies.

In this context, electric vehicles (EVs) can become valuable resources to support the operation of the power system, as they are usually connected to the grid when parked. They can be charged according to electricity prices or grid needs [4], [5] and they can feed power back when needed, through vehicle-to-grid (V2G) [6], [7]. Hydrogen fuel cell electric vehicles (FCEVs) can also be used to provide V2G [8]–[10]. Surplus generation from VRES can be converted to hydrogen, which can be stored and then used by FCEVs for transport and re-electrification [11], [12]. In general, battery EVs are deemed more suitable for providing ancillary services [6]. For FCEVs, V2G has mostly been explored for local electricity supply [8], [9] or in microgrids, especially in the context of the Car as Power Plant, an integrated energy and transport system based on FCEVs as power plants and storage of renewable electricity in hydrogen [13]–[15].

The role of EVs and FCEVs in wholesale markets deserves more attention as the penetration of VRES in European electricity systems continues to increase. Although a large part of the focus for EVs in the literature still remains in ancillary services, some authors [16]–[18] provide a wider view by considering wholesale markets as well. In [16] the authors calculate the profits for EV drivers during a five-year period using locational marginal price data. The authors use different V2G participation scenarios to calculate the profits that a driver can realize: work-hour price-taker V2G, arbitrage-guide V2G with perfect information, and user-defined selling price V2G. With different strategies, the maximum average savings for a driver throughout 5 years is of $201. With a carbon tax of $50, this amount increases by $31. In [17], the authors present a framework to explore the role of an EV aggregator in wholesale markets and reserve markets. To increase profitability of V2G and attract drivers, Richardson [18] introduces a premium tariff rate for V2G power. Three markets are considered: peak power, operating reserves, and regulation. Based on the hours of participation per year, a premium tariff is calculated to provide a 11% rate of return. The tariffs range between $173.4/MWh and $236.2/MWh when participating in all three markets. The authors above use historical electric prices to assess the profitability of V2G. Therefore, possible changes in electricity prices in the future caused by increasing VRES penetration are not considered.

Moreover, while past studies consider the driving needs and the actual availability of cars when calculating the profit potential, there is limited focus on how the availability is managed or agreed upon. Previous literature on contracts for V2G propose agreements on energy requirements and plug-in hours for drivers [19]–[21]. Broneske et al. [21] analyze how contract parameters such as plug-in duration and timing or guaranteed driving range, among others, influence the profit levels of drivers in the German reserve market. They conclude that higher guaranteed driving range requirements decrease profits, as they limit the energy available for V2G. Thus, the

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profit potential depends also on the conditions defined in the agreements between the driver and the aggregator.

Therefore, the purpose of this paper is to explore the role of price-based V2G contracts in assessing the profitability of V2G for heterogeneous FCEV drivers in the wholesale market, under different energy scenarios. To do this, we build an agent-based model that represents a car park that is operated as a virtual power plant. We model a number of driver agents, an aggregator agent, and the day-ahead market. We explore the interactions between drivers and the aggregator, taking into account the market prices, the V2G contract parameters, and the drivers' daily driving behavior. We use several energy mix scenarios that result in different electricity prices in order to explore the profit levels in systems with increasing wind capacity and carbon prices.

The paper is organized as follows: in Section II we describe the concepts in the agent-based model, and in Section III we explain the energy scenarios used to calculate different prices, as well as the input parameters used in the simulation runs. In Section IV we discuss the results of the different scenarios and in Section V we end with conclusions about our work and explain the next steps in our research.

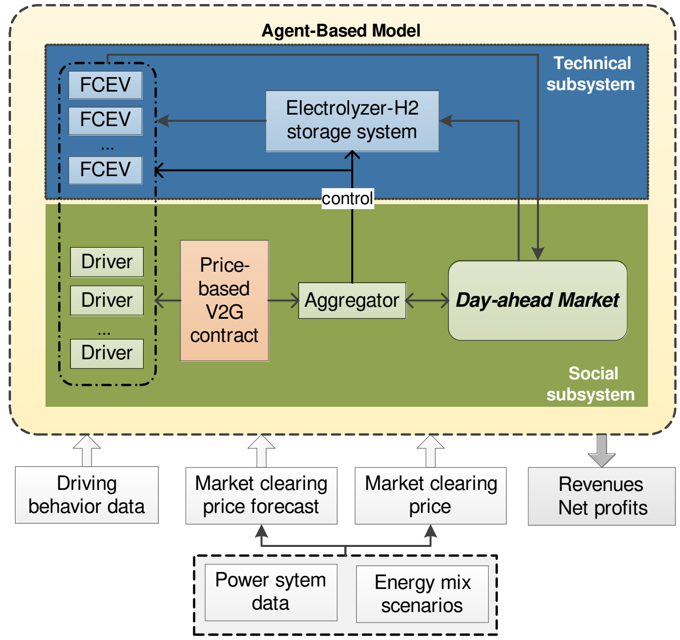

Fig. 1. Model concepts

II. Agent-Based Model Description

As introduced above, we use agent-based modeling and simulation to explore the actions and interactions of the agents and their effects on the aggregated system performance. We use this approach to capture the effects of individual driver agents on the aggregated availability of FCEVs in the car park, which determines whether the aggregator offers V2G in the market or not. Moreover, we consider the different driving needs, which leads to a variety of contract parameter values among the vehicle pool. These contract parameters define the conditions under which the aggregator can operate the FCEVs, as shown in Fig.1.

To define heterogeneous driving schedules (arrival and departure times and daily driving distances) we use probability distributions derived from driving data [22]. The market clearing prices are calculated externally using power system data and historical wind generation profiles [23], [24]. Load and renewable generation forecasts from [23] are used to calculate market clearing price forecasts, used by the aggregator agent. Based on the availability of the vehicles, contract parameters and the market prices, the revenues from the market and net profits for drivers and aggregator are calculated.

A. Agents and objects

a) Driver agent: This agent represents both the characteristics of the driver and the technical characteristics of the car.

- Driving schedule: Defined by the arrival and departure times and the daily driving distance.
- Parking profile: Indicates whether the driver parks the car during work hours or home hours.
- Fuel level: Indicates the level of hydrogen in the tank.
- Vehicle states: Driving, refilling, plug-in, V2G.
- Hourly revenues, total revenues, net profits: Calculated revenues and net profits from V2G.
- V2G contract (object): A price-based V2G contract that the driver has with the aggregator.

b) Aggregator agent: The aggregator participates in the day-ahead market to sell V2G or buy electricity to operate its electrolyzer.

- Electrolyzer-Hydrogen storage system (object): An electrolyzer and a hydrogen storage system are used by the aggregator to produce hydrogen with electricity and to sell hydrogen to the drivers.
- Market price forecast: Hourly electricity price forecasts for the next day, used to make offer/bid decisions.
- Availability forecast: Past availability of FCEVs in the car park, used to estimate the hourly availability of FCEVs for the following day.
- Market price: Market price for electricity purchased/sold.
- V2G revenues: Calculated revenues from V2G for the aggregator.

c) Day-ahead market agent: The day-ahead market is a simple agent that provides every day the market clearing prices for the following day.

d) V2G contract object: Price-based contracts between drivers and the aggregator allow the aggregator to know when the FCEV can be used for V2G.

- *minPrice*: Minimum price that the driver is willing to accept for providing V2G.
- *guarFuel*: Fuel level that the aggregator has to leave in the tank after using the car for V2G.
- *driverMargin*: Profit margin that the driver gets for the difference between market clearing price and the *minPrice*.

B. Process overview

Fig.2 illustrates the overview of processes in the agent-based model. The actions of the aggregator are based on the steps indicated in the USEF framework [25].

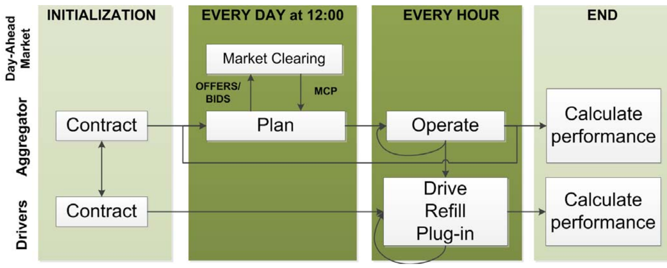

Fig. 2. Process overview per agent type

a) Day-ahead Market: Every day at 12.00, the day-ahead market provides the market clearing price for each hour of the following day.

b) Aggregator: Every day at 12.00, the aggregator makes an assessment of the electricity price forecast for the next day, as well as the past FCEV hourly availability profile, and makes decisions on selling V2G. If prices are expected to be low, the aggregator places bids to buy electricity for its electrolyzer-hydrogen system. The next day, the aggregator follows the plan based on accepted offers/bids. When V2G is sold, tge aggregator uses the available FCEVs to deliver electricity. At the end of the simulation, the revenues for the aggregator are calculated, using eq. 1. The symbols used in this section can be found in the Nomenclature section.

$$r_{a,T} = \sum_{t=0}^{T} \sum_{d=0}^{D} E_{d,t} * (MCP_t - minPrice_d) * driverMargin_d \tag{1}$$

c) Driver: Every day, driver agents drive in and out of the car park for commuting purposes. When drivers arrive, they park and connect the car to the grid. Based on the percentage of fuel available for V2G, the *driverMargin* parameter is defined. Once plugged in, and based on the electricity offered in the market, the aggregator may use the cars to provide V2G. Before leaving the car park, drivers may refill their vehicle depending on the fuel level in the tank. At the end, the revenues and net profits for the driver are calculated, as well as the volume of energy provided. Equation 2 shows the revenues per driver for a single time step. Using eq. 4 the total profits for a period are calculated.

$$r_{d,t} = E_{d,t} * (minPrice_d + (MCP_t - minPrice_d) * driverMargin_d) \tag{2}$$

$$c_{v2g,t} = E_{d,t} * (\frac{c_{pe}}{HHV * \eta_{FC}} + \frac{c_{FC}}{L} * 0.5) \tag{3}$$

$$p_{d,T} = \sum_{t=0}^{T} (r_{d,t} - c_{v2g,t}) \tag{4}$$

The cost of providing V2G is calculated using eq. 3, where the first part indicates the cost of energy and the second part the degradation cost. Similarly as in [11], the degradation cost of V2G operation is assumed to be 50% that of the degradation when driving.

C. Model assumptions

The assumptions used in the model are:

- The aggregator only participates in the day-ahead market.
- The aggregator only uses the electrolyzer-hydrogen system and FCEVs in the car park to buy and sell electricity.
- Drivers have constant driving schedules (weekdays/ weekends) throughout the simulation.
- Once in the car park, cars do not leave until the scheduled departure time.
- Drivers only refill their hydrogen tanks in the car park.
- When drivers need to refill, they do it right before they leave the premises.
- The price of hydrogen is constant throughout the simulation.
- The only cost considered in this paper is the cost of V2G.
- The costs for participating in the market or infrastructure costs that drivers may have to pay to the aggregator are not included in this paper.

III. Scenarios and Input Parameters

A. Scenarios and market clearing prices

As shown in Table I, we used power plant and power system data of Germany in 2015 [23], [24] to reproduce the German electricity system and build three energy mix scenarios. The power plant data in [23] includes a list of the German conventional power plants and their characteristics, such as the location, fuel type, installed capacity, and efficiency. The Base Case scenario was built using the conventional generation plants that were active until 2015 and the installed solar and wind generation capacity by the end of 2015, in total 183.8 GW. For building the Mid-Wind and High Wind scenarios, the total installed capacity remained the same, but the wind capacity was increased from 42.7 GW to 71.4 and 92.3 GW respectively, replacing hard-coal and/or lignite power plants. For the High Wind High Carbon scenario a higher carbon allowance price was used.

TABLE I
Scenario Inputs

Scenario	Base Case	Mid-Wind	High Wind	High Wind High Carbon
Wind capacity (GW)	42.7 [23.3%]	71.4 [38.8%]	92.3 [50.2%]	92.3 [50.2%]
Solar capacity (MW)	38.5 [21.0%]	38.5 [21.0%]	38.5 [21.0%]	38.5 [21.0%]
Other (MW)	102.6 [55.8%]	73.9 [40.2%]	53.0 [28.8%]	53.0 [28.8%]
CO_2 allowance price (Eur/ton)	8.00	8.00	8.00	50.00

For each scenario, the market prices were calculated using a simple market clearing model. For each power plant, the marginal costs (mc_{pp}) were estimated using eq. 5.

$$mc_{pp} = \frac{c_{fuel} + c_{carbon} * v_{carbon}}{E_{fuel} * \eta_{pp}} \text{ [Eur/MWh]} \quad (5)$$

The fuel costs per MWh were calculated using data from several sources [26]–[28], and for renewable sources costs we assumed a cost of 0. A supply curve was built using the cumulative capacity of all power plants and their marginal costs. The hourly residual load was derived using the demand and VRES generation. Then, the residual demand and the supply curve were matched to find the market clearing price. Thus, the cost of the last power plant was used to determine the market clearing price (MCP_t). The resulting hourly prices for all scenarios were used as inputs in the agent-based model. By ordering the prices from highest to lowest we created the price-duration curves shown in Fig. 3. When comparing the curve for the Base Case and the actual day-ahead prices in Germany in 2015, we observe that the simulated values are usually lower. This is due to simplifications of the market clearing model that include: marginal price bidding, fixed fuel and marginal prices, no strategic behavior, no negative prices, and no interconnection with neighboring countries. Moreover, the value of lost load was not used in this model. We assumed that the highest prices possible are those of the last power plant in the supply curve, even under scarcity.

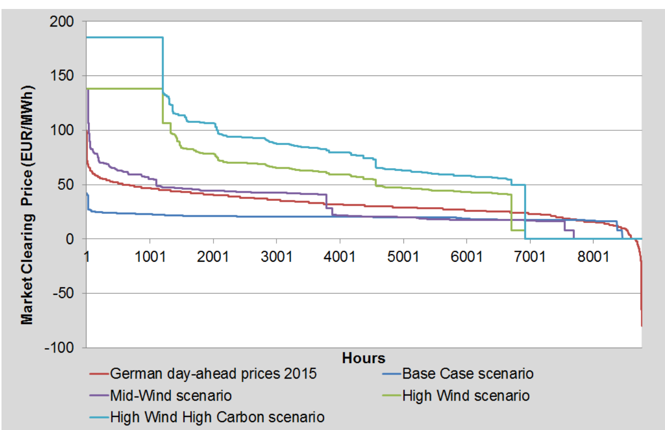

Fig. 3. Price-duration curve of the calculated market clearing prices for all scenarios vs day-ahead prices in Germany in 2015

B. Input parameters and system description

Table II shows the input parameters for all simulations. For each scenario, the model was initalized with 100 driver agents, one aggregator agent, and it was run for scenarios MW, HW and HWHC for an entire year. The initialization of driver agents and their V2G contracts is shown in Table III.

IV. Results and Discussion

An overview of the results for the aggregator and the 100 driver agents in the three scenarios is shown in Table IV. For the drivers, the profits indicate the net profits realized by the drivers with their V2G participation, which is influenced by the driver margin in their contract. Since this margin depends on the fuel availability at plug-in, it can change on a daily basis. The potential profits indicate the total profits if the driver margin had been always the maximum value, 75%. The V2G supplied indicates the volume of energy delivered, and the start-ups indicate the number of times the FCEV was switched on for V2G. For the aggregator, the revenues from V2G are calculated for the entire year.

TABLE II
Input Parameters

Parameter	Value
Hydrogen price (Eur/kg)	1.5
FCEV efficiency (%)	60
Fuel cell cost (Eur/kW)	26.9
Fuel cell lifetime (hours)	8000
Higher Heating Value (kg/kWh)	39.4
FCEV preferred operating point for V2G (kW)	10

TABLE III
Drivers and V2G contract initialization

Variable	Value
Driver agents	
Driving schedule	Using distribution derived from [22], weekdays and weekends
Parking profile	50% work hours, 50% home hours
Initial fuel level (kg)	Random from 3.0 to 5.65 (max)
V2G contract	
minPrice	cost of V2G per kWh (based on eq. 3)
guarFuel (kg)	factor * daily driving distance
driverMargin (%)	According to fuel % at arrival: [75–100%]: 75, [50–75%]: 50, [25–55%]: 25, [0–25%]: 10

TABLE IV
Results

	MW	HW	HWHC
Driver results			
Profits (Eur/year)	0.87-15.09 (7.03)	18.52-335.10 (144.05)	39.75-671.95 (305.37)
Potential profits (Eur/year)	1.77-19.33 (9.77)	32.03-369.30 (178.87)	67.09-710.66 (363.67)
V2G supplied (MWh)	0.21-1.53 (0.82)	1.18-12.57 (6.35)	1.85-18.05 (9.1)
Start-ups	11-61 (34.7)	59-314 (201.8)	72-388 (252.9)
Aggregator results			
Revenues from V2G (Eur/year)	598.88	9,443.60	17,951.60

The results indicate that given the heterogeneous driving schedules of agents, and the different fuel availability, the range of profits varies widely in all scenarios. On average, the higher the electricity prices (HWHC $>$ HW $>$ MW), the higher the profit potential for the drivers. While we mainly focused on the revenues from the market, aggregators may pass on infrastructure and market participation costs to the drivers – reducing their profits. For a better understanding of business models for aggregators, these costs should be taken into account.

Figures 4, 5 and 6 show the distribution of profits obtained by drivers under the different energy mix scenarios – where the dashed line indicates the average. Although there are around 1000 hours with the highest electricity price in the HW and HWHC scenarios, the actual availability of a vehicle does not always match the hours with highest prices. Aggregators may use strategies to maximize drivers' profits by improving price forecasts or by increasing their pool of vehicles and acting as price-makers in the market.

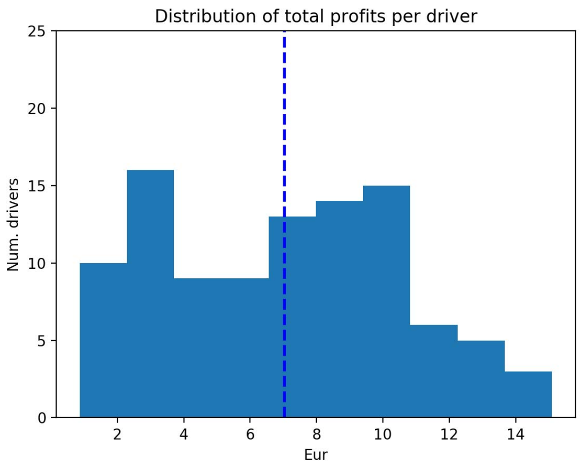

Fig. 4. Distribution of yearly profits in the MW scenario

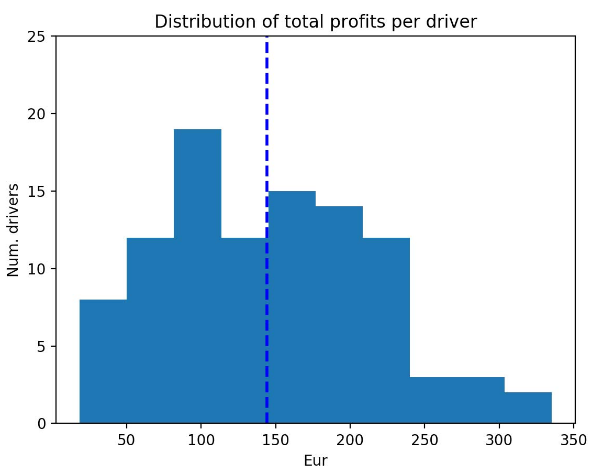

Fig. 5. Distribution of yearly profits in the HW scenario

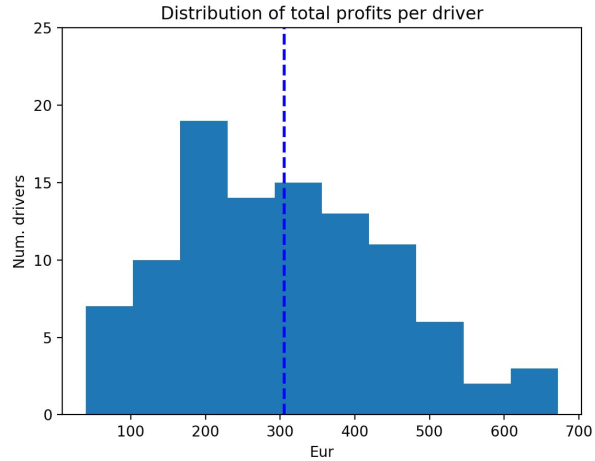

Fig. 6. Distribution of yearly profits in the HWHC scenario

The results show that major developments in the power sector should be taken into account in order to determine the value of aggregated FCEVs in future electricity systems. While some studies have previously drawn conclusions about the profitability of electric vehicles in different markets, the revenues were calculated using historical electricity prices. The use of price-based V2G contracts in the agent-based model shows that due to the heterogeneous characteristics, not all drivers can profit equally. Even when all FCEVs have the same costs for V2G, the differences in their driving behavior influence the other contract parameters – especially the driver margin. When implemented, it is also expected that not all drivers will participate in V2G equally. Thus, the use of contracts and the different driving behaviors in the model can provide insights on how drivers would participate in V2G in future electricity systems. We believe that it is necessary to understand the participation of individual drivers to better assess the role of aggregated FCEVs in the system.

V. Conclusions

In this paper, we explored the profitability for FCEV drivers in day-ahead markets with different energy scenarios using an agent-based model. We formalized the driver-aggregator relationship with price-based V2G contracts, defining the minimum price for V2G, the guaranteed fuel level, and the drivers' profit margin. The results show that with a moderate increase of wind capacity (Mid-Wind scenario), the average profit for the drivers is 7 Euro/year. In the High Wind scenario, the average profit increases to 144 Eur/year, and in the High Wind High Carbon scenario, the average profit is doubled to 305 Eur/year. As the price-duration curves show, a higher wind capacity and higher carbon price lead to an increase in hours with the highest electricity prices. However, to profit as much as possible from peak prices, drivers have to be available during those hours. Due to the heterogeneous driving schedules and contract parameters in the model, profits obtained by each driver vary widely; from 40 to 672 Eur/year in the most profitable scenario. To increase profits without changing their driving behavior, drivers could adjust their contract parameters or refilling strategy accordingly.

The revenues for the aggregator also increase with higher wind capacity and carbon prices. Since the focus of this paper was on the drivers and their participation in the market, the hydrogen price was fixed and did not depend on the cost of operating the electrolyzer. To analyze possible business cases for the aggregator, the purchase cost of hydrogen should be linked to the costs of production. Taking these costs into account, we could explore the level of wind capacity at which FCEV-electrolyzer business models would be profitable. Finally, the current model will be further developed to also include day-to-day variability in the driving schedules of drivers, as well as the adaptive behavior of drivers and aggregators.

ACKNOWLEDGMENT

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NOMENCLATURE

c_{FC}	Unit price of fuel cell [Eur/kW]
c_{fuel}	Fuel price per unit [Eur/ton, Eur/m^3...]
c_{carbon}	Carbon price [Eur/ton]
c_{pe}	Cost of purchased energy (hydrogen) [Eur/kg]
$c_{v2g,t}$	Cost for V2G supplied at time *t* [Eur]
$E_{d,t}$	Energy supplied by driver *d* in a one-hour time step [MWh]
E_{fuel}	Energy value of fuel [MJ/fuel unit]
η_{FC}	Fuel cell efficiency [%]
η_{pp}	Power Plant efficiency [%]
L	Lifetime of fuel cell [hours]
mc_{pp}	Power plant marginal costs [Eur/MWh]
MCP_t	Market clearing price for time step *t* [Eur/MWh]
$p_{d,T}$	Total profits of driver *d* at the end of period *T* [Eur]
$r_{a,T}$	Revenues for the aggregator at the end of period T [Eur]
$r_{d,t}$	Revenues for driver *d* in a one-hour time step [Eur]
v_{carbon}	Carbon emissions [ton/MJ]

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