Integration of private electric vehicles into the balancing power market in the case of Germany

Master Thesis to obtain the degree of Master of Science in the course of studies Renewable Energies at the Faculty of Plants, Energy and Machine Systems of the Cologne University of Applied Sciences

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Abstract

The increasing share of electric vehicles and the decrease of fossil power plants in Germany offer potentials for the use of electric vehicles for the provision of balancing power. This paper investigates the potential of private electric vehicles for providing balancing power, in particular frequency containment reserve, in Germany. The aim of this thesis is therefore to investigate to what extent private electric vehicles can be used today and in the future for the provision of frequency containment reserve in Germany. The thesis uses 100 representative charging profiles based on two household profile and charging profile generators to simulate the availability of electric vehicles at 15-minute intervals throughout the year 2022. Market conditions, including technical, economic, and regulatory factors, are also considered. The work concludes that the availability of the electric vehicles in the simulated pool varies widely on a daily and weekly basis (simultaneity factor fluctuates between 24% and 100%), but can be increased by targeting specific time periods, such as nighttime hours. However, targeted supply windows and widespread availability of vehicle-to-grid are necessary for optimal use. The willingness of electric vehicles owners to offer their vehicles was also identified as a success factor. A minimum number of 521 electric vehicles was identified, for offering the minimum offer of 1.25 MW for the whole year of 2022. Based on a simulated pool of 500 electric vehicles, a revenue potential of up to 900 € per vehicle per year was identified, with optimization potential in smaller supply windows and improved charging behavior. Although technically feasible, regulatory hurdles and the need for aggregation by an aggregator still pose a challenge. With rapid technological advances and political support, further progress is expected.

Tags: *Electromobility, Frequency Containment Reserve, FCR, Ancillary Services, Balancing Power, Electric Vehicle*

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At this point I would like to thank all those who have supported me in the writing of this thesis. A special thanks to my supervisors and the Erasmus team of the TH Köln, who supported me in my plan to write the thesis in Spain.

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List of abbreviations

Abbreviation	Definition
AC	Alternating Current
aFRR	Automatic Frequency Restoration Reserve
CCS	Combined Charging System
CS	Charging Station
CPGeM	Charge Profile Generator for e-Mobility
DC	Direct Current
DOD	Depth of discharge
EMS	Energy Management System
ENTSO-E	European Network of Transmission System Operators for Electricity
EV	Electric Vehicle
FCR	Frequency Containment Reserve
LPG	Load Profile Generator
mFRR	Manual Frequency Restoration Reserve
OCPP	Open Charge Point Protocol
Ooha	Out-of-home activity
RG	Reserve Group
RU	Reserve Unit
SF	Simultaneity factor
SOC	State of charge
TSO	Transmission system operator
TU	Technical Unit
V2B	Vehicle-to-Business
V2G	Vehicle-to-Grid
V2H	Vehicle-to-Home
V2X	Vehicle-to-Everything
VPP	Virtual Power Plant

List of formula symbols and untis

Formula symbol	Description	Unit
SOC_{Total}	Total battery capacity of the EV	%
$SOC_{Leaving}$	SOC, where the EV leaves	%
$SOC_{Maintaining}$	SOC, where the EV reached a maintaining limit	%
$SOC_{upperLimit}$	Upper SOC of the usable part of the battery	%
$SOC_{Maintaining}$	Lower SOC of the usable part of the battery	%
$t_{charging}$	Time, the EV is charging	s
$P_{charging}$	Charging Power of the system (EV+wallbox)	kW
P_{EV}	Charging Power of the EV	kW
P_{CS}	Charging Power of the wallbox	kW
$E_{Battery}$	Total battery capacity of the EV	kWh
$E_{available}$	Energy, which is available for FCR	kWh
$P_{Limitation}$	Minimum usable power	kW
P_{max}	Maximum total power of a EV pool	kW
N_v	Number of available EVs in the pool	
N_v	Minimum available number of EVs in the pool	
$N_{required}$	The vehicles to provide enough power	
$P_{pool,24\%}$	The power, 100% of a pool can offer	kW
$P_{pool,24\%}$	The power, 24% of a pool can offer	kW

Introduction

The German government is working on both, expanding the share of renewable energies as well as electromobility. As a result of the energy transition, the share of fluctuating renewable energies in electricity generation is to increase significantly. In this context, Germany aims to increase the share of the renewable energy sources to 80% by the year 2030. At the same time, electricity generation from fossil fuels such as lignite and hard coal, which previously provided a large share of the balancing power, is declining [1].

At the same time, the number of electric cars in Germany is also rising steadily. 15 million electric vehicles (EVs) are expected to be registered in Germany by 2030 [2]. A large number of the EV batteries, which are connected to the grid, can be interpreted as a virtual electricity storage [3]. With this assumed 15 million EVs, and an average available battery capacity of about 10 kWh per EV, [3] a potential capacity of 150 GWh can be reached. Assuming that a private vehicle is only used for one hour a day on average [4], a large potential to use the storage of the EVs is detected, which is currently unused.

Balancing power is an ancillary service and is used to keep the balance in the grid at a frequency of 50 Hz [5]. In the current framework, this is primarily provided by large power plants, mostly water, lignite, hard coal and gas [6]. The development of the energy transition, the increasing number of EVs and the high idle times offer a potential to use electric vehicles as decentralized battery storage for the provision of balancing power.

However, even if the theoretical potential is great, many prerequisites must be met in order to provide balancing power through EVs in Germany. The actual availability of electric vehicles is particularly relevant. Only if they are connected to the grid with the appropriate infrastructure, they are able to actually provide balancing power.

Therefore, the aim of this thesis is to determine the potential and the requirements to integrate private EVs, charging at home, into the balancing power market in Germany. The work is limited to the ancillary service frequency containment reserve (FCR) at the usage of the own wallbox at home.

This results in the research question: *To what extent can private electric vehicles in Germany be used for the provision of FCR?* To answer the main research question, this thesis addresses three further sub questions dealing with the technical, economical, and legal dimension of the topic. These are as follows.

- To what extent is the implementation technically feasible in Germany at present and in the future?
- How economical is the implementation currently and in the future regarding market design?
- What are the current legal and regulatory framework conditions, and which are necessary to provide FCR by private EVs in Germany?

The structure of the thesis is as followed:

After the introduction, chapter 1 explains the technical and regulatory background. First, the network structure in the German market is described. This is followed by a description of the balancing energy market. Then the prequalification conditions, i.e., the participation conditions for the provision of system services relevant for EVs, are described. Furthermore, a description of Vehicle-to-Grid is given. The required components, actors and framework conditions are described, specified in more detail and the current and future availability in the German market is researched.

Chapter 2 provides an overview of relevant literature that has dealt with the topic of control power from electric vehicles. This is followed by a presentation of current projects in which the functionality of EVs for the provision of control power is being tested in Germany, as well as a presentation of their results.

In chapter 3 the methodology is presented. First, the framework, the procedure and the assumptions made, with which the simulation was carried out, are described. This is followed by an explanation of the input data. The thesis is based on 2 existing tools, the *Load Profile Generator (LPG)* by Dr. Noah Pflugradt [7] and the *Charge Profile Generator for e-Mobility (CPGeM)* by Marian Sprünken [8]. The *CPGeM* was adapted within the scope of the thesis and the input parameters were used based on the findings of the literature research. Subsequently, a description of the simulation is given. In the simulation, the results from *LPG* and adapted *CPGeM* are used to generate charging profiles for household members of a number of representative households. The focus is on the availability status of the vehicles, i.e., when they are connected to the grid at home and ready for FCR. With the availabilities, simultaneity factors are generated for each time step, which are then displayed and evaluated. The evaluation includes an economic consideration, as well as an analysis of the supply time slices and charging patterns.

In chapter 4, the results are presented and discussed. First, the potential for EVs to provide frequency containment reserve was analyzed. Subsequently, these results were used to determine the potential revenue from providing FCR in the German market in 2022. Furthermore, an analysis of the reduction of time slots and changes in charging behavior was conducted. Based on this analysis, a concept was developed for the economic, legal, and technical requirements under which private electric vehicles can offer FCR. Finally, the limitations of the study and the limits that have been reached are presented.

Finally, a conclusion is drawn in chapter 5. It includes a summary of the findings as well as an outlook.

1 Theoretical background

For the development of a model for the provision of balancing power, the grid infrastructure, the balancing power market with the necessary prequalification procedures, and the state of the art for bidirectional charging are important. The most important fundamentals are explained in this chapter.

1.1 Grid Infrastructure and ancillary services

The public power supply network is divided into seven functional levels. These are the four voltage levels and the three transformation levels between the individual voltage levels. The voltage levels are divided into the transmission networks of the extra-high voltage level and the distribution networks of the high-voltage level, the medium-voltage level and the low-voltage level [3]. Figure 1 shows the functional levels of the public electrical power supply networks in Germany.

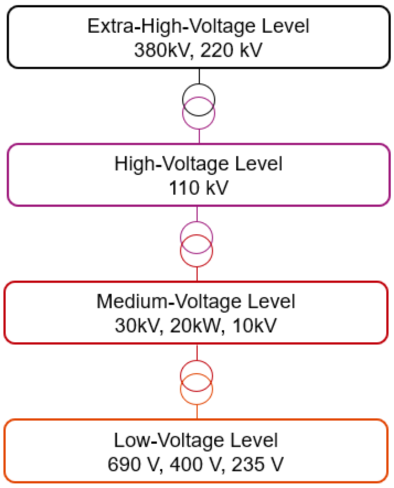

Figure 1 Different voltage levels in the German power grid (Source: own illustration, based on [3]

Various system services are required to run the electricity transmission network. The transmission system operators (TSO) define the system services required in their control area [9]. These services, which are essential for the proper functioning of the power supply, are referred to as ancillary services. A distinction is made between the four system services: Operation management, frequency maintenance, voltage maintenance and supply reconstruction [10].

The transmission grid in Germany consists of four zones. The zones are each assigned to a transmission system operator. The four TSOs in Germany are *50Hertz, Amprion, Tennet,* and *TransnetBW* [11].The *continental European transmission network of the European Network of Transmission System Operators for Electricity (ENTSO-E)* includes (02/2023) 39 members from 35 countries [12].

1.2 Balancing Power

The task of the four TSOs is to balance supply and consumption in their control area to keep the grid frequency stable. The goal is to keep the frequencies in the European grid at a constant 50 Hz. A illustration of the grid balance is shown in Figure 2 [13]. In order to fulfill this task, the TSOs define the demand for balancing energy and procure the corresponding power reserve from suitable producers [5].

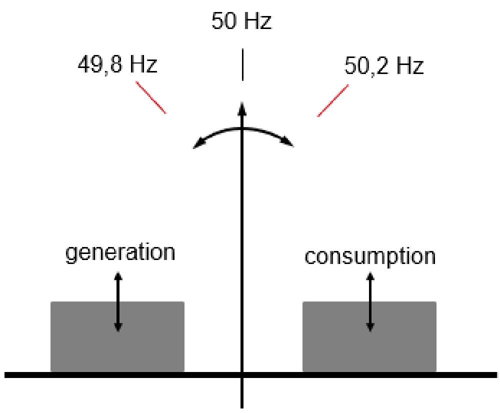

Figure 2 Balance between consumption and generation in the power grid to maintain the frequency of 50Hz (Source: own illustration, based on [13]).

Frequency maintenance requires two separate services, which are often summarized under the term balancing power.

- Control work is the supply of the work [MWh] to balance the control area. Both positive and negative control work is required to compensate for positive and negative frequency deviations. A payment is agreed for the balancing power depending on the energy supplied or purchased [14].
- Control power is the reservation of capacities [MW] so that in the event of an imbalance, secured capacities are available to balance the control zone. If necessary, a performance payment is made for the control reserve, regardless of the actual deployment. In return, the providers enter into a commitment to maintain the standard service for a certain period of time [14].

1.2.1 Types of balancing power

Balancing power is provided in different stages. Figure 3 gives an overview of types of balancing power.

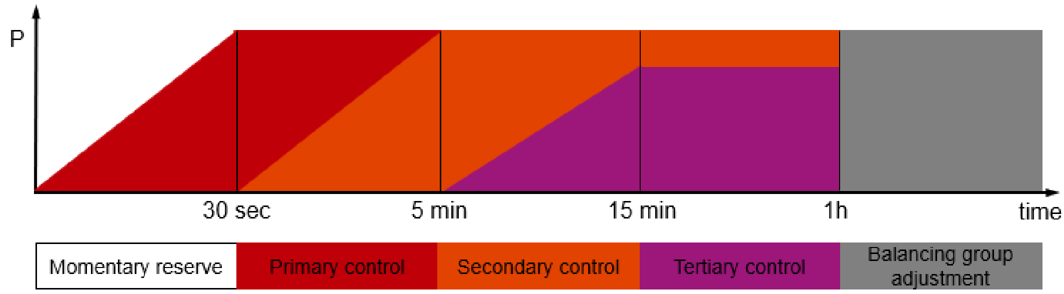

Figure 3 Schematic sequence of different types of balancing power (Source: own illustration, based on [15]).

Based on the European Network of Transmission System Operators for Electricity (ENTSO-E), the German TSOs procure the following types of control reserve [5]:

- Primary control / Frequency Containment Reserve (FCR): The main task of the primary control reserve is to stabilize the grid frequency as quickly as possible after a disturbance event. The FCR is activated unselectively and in solidarity in the entire network system and the full activation must occur within 30 seconds [14].
- Secondary Control / Automatic Frequency Restoration Reserve (aFRR): Unlike primary control, which is exclusively frequency-controlled, secondary control aims both at minimizing the grid frequency deviation from its setpoint and at maintaining the agreed transfer services to the interconnected partners. The complete provision must be provided within a maximum of 5 minutes [14].
- For Tertiary Control / Manual Frequency Restoration Reserve (mFRR) the activation has to be made in 15 minutes. The aim is usually to replace aFRR that has been activated over a longer period of time, so that the aFRR band is fully available again for short-term control interventions [14].

1.2.2 Regulatory and framework

At the international level, the ENTSO-E regulates the control area. It is defined in the *Continental Europe Operation Handbook – appendix 1 load frequency control and performance* [16].

Since the TSOs no longer have their own power plants due to unbundling, they have had to contract the required balancing power on an open, transparent and non-discriminatory market in accordance with the specifications of the *Federal Cartel Office and the Federal Network Agency* [17]. The amount of balancing power to be held in reserve is determined by the TSOs. The procurement of balancing power is carried out as a competitive bidding process on the German balancing power market with the participation of numerous suppliers (both power plant operators and electricity customers). For this purpose, the German transmission system operators have set up a joint Internet platform *(www.regelleistung.net)* [5]. The requirement for participating in the bidding process is to have a framework contract with the TSOs, which is entered into when the prequalified performance exceeds the respective minimum offer size for a regulation reserve type [18].

In relation to FCR, the acquisition of control work and control power is done on a joint market. Prior to November 3, 2020, the acquisition of control work and control power for mFRR and aFRR were also procured on a combined market. However, a control work market was established in Germany in November 2020. Daily tenders are conducted for the procurement of FCR, aFRR and mFRR, with uniform procurement for all control reserve qualities offered in six distinct products. Each day is divided into time slices of four hours each. FCR is procured as a symmetrical product, while positive and negative control reserves are tendered separately for aFRR and mFRR. FCR suppliers are required to provide both power increase and reduction in the amount of the bid power. The additional amount of FCR must be provided from the pool and is dependent on how much the current frequency deviates from 50 Hz. Revenues for FCR providers are determined based on the requested service price, with the highest bid price for successful bidders serving as the pay-as-cleared service price. If the bid is approved on the control power market, a right to remuneration arises equivalent to the bid price for the provision of the service [13, 19–21].

A summary of the types of balancing power and their specifications are in table 1.

Type of balancing power	**FCR**	**aFRR**	**mFRR**
Provision	ENTSO-E	TSO	TSO
Bidding Period	daily		
Time slices	6x4 hours per block		
Minimum bid size	1 MW, symmetric	5 MW, positiv or negativ	5 MW, positiv or negativ
remuneration	Pay- as -cleared power price	Working and performance price	Working and performance price
activation	automated	automated	manual
Full power	30 seconds	5 minutes	15 minutes
Period to be covered	Up to 15 minutes	From 30 seconds up to 15 minutes	From 15 minutes up to 60 minutes

table 1 overview of the characteristics of the types of balancing power: FCR, aFRR, mFRR (Source: [13, 19–21]).

1.2.3 Balancing power market in Germany

The average amount of balancing power required per day can be determined from archive data. Overall, the balancing power market is comparatively small in terms of volume; in 2021, the total volume of FCR tendered in Germany was 562 MW, in 2022 555

MW [22]. By comparison, the positive aFRR in 2022 was 1995 MW [22]. Even if the entire control reserve is seldom called up in operational network operation, the required control reserve must be permanently held by the suppliers as a safety reserve for stable network operation. As of January 2022, 6.94 GW of capacity was prequalified. For FCR, the share of battery storage was 0.63 GW. For aFRR and mFRR 0.06 GW [6]. The development of the power price in 2021 and 2022 is shown in Figure 4. The data is generated from the datacenter of the *regelleistung.net* platform [22]. Historical result and tender data can be retrieved there.

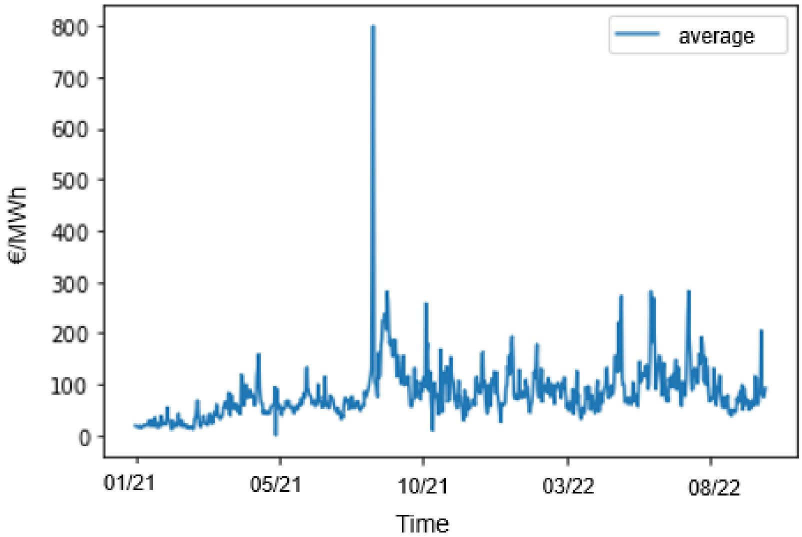

Figure 4 Average value of the results of the tenders for FCR in Germany in 2021 and 2022 (Own illustration, data by [22]).

Evaluations show that for all three control reserve qualities, the bid for power procurement exceeded the requirement at all points in time. On average, for both FRR and FCR, the power bid in each case was about 2.5 times higher than the corresponding demand in 2020 and 2021 [13].

1.3 Prequalification

The companies that supply balancing power must meet specific and generalized standards for providing power and energy. These requirements are referred to as prequalification criteria. Suppliers must not only meet technical requirements, they must also ensure that the requested service can be provided under all circumstances. The prequalification processes are carried out by the TSO in whose control area the plant is located [13]. A balancing power provider can apply for prequalification for a reserve unit (RU) or a group of reserve units (RG). A reserve unit is comprised of one or more power generation and/or consumption units, connected to the grid at a common point, and satisfying the requisitions for offering frequency control reserve or fast reserve response. On the other hand, a reserve group is composed of reserve units linked to distinct points on the grid. The technical units (TU) that constitute an RU or RG are identified as power generation and consumption units and are organized into pools [11]. The connection between the units is shown in Figure 5.

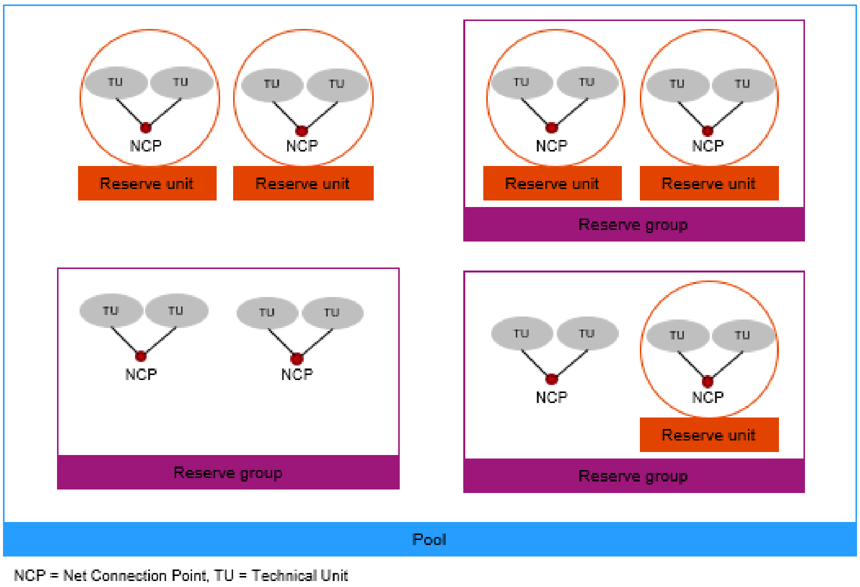

Figure 5 Overview of reserve units, technical units, reserve groups and pooling system in the prequalification process for providing FCR (Source: own illustration, based on [11])

There are many technical requirements that must all be met. The ones that are most relevant to the provision of FCR by electric vehicles are mentioned here.

To offer various types of control reserves, a control reserve provider is required to establish a separate pool for each type. The composition of each pool cannot be altered for at least 15 minutes, regardless of the specific type of control reserve. It is possible for positive and negative primary reserve power to be supplied by different entities. Additionally, the reserve power can be supplied proportionally by either some or all of the systems allocated to a pool, provided that the entire pool responds to frequency deviations ranging from 0 to +/-200 mHz [11, 18].

For reserve unit or groups, including EVs, which have a limited storage capacity, there are certain requirements that need to be met before participating in the FCR market. These requirements comprise a minimum work capacity, the implementation of appropriate storage management practices, and appropriate sizing of maximum power and power consumption. With a minimum activation time of 15 minutes, an RE or RG with a marketable capacity of 1 MW must have a work capacity of at least 0.83 MWh in the case of FCR in order to serve a full call of 15 minutes. Also, the maximum power must exceed the marketable capacity by at least a quarter, so that full provision of FCR is possible despite simultaneous storage management practices. This means, that if the marketable capacity is 1 MW, the power must be 1.25 MW [11].

For RU and RG that have limited energy storage, it is essential to demonstrate their usable work capacity during operation, which can be done through one of two options explained below. The first option involves adding another hub after the second one and providing capacity until the minimum required work capacity is proven. Figure 6 provides an illustration of this method for the FCR scenario. Alternatively, the reserve provider can repeat the hubs until the minimum required work capacity is demonstrated [11].

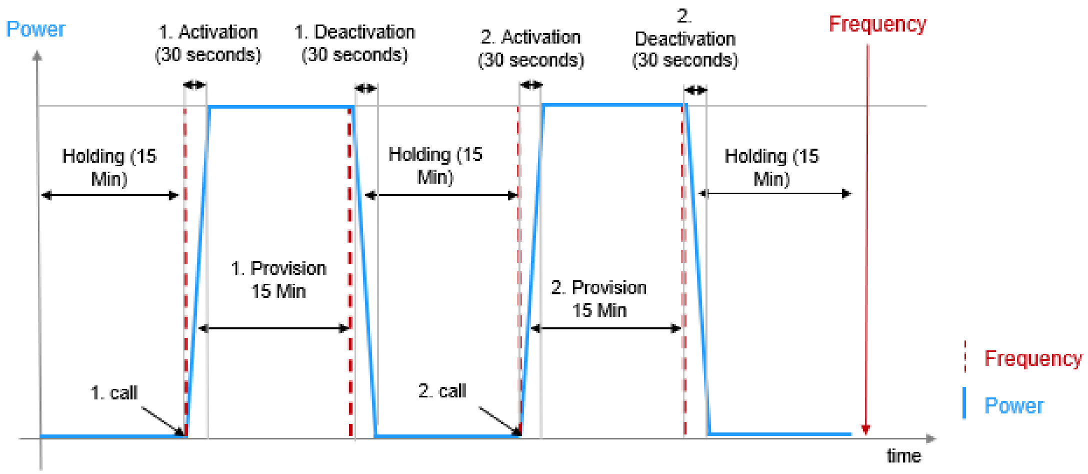

Figure 6 Schedule to demonstrate the usable work capacity of a battery storage system to prequalify for providing FCR (Source: own illustration based on [11]).

Currently, there are no official guidelines for EVs to participate in the FCR market. There are suggestions which resulted out of a research project about bidirectional charging by [18]. The authors suggested to improve the ability for provision by EVs. On is, that the development of the prequalification conditions should consider the combination of the charging station and the EV, and not just the charging station or the EV alone, to make it easier for EVs to participate in the market. They also suggest, that the manual prequalification process should be automated and streamlined to accommodate a large number of EVs, and the costs of fulfilling the technical requirements for prequalification should be minimized. Also, they suggested that the prequalification conditions for EVs should not lead to any disadvantage compared to other market participants such as stationary household battery storage systems [18].

1.4 Vehicle-to-grid (V2G)

Vehicle-to-grid (V2G) is based on the ability of the EV to be able support to the grid while parked and connected to the electrical grid [23]. V2G enables energy exchange between the battery of the EV and the power grid for EV charging or grid support [24]. Fundamentally, V2G may collect energy from EVs and trade it to the power grid through the control administration of a local aggregator. Figure 7 depicts the framework. The grid serves as a one-way conduit for power to travel from generators to consumers. Electricity flows from EVs back to the grid or in the opposite direction [23].

In addition to V2G, there are other terms that encompass vehicle regenerative power. Vehicle-to-everything (V2X) summarizes different ways an electric vehicle can be integrated into the energy system. Vehicle-to-Home (V2H) describes a scenario in which private households with EVs leverage the EV's battery capacity as additional flexible energy storage system. Vehicle-to-Business (V2B) describes the integration of the EV into a business fleet [24, 25].

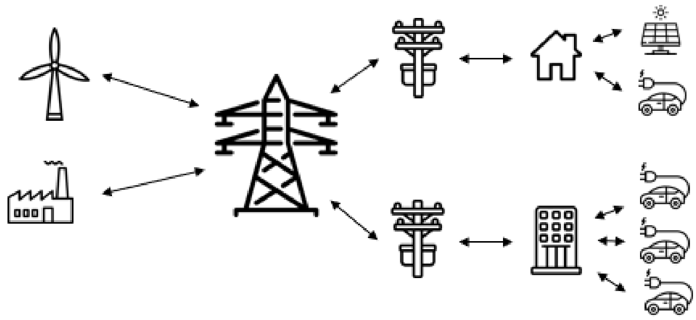

Figure 7 Overview of the connections in the V2G system between the individual components and actors (Source: own illustration, based on [23])

The V2G function offers a range of new or expands existing use cases for both private EV users and fleets like the optimization of local consumption/self-consumption, grid-serving charging, marketing of electricity and ancillary services such as the provision of FCR [26].

V2G systems involve the following technical components [24]:

- V2G chargers and power sources
- communication system
- electric vehicles
- power grid aggregator and power transmission system

Also, there are legal requirements, which must be considered as well as the impact of different charging strategies. These points are described in more detail in the following section.

1.4.1 V2G chargers and power sources

In general, a difference between alternating current (AC) und direct current (DC) charging is made. EVs can be directly linked to a single-phase or three-phase AC grid thanks to AC charging infrastructure. Low charging power (up to 43 kW, mostly used to 22 kW) is a feature of AC charging infrastructures, while high-performance chargers for DC charging can provide up to 350 kW of power [27]. There are other charger types, however at the moment the DC systems—*CHAdeMO* and *Combined Charging System (CCS)* — are the most pertinent charger types for V2G. Nissan, Toyota, and Mitsubishi were among the Japanese businesses who backed the *CHAdeMO* system, which was the first bidirectional charging system available. The *CCS* is another fast-charging system that combines the AC charging connection with the DC fast charging pins in one inlet. In Germany and the rest of Europe, *CCS* is the industry standard [28]. There are also two approaches to implement bidirectional charging: either on the vehicle side or on the side of the charging station. The difference is the place, where the electricity is converted from direct current to alternating current [26]. In the case of on-board chargers (integrated chargers), the bidirectional charging is implemented in the vehicle. Here, the inverter must ensure that the power can flow back. In addition, the communication standard must be adapted to ISO 15118-20 [29]. In the case of off-board chargers, the charger is mounted on the charging station and the feed-in and feed-back takes place directly as direct current through the charging station. Accordingly, this charging station must convert the alternating voltage from the grid to direct current using an inverter. However, communication must also be implemented [30, 31].

So, to realize the V2G mode of operation of EVs, either bidirectional on-board converters or off-board charging stations are required. The biggest advantage on board V2G has, is that EV owners do not have to pay for an expensive DC charging station. One of the biggest benefits when off-board charging is enabled is that charging is faster and more efficient. The biggest disadvantage is the price, mainly due to the expensive DC cable and plug. Thus, depending on the charging technology, changes to the vehicle side or to the charging equipment are necessary for the use of bidirectionality. These changes are associated in each case with additional costs for the charging infrastructure or the vehicle side [26].

The communication protocol standards currently used in the German automotive industry are not yet designed for bidirectional charging in the published editions. The communication standard ISO 15118-20 [29], which is currently being finalized and will be used by European and American vehicle manufacturers along with the *CCS* enables bidirectional charging via both AC and DC. Bidirectional charging is already possible for multiple years for the *CHAdeMO* technology [26]. As of February 2023, bidirectional charging stations are not yet readily available in Germany. The current offerings from various manufacturers are mostly announcements or products used as part of pilot projects. There are some charging stations listed in table 2 that are expected to offer bidirectional charging in the future and are expected to be available soon.

Name	**Manufactuer**	**AC/DC**	**Charger**	**Power**	**Price**
Quasar 2 [32]	Wallbox	DC	CCS	11,5 kW	3000 – 5000 €
Sono Wallbox [33]	Sono Motors	DC	CCS	11 kW	Low 4-digit range
BDL [34]	KOSTAL	AC, DC	CCS	11 kW	-
Sospeso&Charge [35]	EVtec	DC	CHAdeMO, CCS	10 kW	-
ambiCHARGE [36]	ambibox	DC	CCS	11 kW 22 kW	-
Honda Power Manager [37]	Honda	DC	CCS	22 kW	-

table 2 market overview: bidirectional wallboxes (Source: [32], [33], [34], [27], [36], [37]).

In summary, as of 02/2023, no wallbox is yet available for residential customers, but it is foreseeable that this will soon be the case. The announced wallboxes are mainly equipped with *CCS* and have a power of 11 kW.

1.4.2 Communication system

A sufficient number of EV batteries, which are connected to the grid, can be used virtual electricity storage system. Therefore, a bidirectional connection and intelligent management and communication system for the EVs is needed [3]. Due to this enormous potential for storage capacities, both the technical and regulatory basis for this must be defined [38]. There are a variety of communication protocols and standards which are introduced in this chapter.

To communicate the maximum charging current permitted, the EV and charging station at least use pulse-width modulation signals. The ability to functionally integrate electric vehicles into the infrastructure and optimize the charging process is made possible by digital and bidirectional communication via ISO 15118 [39]. The released version of ISO 15118-20, which was released in April 2022, specifically addresses the problems associated with bidirectional charging or use cases including V2H/V2G/V2X. The technical basis for this is, on the one hand, the ability of electric vehicles to transmit the required information and, as well as, the infrastructure to process this information appropriately and securely [38].

The IEC 61850 protocol can be utilized for communication between the grid and the charging infrastructure. Depending on the voltage level, with or without an intelligent metering system, this communication protocol facilitates data transmission between the network operator and the customer's facility. Controlling the customer's facility, gathering network status data (measurements, operational, and alarm messages), offering diagnostic functions to the network operator, exchanging the data model in the event of an expansion of the data model, and firmware and parameter updating for addressing detected security gaps are all supported by the functional model approach described in the DIN EN 61850 standard [39].

Communication methods are already in use for communication between the charging station and the backend system. For this use, the Open Charge Point Protocol (OCPP) is a commonly used protocol. This protocol enables the charging station to receive queries. The charging station reports its features, including authorisation, managing the charging current, and querying events, measurements, and counters. Version 2.0.1 is the most recent version (as of 02/2023), while version 1.6 is also extensively used [39].

The schematic connection between ISO 15118, IEC 61850 and OCPP is shown in Figure 8 [40].

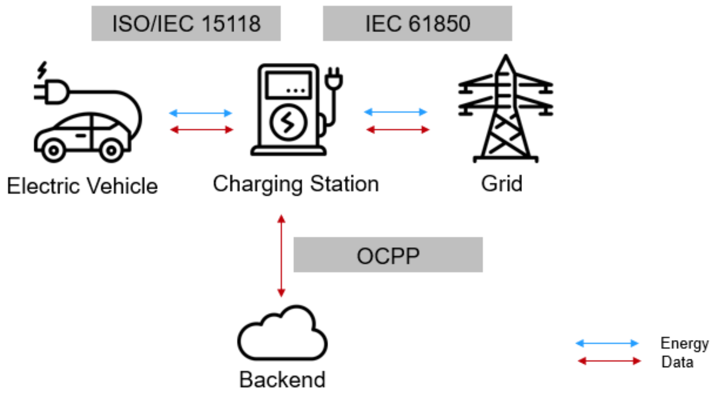

Figure 8 Schematic connections of the EV, charging station, network and backend with the communication standards OCPP, ISO/IEC 15118 and IEC 61850 (Source: own illustration, based on [40]).

Other relevant communication protocols for bidirectional charging are *EEBus, Modbus-TCP, OpenADR* and *CHAdeMO* [25].

EEBus regulates the communication between charging infrastructure and IT backend. *EEBus* is used to standardize the interface between electrical consumers, generators, storage units and the charging infrastructure. *Modbus-TCP* regulates the communication between the charging infrastructure and the IT backend. In this context, *Modbus-TCP* is a global industry standard and is used in EMS in larger buildings such as hotels or industry. Due to its flexibility, it allows for easy customization. *OpenADR* manages the communication between the IT backend and the energy market. *OpenADR* is an open, cloud-to-cloud communication protocol and transmits control signals between grid operators and aggregators. As mentioned earlier, there is also the *CHAdeMO* standard, the Asian standard for DC charging, for communication between e-vehicles and charging infrastructure. *CHAdeMO* is also used in Germany [25].

1.4.3 Electric vehicles

To participate in V2G, electric vehicles have to have the ability for bidirectional charging. Many manufacturers have started to enable their vehicles for V2G. While some manufacturers already have the ability to use their vehicles for supplying electricity to small consumers with the V2H function, the V2G functionality is only available for vehicles with the *CHAdeMO* standard. Table y gives an overview of the current state of technology among automotive manufacturers who already provide or are working on providing V2G.

Manufacturer	V2X	Description
Nissan [41]	2VG	The two vehicles, the Nissan LEAF and the Nissan LEAF e+, have the CHAdeMo charging standard which allows bidirectional charging for them. The V2G technology has been successfully tested in a field study with 13 Nisan LEAF and fitting charging stations.
Stellantis [42, 43]	V2G	The Citroen oli concept study has been announced to include both V2G and V2L. FCA, Engie and the Italian power grid operator Terna have inaugurated a V2G pilot project at the Drosso logistics hub in Turin with the Fiat500e. The project will explore and test the interaction between the used EVs and the Italian power grid.
Mercedes [44]	V2G	The EQS is in Japan able to charge bidirectional with the CHAdeMO standard.
Renault [45], [46]	V2G	A successful project test was carried out in Fernando de Noronha, Brazil, with 2 Renault Zoe prototypes. The Renault Megane E-Tech Electric is also expected to have the technical capabilities for V2G.
Honda [37]	V2G	The bidirectional Honda Power Manager has demonstrated its V2G capabilities in several pilot projects. More information can be found in section 3.2.
BWM [47]	V2G	The BMW i3 V2G pilot project involved 50 specially equipped BMW i3 vehicles which were able to return power to the distribution grid.
Hyundai, Kia [48]	V2H	The Hyundai Ioniq 5 is already capable of V2H can charge or operate electrical devices with up to 3.6 kW through an adapter. However, further development and expansion of V2G is planned. It’s the same for the Kia EV6, which is its sister model.
VW [49]	V2H	All ID. models with the 77-kWh battery will be enabled for Vehicle-to-Home technology in the future. For vehicles that have already been delivered, the technology will also be available via an over-the-air update. The power transfer and communication will be carried out through a special DC-BiDi wallbox.
Ford [50]	V2H	The F-150 Lightning is capable of V2H. It is currently only available in the USA and can be used as a backup power generator.

table 3 overview of V2G ready electric vehicles (Source: [41-50]).

In summary, there have been many successful tests and pilot projects and manufacturers are showing that they are involved in the planning of V2G. Only *CHAdeMo* is currently available or V2H solutions with slow AC charging power. Actual V2G vehicles have only been used for pilot projects in Germany, as described in more detail in chapter 2.2.

1.4.4 Aggregation infrastructure

Not only must EVs be linked to the charging station, but they must also be interconnected and intelligently linked, to control the energy, collect it and sell it.

These capacities can be combined in a variety of ways. There are two primary V2G designs suggested in [51]. The first approach, the centralized approach, is that each EV provides V2G services on its own, directly controls it, and connects to the TSO via power and communication connections. The second one, the decentralized approach, consists of a framework that offers V2G using an EV fleet. The aggregator serves as a point of contact for EV fleets and TSO. The aggregator, who has agreements with the EV owners, has access to and control over the EV capacity and charging operations. The aggregator establishes and maintains the standards and conditions for using V2G services [51] . Figure 9 gives an overview about the 2 different systems. At the left side is the centralized aggregation shown, at the right side the decentralized version.

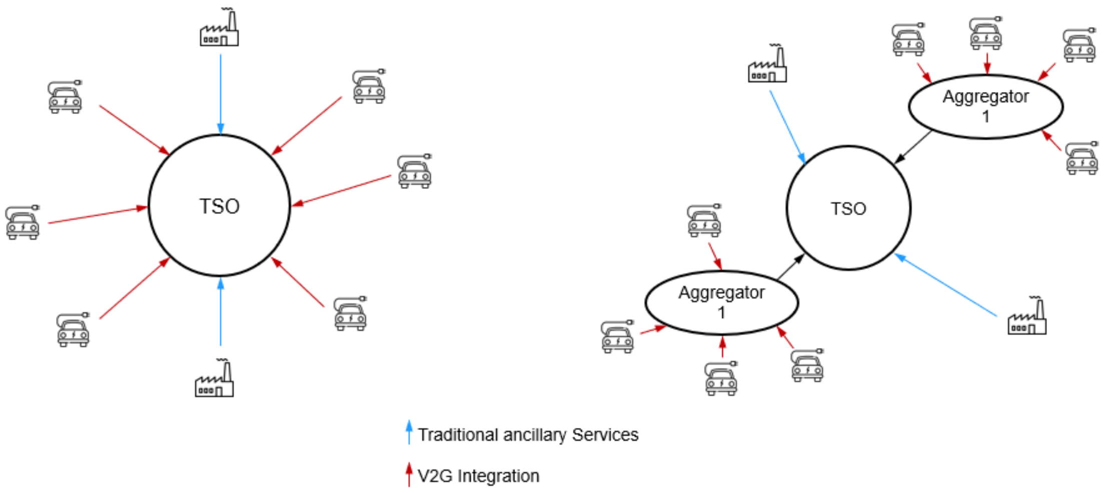

Figure 9 Difference between centralized and decentralized aggregation of EVs and power sources in the energy system (Source: own illustration, based on [51]).

The aggregator mostly works as a virtual power plant (VPP): A virtual power plant is a collection of decentralized units in the power grid that are coordinated through a shared control system. These units can be power producers, consumers, and storage facilities, including biogas, wind, photovoltaic, cogeneration, or hydropower plants, as well as power-to-x plants (power-to-gas, power-to-heat). The purpose of a virtual power plant is to collectively market electricity and flexibility from the aggregated plants. Each actor producing, storing, or consuming electricity can be part of a virtual power plant. The swarm of individual units is controlled by a central control system that coordinates the individual plants, responds to grid conditions and command signals for regulation energy by transmission system operators, and adjusts the power output to respond to price signals from electricity markets. Virtual power plants resemble large power plants in their market role and can provide similar levels of power as one or more nuclear power plants, but they are built on a network of renewable power generation plants, which are subject to continuous variations in power output. The development of virtual power plants was first theorized in the late 1990s but became possible after advances in computer technology and new regulations were introduced in Germany in the 2010s to facilitate the energy transition to renewables [52].

VPP and aggregators, that have already aggregated several electric vehicles into a virtual power plant in Germany are *Next Kraftwerke* [53] The *Mobility House* [54] or *sonnenVPP* [55].

Next Kraftwerke is a virtual power plant that connects decentralized energy producers and consumers. If a battery or sub-pool of storage units has a power of at least 1 MW and a one-hour storage capacity and is equipped with a remote control unit like the Next Box, it can become part of the Next Pool virtual power plant. *Next Kraftwerke* provides the remote control unit and handles the pre-qualification process for the regulation energy market. Integration costs are typically in the low to mid four-figure range. By marketing the regulation energy from the battery storage with *Next Kraftwerke*, the owner receives a portion of the performance price as compensation. The more flexible and longer the time windows for regulation energy provision, the greater the potential additional revenue. Additional revenue can also be obtained through cross-marketing in the intraday market. Since EVs don’t have a the required power alone, they are to small to join on a regular base. Nevertheless has *Next Kraftwerke* integrated EVs into their VPP in pilot projects [56].

The Mobility House has announced its connection to the European power exchange *EPEX SPOT SE* to trade the flexibilities of 4,500 EV batteries (100 MW) using its own EV Aggregation Platform. The technology company has been marketing the flexibilities of stationary and mobile electric EV batteries since 2016 through its own platform or partners in various countries and applications. The company's direct participation as an official exchange member is necessary due to the increasing use of V2G applications. *The Mobility House's* EV Aggregation Platform enables the identification of the storage or flexibility potential of mobile electric EV batteries, providing valuable energy, network, and system services during the EVs' stationary times. The technology is currently being used in Germany, France, and the Netherlands and will soon be deployed in the UK and the US. The platform will also be used in products that target private customers to enable them to directly benefit from the energy markets' participation and the flexibility potential of their EVs [54].

Sonnen's Virtual Power Plant connects thousands of *sonnenBatteries* to form a large virtual power plant. Each battery is controlled and coordinated within the network using special algorithms to actively participate in the energy market and stabilize the public power grid. This was previously only possible for large power plants, but now even private customers can contribute to the success of the energy transition. *Sonnen* has received qualification for primary control power from the transmission system operator *TenneT*, allowing it to use its network of home energy storage units, the *sonnenVPP*, for further services in the power grid. Customers who have been using the tariff since 2020 are entitled to a share of the revenue generated by the *sonnenVPP*. *Sonnen* guarantees a profit-sharing for the first 10 years, based on technical framework data of the *sonnenBattery* used. Additionally, all customers with *sonnenFlat* tariffs benefit financially from their free electricity quantity, providing an economic advantage to the use of their sonnenBattery. *Sonnen* specializes in PV and batteries as home storage but has also integrated EVs into the VPP in initial pilot projects [55]. More their projects can be found in chapter 2.2.

1.4.5 Legal requirements

In addition to the communication standards and the requirements that must be observed in general for the development of charging infrastructure, there are other legal requirements and obstacles that are relevant for V2G. In Germany, there are regulations for the installation and operation of electric vehicle charging infrastructure, outlined in the VDE Application Regulation VDE-AR-N 4100 for low-voltage systems and VDE-AR-N 4105 for systems that can feed energy back to the public grid. Charging infrastructure with a capacity of 3.6 kVA or more must be reported to the grid operator, while charging systems with a capacity over 12 kVA require prior approval [39].

The treatment of electric vehicles at the transfer point as consumption or generation plants is reflected in various metering concepts based on legal requirements. The circumstances for effective energy consumption and smart grid applications are created by the implementation of intelligent metering systems (iMSys), which are also called smart meters. Smart meters are intelligent metering systems made up of a digital electricity meter and a Smart Meter Gateway (SMGW) communication unit that allows for data exchange. The digital electricity meter and flexible consumption and generation devices are linked to the smart grid through a smart meter gateway. The effective integration of flexible consumers and generators into the energy system requires the rollout of iMSys. However, the rollout has been slow so far. A new draft law by the Federal Government is going to accelerate the rollout and thus the digitization of the networks while ensuring data protection and IT security [57] [58].

Another legal issue is unequal treatment of stationary and mobile storage in terms of energy surcharges, taxes, and levies, leading to economic disadvantage for mobile storage. Bidirectional EVs can offer system services both during controlled charging and during controlled vehicle discharge. In terms of the legal and regulatory framework, the problem of potential double taxation for power fed back into the public grid from these vehicles must be addressed, as well as the distinction between electric vehicles as end-users (while charging) and feed-in users (when dis-charging and feeding back into the grid). For stationary energy storage systems that are fed back into the public grid, there are now exemptions to prevent double taxation; however, these benefits do not apply to mobile battery storage and bidirectional electric vehicles. This means that bidirectional EVs must pay the full taxes, fees, and charges, including network fees, for the power they draw from the public grid, even if the stored power is fed back into the grid as V2G [18].

The *Bidirectional Charging Initiative* found further regulatory obstacles and demands: The current lack of definition for mobile battery storage and the differing legal frameworks creates uncertainty for the legal classification of bidirectional charging electric vehicles. The initiative calls for a clear legal definition to be created. The current regulation of network operators only regulates consumption and not generation and doesn't utilize market-based procurement. The initiative calls for bidirectional charging to be considered in the regulation and to provide regulatory incentives. Also, a challenge is the lack of economic motivation for distribution network operators to adopt bidirectional charging, due to the focus on capital costs in current regulations. Their solution is to consider the operational costs of flexible energy storage and digitalization of the energy network in regulation and incentivize the reduction of network expansion costs [59].

The goal of the German Federal Government's Masterplan Charging Infrastructure 2 of 2022 (number 47) is to enable bidirectional charging without discrimination. They are therefore examining, how the legal, technical, tax, and economic framework conditions can be improved to remove any obstacles to the non-discriminatory use of the possibilities of bidirectional charging, initially mainly in the non-public space. They are examining to what extent new regulations are required, so that they can be incorporated into the framework for network- and market-friendly flexibilities [60].

1.4.6 Charging strategies

The literature on V2G charging has reported several strategies [57, 61]. These include:

- Dumb Charging: When EVs are plugged in, they are always charged to the maximum capacity that is available.
- Controlled Charging: The EVs are recharged in accordance with the requirements of both the system operator and the vehicle owners.
- Smart Charging: The EVs are also charged in accordance with the requirements of both the TSO and the EV owner, but it is more sophisticated than controlled charging because it makes use of an automated and management system

EV owners are always able to plug in and charge their vehicles with dumb charging. With controlled and intelligent charging, the process can be done manually by the automobile owner or automatically by an intelligent charging system. In manual controlled charging, the owner chooses when and how to charge his EV, but the system operator can influence this decision through incentive schemes. In automated smart charging, a hierarchical management system chooses the charging profile to maximize the advantages for the network and owners, either monetarily or technically [57, 61].

To make the best use of the battery capacity, driver and TSO can profit from the battery, some form of control and communication must be implemented. A proposal of such a control came from Kempton and Letendre in 1997 [62].They were among the first to investigate the use of V2G and EVs as a potential source for grid services. They recognized the potential of using EVs as storage and found the different requirements of EV owners and TSO. The EV owners always want to be able to use the EV without restrictions, while the TSO wants to use as much capacity as possible. Therefore, the vehicle owner needs a limit to discharge the vehicle [62].

Their approach was a computer-controlled dashboard in the EV. Here, the driver can make various settings with the help of a dashboard. For example, he can plan the time and the expected distance of the next trip. He can also reserve a buffer that must always remain available. When the driver has enough battery capacity to meet his driving needs, the rest can be used for ancillary services such as FCR [62].

This approach has continued to evolve since 1996 and can be found in a modified version the market today. There are many approaches how smart and user-controlled charging works, which depends on the provider. It can be implemented either directly in combination with a smart wallbox or through a separate smart charging platform provider. Different use cases are in focus, such as price-controlled charging, peak shaving for fleets, or grid-friendly charging. These functions can also be used in pilot projects to provide FCR. There are many different providers in the European market, who offer control, charging management and smart charging platform solutions. One example of a provider who has used their app in a pilot project to provide FCR is *Jedlix*. The Dutch smart charging platform operator has developed an app that aims to ensure that customers charge their EVs when it's most cost-effective. In their app, users must indicate when they need their EV to be fully charged, and it happens when it's the cheapest. The Smart Charging API was used for this in a pilot project (s. 2.2) [63] [64].

1.4.7 User acceptance and economic benefits

The financial value of offering FCR is dependent on several factors, including payment plans, market structure, operating strategy, degradation costs, unavailability fines, and penalties brought on by an increase in peak load that results in technical problems with the distribution grid. Because of this, the financial advantage for specific EV owners may differ [65].

There are different possibilities of business models. Basically, the VPP receives money from the TSO when it offers control power and is commissioned. The VPP returns this money to the EV owner, usually with a retention of a share. As described in 1.4.4, there are different possibilities how the payment between VPP and EV owner can work. For example, the VPP retains a share of the revenues or the EV owner uses the infrastructure of the VPP and pays a flat fee for it [66].

The attitude and acceptance of EV towards V2G applications is an important success factor for the successful implementation of V2G [67].

Since the topic of V2G is relatively new and has not yet reached everyday life, its acceptance has not yet been studied in such detail. Nevertheless, the results thus far how crucial user approval is for the adoption of controlled charging solutions. The motives and concerns of potential users, as well as various consumer categories and use cases, must therefore be taken into account, especially when developing charging systems for supplementary services [68]. There are several studies that have dealt with user fears and acceptance criteria. The results are quite similar and show financial incentives as being very relevant, fear of reach and fear of restrictions as obstacles.

Motivators which have be found in [68] for participating in an electric mobility program include financial incentives such as payouts, discounts, subsidies or guarantees, environmental protection, bonuses or rewards for using electric vehicles or related technologies, testing new technology or using specific app features, more efficient energy use, and contributing to network stability. Participants may also benefit from a positive social status. However, there are concerns about financial costs, battery wear and tear, reduced flexibility and mobility, loss of control over processes and systems, transparency and privacy issues, and potential security risks to personal and technical systems [68].

In the Netherlands, a study about factors which determine the acceptance of vehicle-to-grid was conducted with 20 EV drivers [69]. The items most frequently cited by users to accept V2G were financial compensation, transparent communication, and reliable system control. Negative influences on acceptance have range anxiety and fear of battery overuse and degradation [69].

A project, in which secondary control power with 20 bidirectional charging systems, was provided *(INEES),* the user acceptance was found to be an important factor, with users needing to be able to customize charging plans to meet their needs using a mobile app or the EV's interface. To ensure success, three factors were identified: frequent charging, releasing some battery capacity, and planning future departure times. A financial incentive was found to be the most important factor in encouraging participation [70].

A study conducted with early adopters of electric vehicles to determine their attitudes towards charging, self-generation, and management found out, that majority (80%) of the 432 respondents expressed interest in charging management, but some were not interested due to existing management practices or lack of control. Energy providers were seen as the most likely party to manage charging, with compensation for management varying in importance to respondents. The study found no clear preference for compensation levels, which suggests a lack of understanding of the value of such incentives in the market. The study also found that respondents were open to the idea of tariff-based charging but had no clear preference for specific tariffs. Finally, it was investigated which discounts on the electricity bill could motivate electric vehicle users to participate in an electric mobility program. The largest group, with around 25 percent of respondents, wanted a discount of at least 10 to 20 percent [71].

To summarize, the literature review suggests that the technical prerequisites for V2G are mostly in place but are not yet fully implemented in the market, particularly in terms of communication and infrastructure. The necessary components, such as electric vehicles, charging stations, communication devices, and VPP, that can provide ancillary services through V2G, exist and are technically usable. Additionally, there are also charging strategies, software providers and their apps that can control smart charging. Nevertheless, the implementation of V2G is for private individuals without an aggregator currently not possible, but the development of regulations and legal proposals suggest that it could be implemented in the near future. The implementation of the secure communication standard ISO 15118-20 and the Smart Meter Gateway rollout could help to make V2G possible. Nevertheless, to utilize V2G, enough EV must be connected to the grid and available for use through a VPP or aggregator.

2 State of research

Many studies with various focuses and input data have been written regarding how EVs provide ancillary services, especially FCR. Particularly the economic viability of EVs is researched in the literature. Significant ones are briefly summarized in chronological order. The results of some recent research projects are then presented.

2.1 Literature review

Kempton and Tomic [23] developed a model to assess the potential for grid power generation from EVs vehicle-to-grid V2G in the US in the year 2005. This model takes several variables into account, including the revenues and expenses related to V2G electricity as well as the technological viability and financial drivers for adoption of this technology. Based on certain assumptions, such as a high vehicle availability, a connected load of 15 kW, and a daily connection period of 18 hours, the model's findings indicate that there is a sizable potential profit to be earned via V2G, with an estimated profit of over 2,500 $ per EV per year. However, it should be highlighted that rather than real driving profiles, these results were based on average driving values of 32 miles per day. The model also considers various payment options for V2G electricity [23].

In 2011, Anderson et al. [72] looked into the extent to which plug-in hybrid electric vehicles can offer grid services through primary, secondary, and tertiary frequency control. Using information from 2008, the study examines the potential revenue that plug-in hybrid electric vehicles can generate in the balancing power markets of Sweden and Germany. The behavior of 500 distinct vehicles was modeled using a Matlab simulation. It was estimated that each day, the automobiles would drive for around 35 minutes, or about 1 hour, and then participate in the regulated power market for the remaining day. The findings indicate that in Germany, the average monthly revenue per vehicle range from 30 $ to 80 $. The high revenues are a result of the assumption that the vehicles had a low amount of daily driving time and were able to participate in the regulating power market for most of the day. The study does not consider the costs of infrastructure or V2G equipment [72].

In 2013, Schuller and Rieger [73] investigated the economic potential of providing balancing power with EVs in Germany. They did an economic analysis of bidirectional EVs participating in the German energy market. They calculated the revenues using information from 2011 and 2012. Nine potential EV market entry strategies were taken into account, and a daily driving distance assumption of 40 kilometers was made. The input data for the analysis includes energy and capacity payments for three different balancing power products for the months of March through December 2011 and the entire year of 2012. Assumptions of an availability for 18h each day for 365 days are used. The results show that negative regulating energy, which involves charging the EV at a lower price, has the highest economic potential for both the secondary and tertiary regulating energy markets. Annual revenues of up 730 € per vehicle could be reached. For the provision of FCR, the revenues are up to 250 € per year. The sensitivity analysis also indicates that the connection power, availability times on the grid, and variable storage costs are relevant factors, regarding how attractive the EVs are [73].

The business case of providing negative aFRR for balancing power on the German market by a pool of EVs was examined by Jargstorf and Wickert [74] in 2013. A so called agent based java model was used. Vehicle drive according to driving patterns. Driving distances are taken from the study about mobility in Germany in 2008 by the institute for applied social sciences [75] with a profile containing business trips and a profile containing private trips. The aggregator has a certain number of vehicles under contract which he can activate as long as their customers offer him capacity for activation. As an output, the model calculates the available capacity for every time step for a given number of vehicles. Then the minimum capacity available during one week in each period determines the capacity which the aggregator can offer as reserve to the TSO. The simulation displays an annual revenue of less than 60 € per EV. Fully charged batteries are recognized as a significant bottleneck for a secondary reserve provision. Costs associated with communication and customer compensation are also a concern. Based on the simulation results, it is stated that these small units shouldn't be used to enter the secondary reserve market. In this study, the vehicle does not immediately begin to load when linked to the grid. Instead, the driver tells the vehicle when and at what load level it will be needed again. The loading is subsequently postponed by the EV's energy management system (EMS) as far as feasible to accommodate the driver's need for mobility. About 10,000 vehicles can offer 2 MW of reserve during peak time and less than at least 1 MW during off-peak time [74].

In 2017, Hoogvliet et al. [76] conducted research on the Dutch market's potential for electric vehicle owners to supply reserve and regulating power. They were interested in regulating the value that EVs may produce with this kind of power as well as how it would affect the customers. For the years 2014 and 2015, they created a model in which four different EVs participated in the Dutch reserve power market on a minute-by-minute basis. Three distinct user groups were developed by the researchers' using data from earlier studies on the characteristics of Dutch EV drivers, each having predictable daily travel habits and energy usage. They assumed daily energy use of 56% of the battery and two journeys per day per EV, when defining charging sessions for each user type based on their travel habits. To comprehend the potential financial advantages and effects on the batteries of the EVs, the researchers constructed two dispatch scenarios. In the first scenario, the EVs were charged to capacity, whereas in the second scenario, the charging schedule was changed depending on settlement pricing for reserve power to add value for the EV owner. According to the findings, depending on the EV and user group, providing reserve power might result in yearly advantages of 120 € up to 750 € per EV owner. This was followed by increased battery utilization and decreased state of charge distributions, however the latter had minimal effect on the projected travel requirements of the EV users [76].

In 2019, Huhne et al. [77] studied the optimal delivery of system services using V2G. As part of a pilot project, they analyzed the achievable economic value from the delivery of system services for electric fleets. Furthermore, it was based on a simulation method and an optimized charging strategy. The optimization model considers the markets for primary and secondary power provision. The development of charging strategies considers not only the need for regulation services and energy, but also the mobility demand, and the prices to be paid or achieved. On the supply side, a distinction is made between the representative fleet types of *Retail* (vehicles used by private households) and *Car-Sharing* (vehicles of commercial providers). The vehicles are divided into three groups: *Parked vehicles connected to the grid*, *Parked vehicles without connection to the grid*, and *Vehicles in use*. 200 identical vehicles with 40 kWh and 11 kW charging capacity are used. The individual charging or discharging operations are set by the algorithm so that both the necessary charging level for mobility requirements and the punctual delivery of regulation services can be ensured at all times. The simulation of FCR retrievals uses the frequency deviations measured second-by-second over a 12-month period (July 2019 to June 2020). The results show a revenue of 402 € per year and per vehicle. Fleet operators can raise value potentials or consumers can benefit from lower costs for system services [77].

In 2020, Pavic et al. [78] discussed EVs as frequency containment. The objective of their paper was to examine the use of EV fleets as a source of balancing reserve for the grid. To achieve this, a mathematical model was established that optimizes the energy cost for purchasing power in the day ahead market and the sales of FCR up and down capacities. The model considers variables including the EVs' current state of charge (SOC), individual EV behavior, and restrictions. Three distinct vehicle sizes were used in a total of seven case scenarios, which ranged from uncontrolled charging to bidirectional regulated charging with asymmetrical FCR provision and considered both slow and fast chargers. The study was constrained by charging and energy considerations and used activation data and FCR market pricing from the French power system. The value and frequency of attaining the maximum or minimum SOC are calculated by the model. The findings show that adding controllability through V2G discharge or FCR providing significantly lowers the total cost of charging the EV fleet. When compared to uncontrolled charging, unidirectional control without FCR reserve provision cuts the overall cost in half, while symmetrical FCR provision further cuts the overall cost by 10%. The study's conclusion is that improving the capability for FCR reserve provision rather than selling energy is where V2G dispatching's true worth lies [78].

In 2020, Bañol Arias et al. [65] analyzed the economic benefits for electric vehicle owners who provided FCR in the Nord Pool market. Together with operational tactics that simplify the provision of the service, a heuristic strategy for optimizing the power bid that optimizes the income for EV owners was put forth. The revenue from the standpoint of the EV owner is the subject of the economic analysis in this study. In order to examine the behavior and prospective financial benefits that each EV may provide to the owner when supplying frequency control reserve, the algorithm is separately run for each EV. The study suggests three methods for maintaining the battery's operational range while performing services and figuring out how to operate the EV most profitably in terms of availability and battery life. The findings show that EV owners can generate sizable income and estimate yearly advantages of a range between 100€ and 1100€ per vehicle [65].

The impact of FCR flexibilization on the economics of operating an EV fleet is the subject of a study by Figgener et al., conducted in 2022 [79]. The authors studied the electricity delivered by commercial EVs for regulation in 2022. The study used driving logbooks from more than 460 commercial fleet vehicles in 14 different economic sectors, as well as data from 22 commercial EVs across several years. The researchers created a simulation model using this information to determine how much electricity an array of EVs could produce. The model simulates how electric vehicle drivers connect to the grid using charging stations and reserves a particular amount of battery capacity for each vehicle. Its capacity consists of a 30% buffer in addition to the required SOC for the subsequent trip. For grid services, the remaining battery capacity is used. The simulation model distributes trips' timings and distances at random, correlating them to the vehicles. The models allowed the researchers to determine how shorter service durations might affect the amount of power available and the power uncertainty of the EV pool. The study discovered that the uncertainty is low, particularly when the pool power is considerable, showing that commercial fleets can deliver a highly stable power profile during specified service periods. The researchers also looked at the potential earnings of a group of 1000 EVs with 11 kW of charging capacity, giving FCR in the German market. The authors found out, that the average revenue per EV starts at 263 € per year with weekly service periods and decreases to 232 €/a for daily service periods, but increases up to 640 € per year with four-hourly service periods [79].

In contrast to the studies presented Schill et. al. [80] did not take the approach of generating revenue through vehicle fleets, but instead took a holistic approach. They did a study in 2016 on how EVs will contribute to Germany's power grid in 2035. They evaluated the potential of a fleet of 4.4 million EVs in delivering balancing power using a simulation model *(DIETER)* using hourly profiles of energy usage and charging availability from a previous project. Two power plant scenarios and several methods of supplying balancing power, including with and without energy feed-back from EV batteries to the power grid, were explored. Calculations revealed that even in the absence of energy feed-back, the EV fleet could significantly contribute to cost-effective power balancing [80].

To summarize, the core question to be investigated is how private EVs in Germany can provide FCR services. There have been many studies that examine the provision of grid services by electric vehicles and calculate the potential revenues. While most of the studies calculate the potential revenues, the focus is very different, which is reflected in the results. The results range from 100 to 1000 € per vehicle per year and the differences result largely from the different market conditions (other countries, other years) as well as the different assumptions about the availability of the EVs. Many of the literature focuses on technical aspects and not on actual availability. There are many different approaches to calculate the driving performance, which often use average assumptions or actual driving data. The economic analyses mostly focus on high-level, average vehicle utilization times and not on model-based or actual driving data. Average assumptions were used in [23], [72] and [73] such as how many hours a day the EVs are standing or driving. The actual impact of vehicle availability is less discussed. There are studies that use actual driving data or simulation models, but operate in completely different markets, such as [65] on the Nord Pool market or [76] in the Netherlands. Other studies also use real driving data but for secondary reserve [74] or they focus on commercial fleets [79]. On the other hand, [78] and [80] take a holistic approach to integrating BEV into grid services in the most meaningful way possible and focus less on feasibility.

Due to the rapid advancement of technology and the shifting nature of the market, the issue of how private EVs in Germany might supply FCR has not yet been systematically investigated. The possible availability of independent private houses with an emphasis on feasibility, therefore, has a study gap. By exploring the broad potential of private EVs for supplying FCR in Germany and offering details on the accessibility of EVs that can be charged at home, this thesis seeks to supplement earlier research. Also, the technological, legal, and financial viability are highlighted. The difficulty is to have a sufficient number of EVs connected to the grid. These must have a SOC that on the one hand keeps enough capacity available to act a FCR provider and on the other hand be sufficiently filled, to meet the needs of their owners.

2.2 Pilot Projects

The *INEES* research project demonstrated the technical viability of employing a fleet of EVs that can generate electricity to make up for short-term variations in power grid frequency that call for secondary control power. To accomplish this, a concept for secondary control power was developed, and after discussion with a German TSO, it was tested in a one-year fleet experiment. For this use, *Solar Technologies AG* created a limited run of 40 units of a bidirectional DC charging station. Additionally, *Volkswagen AG* built communication between the charging controller and *Volkswagen's* backend and fitted 20 *e-up!s* with a bidirectional charging capability. As a user interface, an app was developed. The integration of the vehicles was added to the *SchwarmDirigent®* by *Licht-Blick SE*, creating a connection between the EVs and energy market [70].

Electric automobiles also can be utilized to supply balancing power, as demonstrated in 2022 in Germany by a project by *Hyundai, Next Kraftwerke*, and *LG Electronics.* In this project, secondary balancing power in *Amprion's* balancing zone was provided by eight charging stations and eight Hyundai *Ioniq 5* EVs. It intends to demonstrate how tiny units and V2G may both significantly contribute to supplying balancing power and so stabilizing the German electricity system. The cooperation's objectives were to prequalify EVs and offer backup balancing power. To properly forecast when EVs would be at charging stations and hence ready for regulating energy supply, *LG Electronics* has developed an app [81].

Five *Porsche Taycans* were successfully connected to the power grid and connected to a cloud-based pooling system as part of a pilot test conducted by *Porsche, TransnetBW,* and the consulting company *Intelligent Energy System Services* in 2022 in Germany. The measurements, in accordance with *Porsche*, demonstrated that the grid balancing system's goal values were met [82].

In a pilot project with *Next Kraftwerke, Honda* has become the first automaker in Europe to receive certification of a fleet of production electric vehicles for prequalification of primary control services by *Amprion* in Germany. In the pilot project, *Honda e* electric vehicles provided FCR for the TSO and qualified to support network stability. In addition to the six *Honda e*, also six *Honda Power Managers* were also used in the project. The *Honda Power Manager* is a bidirectional *CCS* charging system [37].

Honda also demonstrated in a joint project with the V2X Suisse consortium the central role that EVs and bidirectional charging can play in future energy management. The company supplied 50 *Honda e* and 35 H*onda Power Manager,* which were used by car-sharing provider *Mobility* at various locations in Switzerland as part of a V2X project [37].

A project by *TransnetBW*, *Next Kraftwerke* and *Jedlix* has shown that the connection works not only under fleet or laboratory conditions but also with vehicles at different locations. They have completed a large field test for providing regulation services through electric mobility. A total of 155 electric vehicles participated in the practical test between June 2021 and June 2022. The results show that the provision and delivery of regulation reserve from a virtual power plant made up of a variety of pooled electric vehicles is not only theoretically possible, but also practical. The activation of the pool and individual vehicles based on set values from the *TransnetBW* network control system was done according to the requirements for the quality of regulation reserve. Through the EV-Fleet project, the partners tested the technical and communicative infrastructure for providing and activating regulation reserve by electric vehicles placed in various locations. They also explored how charging processes can be controlled in the future so that they consider the current local distribution network conditions and do not create network bottlenecks through system-friendly controlled charging. Here the field test was successful but the prequalification has not yet taken place [64].

In 2023, Energy company *sonnen* has integrated EVs as part of a virtual power plant for the first time, using them to help stabilize the German electricity network. The VPP relies on EVs in the *sonnenCommunity* to provide short-term regulation of energy frequency fluctuations. EV batteries in the community can supply primary regulation power within 30 seconds to compensate for power load changes. In the *sonnenCommunity,* EVs from various manufacturers are used in different households for daily activities, while also being integrated into the *sonnenVPP* to provide primary control power to balance the load changes and frequency fluctuations in the power grid. This is achieved through an intelligent charging process, without causing additional battery wear through discharging. Currently, some vehicles in *TenneT's* network area are already integrated into the *sonnenVPP*. The next step is to expand the program to include 5,000 more *sonnenCommunity* households with an EV and a *sonnenCharger*, which, along with the *sonnenBatteries* in the homes, will create a potential of approximately 80 MW [83].

An initial literature search and review of current research projects indicates that feasibility is technically possible. The regulatory requirements for widespread use are not yet in place but are expected in the next few years based on the projects. Besides the technical and regulatory feasibility, the actual availability of private EVs is a very relevant aspect, which is the focus of this thesis.

3 Methodology

This chapter describes the methodology. First, the framework and approach are defined, including limitations and assumptions. Afterwards, the databases and tools used are discussed. Then, the simulation is described, which was conducted using Python as well as Microsoft Excel (hereinafter referred as Excel) and Visual Basics for Applications (hereinafter referred as VBA). Finally, the evaluation is presented.

3.1 Definition of the framework

The simulation is used to determine the potential for private electric vehicles to provide FCR in Germany. The following approach is taken: Two existing tools are used and modified to generate input data: the *Load Profile Generator (LPG)* [7] by Dr. Noah Plugradt and the *Charge Profile Generator for e-Mobility (CPGeM)* [8] by Marian Sprünken, which is built on base of the *LPG.* The input data used for the two tools is based on the previous literature research. Using these two tools, a pool of 117 representative German mobility profiles, based on [8] is simulated. Based on the simulated mobility profiles, a simulation was conducted to determine the availability of the EVs. It is determined, at what time the household members are out-of-home with their vehicles and when they are at home. The assumption is made that vehicles are available for FCR when they are at home, are plugged in but are not charging. As a result, simultaneity factors (SF) are calculated for 15-minute time steps for the year 2022, to determine how many vehicles are available for FCR. In addition, a charging pattern is considered that simulates charging behavior to ensure sufficient SOC for mobility needs.

Basend on these reuslts, the required pool size is determined to provide the minimum offer quantity, considering the requirements and prequalification conditions of the German FCR market. In addition to the minimum offer quantity, the uncertainty over a year is simulated and resolved. The economic feasibility is then examined, and potential revenues are calculated that could have been generated with a pool of 500 vehicles in 2022. Furthermore, an analysis is performed on the reduction of time slots and a different charging pattern. Figure 10 shows the framework of the thesis.

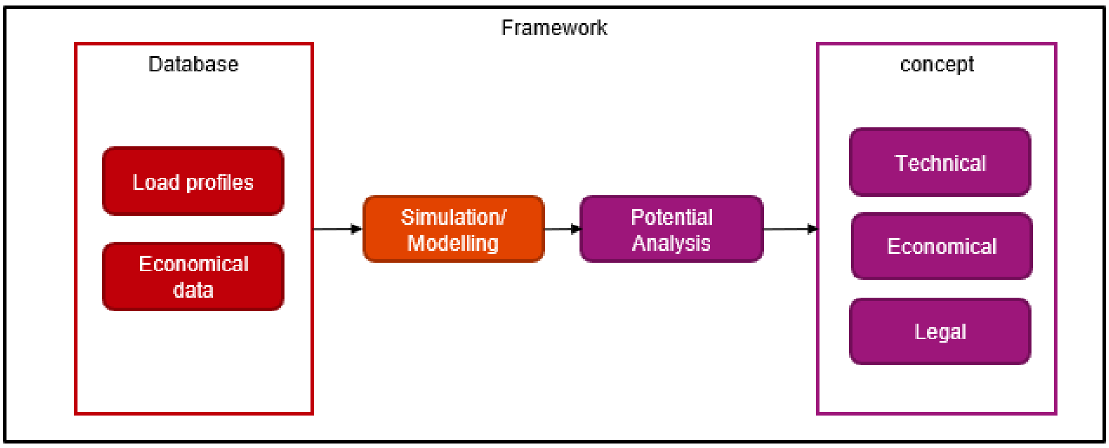

Figure 10 Schematic structure of the thesis (Source: own illustration).

The investigation of the availability on the basis of simulated, private EVs has not yet been carried out in this form in the literature. What findings have been simulated by most of the reviewed literature, is the revenue per year per car. In order to make the results comparable, the annual turnover per car is also simulated. A pool of 500 vehicles is chosen as 100 is too small to meet the minimum bid amount.

To reach the minimum bid quantity, the decentralized aggregator model described in chapter 1.4.4 is selected [51].The aggregator has a certain number of vehicles under contract which he can activate if they allow to use their capacity for activation. The aggregated capacity is sold to the TSO [77]. The framework is shown in Figure 11.

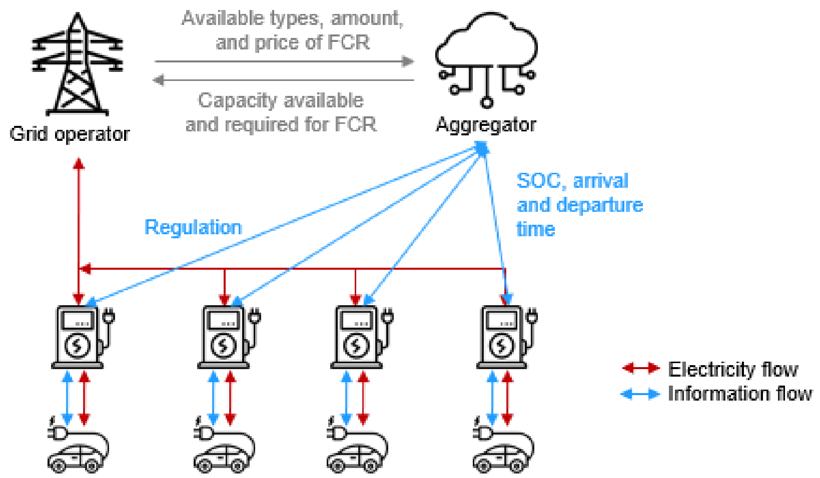

Figure 11 Decentralized framework. The vehicles are connected to the TSO collectively via an aggregator (Source: own illustration, based on [77]).

As described in chapter 1.3, the aggregator must provide at least 1.25 MW of capacity for each 4-hour time slice [11]. The aim is to offer this capacity with as few EVs as possible to increase the average payment per EV. To ensure the availability of enough power and capacity, the number of EVs is determined based on the time when the least number of EVs are available. Therefore, the model must calculate the available number of EVs for each time step. The minimum available capacity during each 4-hour time slice then determines the capacity that the aggregator can offer to the TSO as a reserve.

For a better understanding, figure 12 shows the principle [74]. The x-axis represents the time period, and the y-axis represents the SF, or how many EVs are available. A 4-hour period is depicted. The minimum SF in this example is 42%. Accordingly, only 42% of the total pool power can be offered throughout the entire 4-hour slot, even if more vehicles would be available during the other three hours.

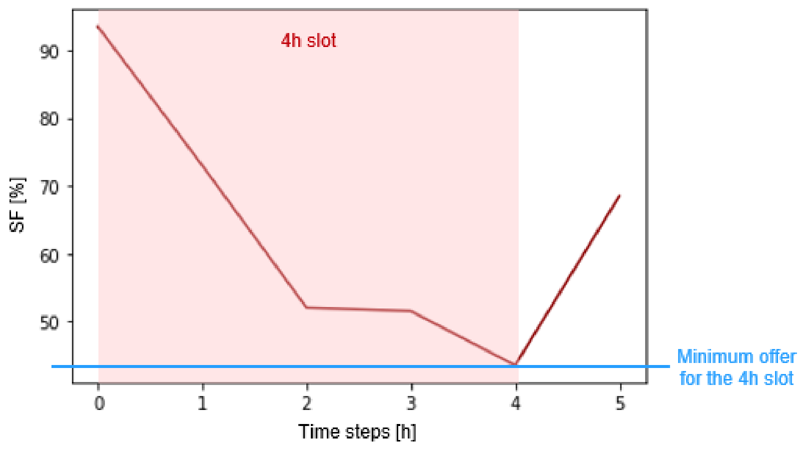

Figure 12 Presentation of the principle that the minimum availability determines the total availability for each 4h time slot (Source: own illustration, based on [74]).

Thus, household profiles are generated in the *LPG*, as a base for the charging profiles which are generated with the *CPGeM*. For the simulation, 100 representative households are chosen, which are representative of the non-urban, village area, since [4] has shown that this type most often has its own parking space and does not park in the public street space. This is relevant, since only home charging at the private wallbox is taken into account, which doesn't require parking in the public parking lots. The script of the *CPGeM* was adapted, which is explained in detail in chapter 3.3.4.

It is assumed that each vehicle has its own bidirectional charging station at home with a charging and discharging power of 11 kW. This assumption is based on the literature research in chapter 1.4.1 that wallboxes available in Germany soon might be offered with 11 kW *CCS.* The average assumed capacity per vehicle is 60 kW. This value was chosen based on the findings in chapter 1.4.3 and corresponds to the *Nissan Leaf e+* [41]. This one of the few vehicles in 2023 that can charge bidirectionally. It is assumed that the vehicles are immediately connected to their wallboxes as soon as their driver arrives at home. This assumption is made because the revenues that can be generated by providing FCR, compensate the EV owners for the effort, to plug in the EV directly upon arrival.

To ensure that the main benefit of private vehicles, transportation [62], can still be guaranteed, a charging pattern is implemented in the simulation. Since studies have shown that vehicles in Germany are parked on average 95% of the day [4], a large part of the battery is usable for further use but it is still important to ensure that availability for transportation is guaranteed at all times. Therefore, the following charging pattern was implemented. As soon as the vehicle arrives at home, it is charged to 60%. The 60% was selected because within this SOC the everyday activities in the simulation can be fully covered. During this charging time, the EV is not available for FCR. Before it drives off, it is charged to 80%. The 80% was chosen because of two different circumstances:

First, the depth of discharge (DOD) has a significant impact on how long battery cells last. The DOD is the total charge applied throughout a cycle. In comparison to routine operation with 80% DOD cycles (meaning the battery is always kept between 10% and

90% charge level), complete full cycles (100% DOD) minimize the total allowable charge utilization by about 20%. The usual DOD for EV batteries ranges from 60% to over 90% [84].

Second, the charging speed decreases as the battery approaches full capacity. Therefore, manufacturers recommend charging the vehicle only up to 80% for regular use [85].

The charging time after an ooha is calculated with the *GPGeM*. It depends on the distance of the ooha [8]. The charging time, before leaving for the next ooha, is calculated as followed: Assuming a total capacity SOC_{Total} of 60 kWh per vehicle, a SOC of 60% ($SOC_{Maintaining}$) corresponds to 36 kWh. A SOC of 80% ($SOC_{Leaving}$) corresponds to 48 kWh. Accordingly, 12 kWh still need to be recharged. With a charging power of 11 kW, the charging time $t_{charging}$ is calculated in equation 1.

$$t_{charging} = \frac{\Delta SOC_{Leaving-Maintaining}}{P_{charging}}$$

$$\begin{aligned} SOC_{Total} &= 100\% = 60\ kW \\ SOC_{Leaving} &= 80\% = 48\ kWh \\ SOC_{Maintaining} &= 60\% \ = 36\ kWh \\ \Delta SOC_{Leaving-Maintaining} &= 48\ kWh - 36\ kWh = 12\ kWh \\ P_{charging} &= 11\ kW \end{aligned} \tag{1}$$

$$t_{charging} = \frac{12\ kWh}{11\ kW} = 1.1\ h$$

Accordingly, 1.1 hours are blocked from each departure time, during which the vehicle is not available for FCR but is being charged.

Meanwhile, while the vehicle is parked at home, it is available for FCR. FCR must be offered in parallel amounts [13]. Since the positive and negative flows usually balance out over time, it is assumed that the SOC remains at a constant level within this range, and the power flows from FCR almost cancel each other out due to the expected almost symmetrical calls [77]. Figure 13 shows the charging behavior [79]. When the EV arrives home with a low SOC after the out-of-home activity (ooha) it is plugged in and charged to 60% (not available). It is then available for FCR (available). 1.1h before it leaves, it charges to 80% SOC (not available).

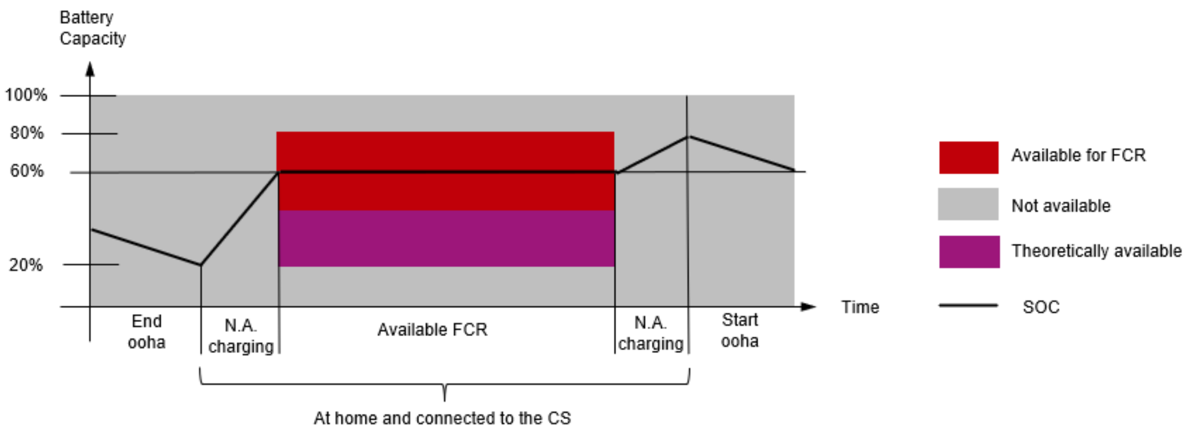

Figure 13 Schematic representation of the charging pattern from arrival at home, through charging, provision of FCR and departure (Source: own illustration, based on [79]).

The aim of the simulation is to determine how many vehicles are simultaneously at home, plugged in and can be used to provide FCR. To do this, it is important to identify how many vehicles it will take to provide 1.25 MW.

In equation 2, the amount of energy $E_{available}$ per vehicle that can be used for FCR is determined. The total capacity SOC_{Total} is 60 kWh. The gray area above 80% SOC $(SOC_{upperLimit})$ and below 20% $(SOC_{lowerLimit})$ is not usable. The $SOC_{Maintaining}$ of 60% SOC is marked in red. The differences between the $SOC_{Maintaining}$, and the upper and lower limits are usable. Since the supply must be symmetrical [13], the side with the lower usable quantity determines the total quantity.

$$SOC_{Total} = 100\% = 60\ kW$$
$$SOC_{upperLimit} = 80\% = 48\ kWh$$
$$SOC_{lowerLimit} = 20\% = 12\ kWh$$
$$SOC_{Maintaining} = 60\% = 36\ kWh$$

(2)

$$\Delta SOC_{upperLimit-Maintaining} = 48\ kWh - 36\ kWh = 12\ kWh$$
$$\Delta SOC_{upperLimit-Maintaining} = 36\ kWh - 12\ kWh = 24\ kWh$$

$$E_{available} = 2 * 12\ kWh = 24\ kWh$$

Figure 14 shows the EVs battery schematically [79].

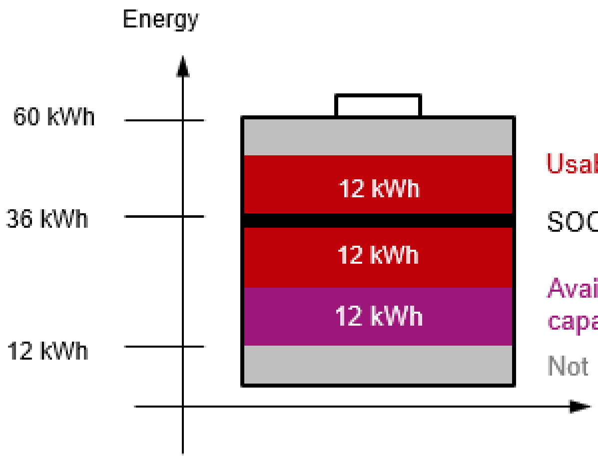

Figure 14 Usable battery capacity for FCR of one vehicle with a 60 kWh battery (Source: own illustration, based on [79]).

Thus, per EV with a capacity of 60 kWh, 24 kWh can be used for FCR. If the SOC limit is extended to 90% or a larger battery is used, then even more capacity can be used. In chapter 1.3, the requirement was found out that 0.83 MWh capacity must be kept available per MW power offered [11]. Extrapolated with 11 kW power and 12 kWh capacity in one direction per EV, this condition is fulfilled.

There are limiting factors for providing FCR, which can be the following [79]:

- the charging power of the wallbox or the EV
- the useable capacity of the battery
- the connected time

For the simulation, bidirectional charging is assumed, which is a prerequisite for the provision of FCR. Equation 3 [79] calculates the minimum power that determines the limiting factor $P_{Limitation}$. Here P_{EV} stands for the power of the EV, P_{CS} is the power of the wallbox, $E_{available}$ is the available battery capacity and $t_{charging}$is the connected time of the EV.

$$
\begin{gathered}
P_{Limitation}(t) = \left\{ min \frac{E_{Battery,usable}(t)}{t_{charging}}; P_{EV}; P_{CS} \right\} \\
P_{EV} = 11\ kW \\
P_{CS} = 11\ kW \\
E_{Battery} = 60\ kWh \\
E_{available} = 12\ kWh * 2 = 24\ kWh \\
t_{charging} = 15\,\mathrm{min} = 0{,}25h \\
P_{Limitation} = \left\{ min \frac{24\ kWh}{0{,}25h}; 11\ kW; 11\ kW \right\} \\
= min\{96\ kW; 11\ kW; 11\ kW\}
\end{gathered} \tag{3}
$$

The minimum is 11 kW, so therefore the limiting factor is the charging power of the EV and the charging station. In equation 4, the minimum required number of vehicles in the pool is calculated.

1. The maximum power P_{max} is equal to the number of vehicles N_v multiplied by the charging or discharging power $P_{charging}$.

$$P_{max} = N_v * P_{charging} \tag{4.1}$$

2. The maximum power must be equal to at least 1.25 MW to guarantee the 25% buffer.

$$P_{max} \geq 1.25\, MW \tag{4.2}$$

3. With the charging or discharging power $P_c = 11$ kW (0.011 MW), the required number of vehicles can be calculated as follows.

$$N_v = \frac{P_{max}}{Pcharging} = \frac{1{,}25\, MW}{0{,}011\, MW} = 114 \tag{4.3}$$

4. With a buffer B = 10% the minimum vehicle quantity is 126 vehicles.

$$N_{v,min} = N_v * B = 113 * 1{,}1 = 126 \tag{4.4}$$

This formula is used to determine the required pool size with the simulation results in order to be able to provide minimum supply quantity for 4-hour time slots. Also, the SF of available EVs is examined on a weekly basis to determine the median values, the deviations, and the uncertainty. To investigate the economic viability, potential revenues are calculated that could have been achieved with a pool of 500 vehicles in 2022. Furthermore, an analysis of the reduction of the supply size as well as the influence of a different charging pattern is performed.

To calculate the revenues, the following method based on [79] is used. The first step is to determine the required SF per timestep. Once the SF has been determined, it is multiplied by the charge/discharge power of 11 kW. Since the pool contains only 100 vehicles so far, it must be extrapolated to 500, by multiplying the calculated power with 5. To ensure a buffer of 25%, the extrapolated value is divided by the factor 1.25. To enable complete bids, the calculated value is rounded down to 1 MW. Once the storage capacity has been determined, it can be used to calculate potential revenues. To do this, the available offering power in MW is multiplied by the revenue value per time slice. The revenues for all time slices are then summed up to calculate the annual revenues.

focus of the thesis is on the potential availability of private vehicles and an estimation of their potential. Therefore, there are limitations and restrictions that have been made. The assumption that EVs are always plug in when they are at home is based on the motivation of drivers to receive revenue for their readiness. Furthermore, only pure battery electric vehicles are considered in the simulation, and bidirectional charging infrastructure is assumed, which is not available for private individuals nowdays. In addition, the evaluation of economic potentials does not include distribution network-related restrictions, taxes or other payments. Also not considered are legal issues regarding warranties and liability if the vehicle battery is *misused.* Additionally, costs such as the financial additional cost for new wallboxes for EV owners or costs due to battery wear are not considered.

3.2 Database

The following chapter is divided into the chapters *Mobility data* and *Economical data*. The chapter *Mobility data* describes the *LPG* by Dr. Noah Pflugradt [7] and *CPGeM* by Marian Sprünken [8], which were used to simulate the mobility data. The chapter *Economical data* describes the economic data used for the revenues which were possible to generate with FCR in 2022 in Germany.

3.2.1 Mobility data

The *CPGeM* is used to generate the driving profiles. The *CPGeM* is based on the output of the *LPG*. The generated profiles are used as input for the simulation. They are used to simulate the driving behavior of the EV owners and households. This results in the availability and the grid connection of the EVs via their wallbox at home.

3.2.1.1 Load profile generator (LPG)

The *CPGeM* (chapter 3.2.1.2) builds on the *LPG* by Noah Pflugradt. The *LPG* is a tool for modeling household energy consumption. It is a tool for creating synthetic load profiles for households. The household profiles can be resolved every minute or every quarter of an hour. A household is composed of one or more household members. A specific list of activities has been assigned to each member. There are 60 predefined German households but it's also possible to define an own household with the list of activities. Activities include for example taking a shower or watching TV. Therefore, the required amount of electricity, hot and cold water is simulated. In summary, synthetic load profiles can be created with the LPG, in which the load profiles of all household consumers are listed. In addition, it is possible to identify at what time which persons were out of the house and which out-of-home activities were performed. This aspect is particularly relevant to the thesis, as it is based on which EV is home and which is not. The output are csv files and additionally various different reports like thoughts of the household members. The thoughts can be used to determine which activity the simulated person is performing at the simulated time. The *LPG* is available on https://www.loadprofilegenerator.de/ and free of charge [7].

3.2.1.2 Charge Profile Generator e-Mobility (CPGeM)

The *GPGeM* was created by Marian Sprünken as a result of his master's thesis. The aim of the thesis was to develop a *Charge Profile Generator for e-Mobility (CPGeM),* which can create unique load profiles for e-mobility. The *CPGeM* is based on the *LPG* by Noah Pflugradt [7], which is discussed in chapter 3.2.1.1. The *CPGeM* may generate distinct load profiles for families and their members using a behavior model. Based on these characteristics, e-mobility charging profiles that are synchronized with simulated household load profiles are generated. Moreover, information from the *Mobility in Germany* (MiD2017) [4] research was used in the *CPGeM's* creation, which analyzed the mobility behavior of various household types in different regions of Germany. The *CPGeM* creates charging profiles based on the actions of the household members after classifying homes based on their mobility behavior based on the findings of this study. Distances traveled, the EVs' predetermined energy consumption levels, and the typical household EV use are included in this. The *CPGeM* uses a variety of input characteristics, including the share of EVs, the diverse charging habits of homes, the average battery capacity of EVs, and the average usage of the household EV, to generate synthetic charging profiles. While Python is used to implement the *CPGeM*, Excel and csv files are used to manage the data [8].

The structure of the folder is shown in Figure 15 [8].

csv_output	16.10.2022 17:41	Dateiordner	
diagramms	11.02.2022 14:04	Dateiordner	
haushaltsprofile	20.12.2022 20:19	Dateiordner	
member_profiles	20.12.2022 20:38	Dateiordner	
13122021_CPGeM_SoCSimulation	21.12.2022 13:31	Python File	69 KB
14122021_CPGeM_MobilityBehavior	21.12.2022 13:31	Python File	111 KB
capacity_and_consumption	21.12.2022 13:31	Microsoft Excel-C...	7 KB
dynamic_out_of_home_activities	21.12.2022 13:31	Microsoft Excel-C...	2 KB
INPUT_Parameter	21.12.2022 13:31	Microsoft Excel-A...	34 KB
out_of_home_activities	21.12.2022 13:31	Microsoft Excel-C...	4 KB
static_out_of_home_activities	21.12.2022 13:31	Microsoft Excel-C...	2 KB

Figure 15 Structure of the CPGeM folder (Source: [8]).

The *CPGeM* consists of two Python files. In the first script *CPGeM_MobilityBehavior* the mobility behavior is simulated, while in the second script *CPGeM_SoCSimulation* synthetic charging profiles are simulated using the mobility behavior and the household profiles. The generated profiles from the *LPG* are stored in the folders *household profiles* and *member_profiles* as described in the instruction. The csv files *dynamic_out_of_home_activities*, *out_of_home_activities* and *static_out_of_home_activities* are also generated from the *LPG* [8].

The *CPGeM* is designed so that different scenarios can be created using various input parameters in the Excel file *INPUT_Parameter*. The first part allows the user to set the region type and the mobility behavior of households. The second part involves setting the average battery capacity, wallbox power, and charging behavior of household members. Additionally, a wallbox power can be specified, and the charging behavior of household members can be defined using five input parameter [8].

The Excel file *Capacity_and_consumption* provides an overview of the EVs in the simulation and their capacity and consumption data [8].

The structure of the *CPGeM_MobilityBehavior* script works as follows: First, the csv files are read in, including the generated csv files from the LPG, csv files with out-of-home activities, and the input parameter Excel file. Then, important information is sorted, and households are categorized based on their characteristics. EVs are assigned based on household properties, and daily distances are calculated, with the average daily distances being allocated to household members. Then, the routes are assigned for each out-of-home activity. After simulating mobility behavior, the files are outputted, with csv files always being saved. In order to generate output diagrams, a confirmation must be made in the input Excel file before the simulation [8].

The Python File *CPGeM_SoCSimulation* is structured as follows: First, the csv files that were previously generated are read in. The *overview_member_ooha* dictionary is created from the imported csv files, which lists all out-of-home activities, including all household member information. Then, parameters are processed, and wallboxes and EVs are assigned. The SOC is then calculated: every minute, it is checked whether an out-of-home activity is taking place at that time. Once the algorithm finds an out-of-home activity, consumption is calculated based on the distance traveled and subtracted from the SOC. After the out-of-home activity is completed, it is decided again whether the electric vehicle should be charged. Then, the household profiles are summed with the charging profiles. The results generated by the script are three diagrams and two csv files. The Python file *CPGeM SoC Simulation* was adapted for this master thesis, which is described in chapter 3.3.4. Figure 16 shows the structure of the *CPGeM* [8].

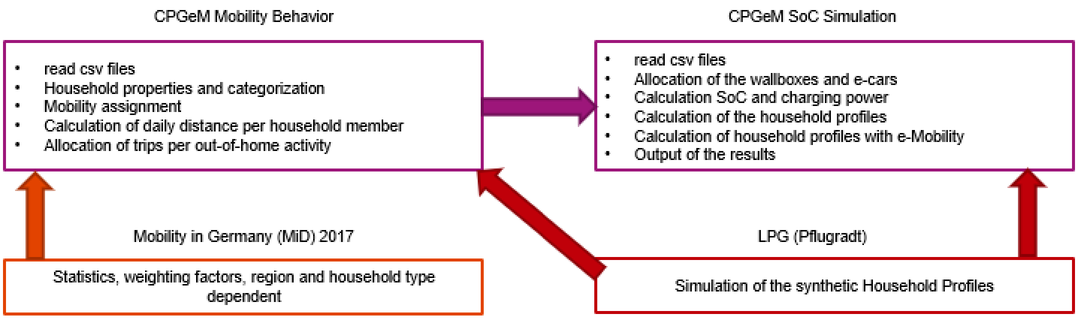

Figure 16 Overview of the CPGeM: Connection between CPGeM Mobility Bevavior, CPGeM SoC Simulation, MiD 2017 and LPG, (Source: own illustration, based on [8]).

3.2.2 Economical data

The simulation considers different historical market prices and demands of FCR for each 4-hour time slot of the year 2022. These data serve as input to the model, and chapter 1.2.3 explains in detail how the FCR tendering process works. The daily FCR auctions' results are published by the TSOs in the form of anonymous bid lists on their website [22]. These lists contain only the winning bids, while the offers of bidders whose units are above the limit price are not published. The data used in the model is historical data, meaning that the generated profits and energy transactions made are theoretically possible if EVs had been on the market. The pay-as-cleared principle is followed in this process, and the revenue value for each time slice is taken from the website and stored. A visual overview of the results of bid lists for FCR in 2022 with the maximum and minimum per 4-hour time slot is provided in the figure 19. The data used in the simulation can be found in the digital appendix and are named *resultsFCR2022.xlsx.*

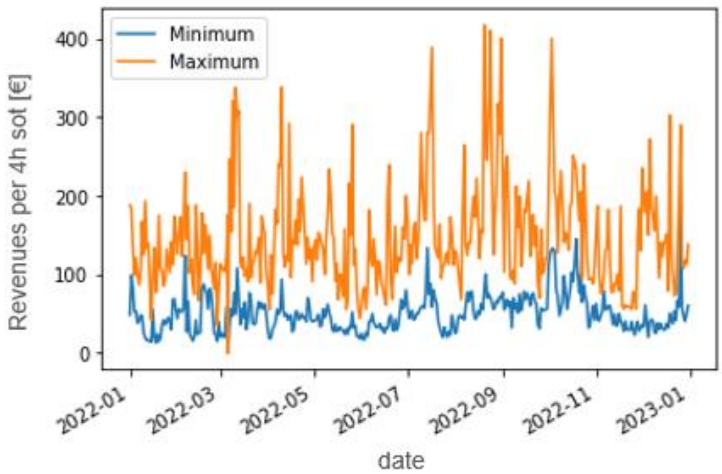

Figure 17 Results of bid lists for FCR in 2022. Maximum and minimum per 4-hour time slot (Source: own illustration, data from [22]).

Forecasts are hard to tell but analysis platforms expect similar FCR revenues per MW in 2023 as in 2022 [86].

3.3 Simulation

The simulation is used to determine simultaneity factors per time step, when the vehicles are at home and available to provide FRC. The simulation is done using the LPG [7], Python, VBA and Excel. First, household profiles and charging profiles are generated with the *LPG* [7]. Then the *CPGeM* [8] of Marian Sprünken is used and further modified and developed. The results are exported to an Excel file *Planned_charging.xlsm* with multiple worksheets and macros for formatting and filtering. Subsequently, a Python script *Calculation_of_SF.py*, which was newly created within the scope of the master thesis, reads in the formatted spreadsheets, and determines a SF for each time step. With these results, plots are created, and an evaluation is done: the required EVs to provide FCR are calculated and the economic efficiency is determined. In addition, analyses are carried out to determine the impact of reducing the time slices and to change the charging pattern.

Figure 18 provides an overview and serves as an overview of this chapter.

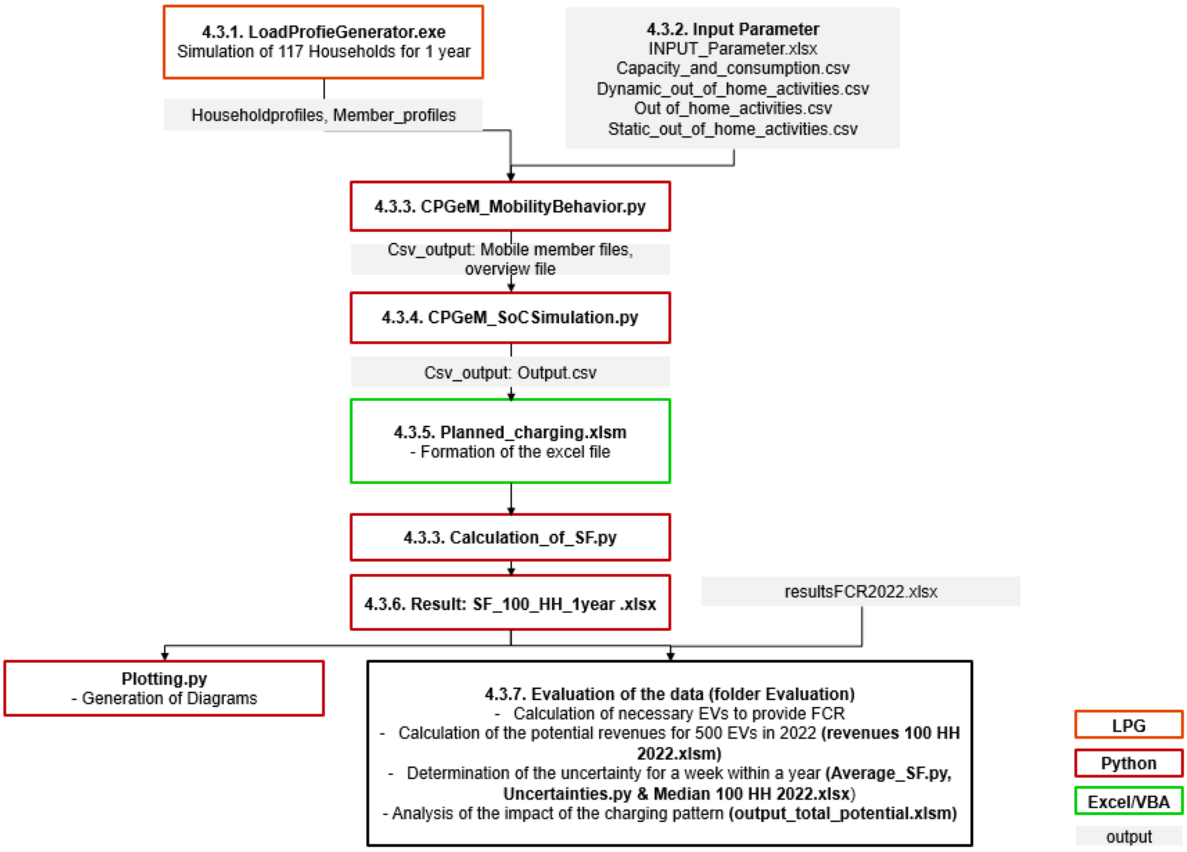

Figure 18 Stucture of the Simulation, including all input and output data, tools and file names (Source: own illustration, based on [8]).

The folder structure of the thesis is shown in figure 19. The files and folders highlighted in red were newly created as part of the master thesis. The green files were used from [8] but modified in this thesis. The files and folders that are not colored were used from [8] without modification.

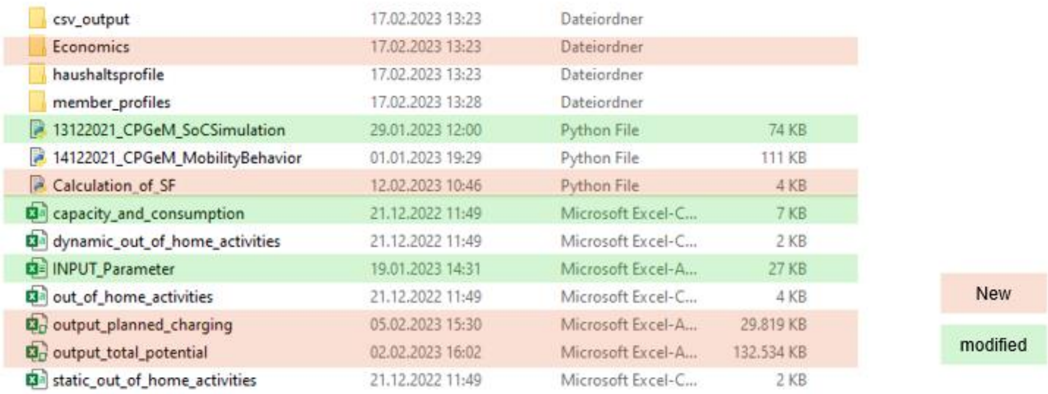

Figure 19 Structure of the modified CPGeM folder. The differences between adopted parts from [8] and own work are marked in different colors (Source: based on [8]).

3.3.1 LoadProfileGenerator

To ensure that the results are representative for Germany, new profiles were simulated with the *LPG*, but the number and distribution were taken from [8]. Analogous to [8], 117 households were simulated with the LPG. The simulation took place over 52 weeks, from 03.01.2022 to 01.01.2023. The period was chosen in order to be able to map complete weeks (Monday - Sunday). With the help of the 117 households, it is possible to simulate a representative network for each of the seven region types. For the thesis household shares of RT2.3 in table 4 were used. Table 4 was taken from [8] and shows the respective share of household categories in the network regions. The household pool also consists of 12 different modular households “CHR04, CHR08, CHR07, CHR27, CHS04, CHR60, CHR55, CHR18, CHR39, CHR35, CHR51, CHR31” [8]. The resulting *Thoughts* files of the household members were stored in the folder *member_profiles*, the resulting files for the electricity consumption profiles in the folder *haushaltsprofile (German for household profiles)* [8]. The thoughts can be used to determine which activity each household member is performing at the simulated time. The thoughts will serve in the simulation to determine when a person performs an ooha.

Furthermore, a *test pool* with 25 households was simulated. This pool was used once to test the functionality of the scripts to increase the speed due to the smaller amount of data. Furthermore, it was used to investigate the analysis of the charging pattern. The test pool consists of the same households only in smaller numbers. For the test pool also only one week was simulated, the period from 03.01.2022 - 09.01.2022.

HH category	**RT1.1**	**RT1.2**	**RT1.3**	**RT1.4**	**RT2.1**	**RT2.2**	**RT2.3**
Young HH age <35 years	11%	11%	6%	4%	6%	4%	4%
HH only adults	36%	34%	32%	31%	32%	33%	36%
HH in age >65 years	34%	37%	40%	41%	45%	42%	38%
Family HH with at least one child	18%	17%	21%	23%	16%	19%	22%

Table 4 Household shares in the seven different region types [8].

3.3.2 Input Parameter

The input parameters which are entered in the *CPGeM* are shown in Figure 20:

Input Parameter für die simulation des Mobilitätsverhalten		
Region	region_type_city	small town, village area
Mobility behaviour	MiT2017	0
coverage_rate_1car (D_{car1})	1	
coverage_rate_2car (D_{car2})	0	
electrification_ratio (e_r)	1	

Input Parameter für die simulation der Ladeprofile		
average battery capacity	60	*Das Minimum ist auf 17 k*
sigma battery capacity	10	*Für jedes mobile Haushalt.*
Wallbox power	11	*Als Wallbox Ladeleistung k*
	state of charge [%]	charging probability [%]
charging decision soc greater t	60	0
charging decision between		100
charging decision soc smaller t	60	100

Figure 20 Input Parameter of the CPGeM (Source: [8]).

For the input of the mobility behavior, the option *MiT2017 is* chosen. Since this simulation is only about households with electric vehicles, only households that own an EV are relevant. Accordingly, the coverage rate, as well as the electrification rate, is set to 1 to avoid generating unneeded households without an electric vehicle in the simulation. For the input parameters for the simulation of the charging profiles, the average battery capacity is set to 60 kWh. The wallbox power is 11 kW and the decision from when to charge is 100% once it is below 60% SOC (according to chapter 3.1).

3.3.3 CPGeM MobilityBehavior

To determine the mobility behavior, the script is executed unchanged. In the script, the input csv files are read in, household properties and categorization are performed, and the assignment of mobility behavior is carried out. Also, the calculation of the daily distance per household member and an assignment of trips per non-domestic activity is performed.

3.3.4 GPGeM SoCSimulation

In the script *CPGeM_SoCSimulation*, the charging behavior is adjusted. As seen in the previous case, a charging decision was made as soon as the vehicle ended an ooha. If the vehicle meets an SOC according to the input parameters, it is decided to charge the vehicle up to 100%. In the thesis, the script was modified so that the vehicle is always charged up to an SOC of 60% only. Figure 21 shows the charging behavior: when a vehicle performs an ooha, the SOC decreases to a new value determined by the performed ooha. When the vehicle arrives home, the SOC status is queried. If the charge level is greater than 60%, no charging occurs. If the SOC is less than 60%, it will be charged up to 60% SOC.

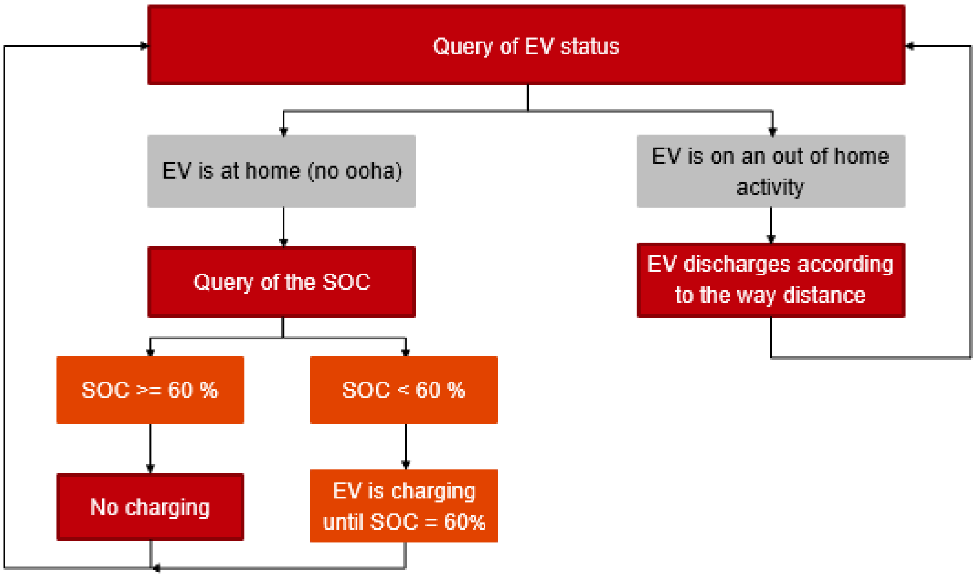

Figure 21 Modified Script Sequence of the file *GPGeM SOCSimulation* (Source: own illustration, structure is based on [76] and data is based on [8]).

Subsequently, new csv files will be generated with contents that are relevant for the calculation in the simulation. First, auxiliary files will be generated per household, which will be created in the *SOC_and_power_files* folder. These will then be combined into a summary csv file called *output.csv,* which will be stored in the *csv_output* folder. The *output.csv* file will be formatted in the next step.

3.3.5 Output Planned Charging

The goal of formatting is to specify how many vehicles are available for FCR per time step. For this purpose, it is necessary to determine per time step when vehicles are at home, when they are charging and what SOC they have. Since these data cannot be taken from the *CPGeM* in this form, a formatting is carried out with the help of macros in order to bring the data into the desired form. For this *output.csv* is loaded into the Excel workbook *output_planned_charging*. Here, the resulting *output.csv* file is opened in the workbook and the macros are executed on worksheet 1 in sequence. The result is a formatted Excel spreadsheet that results for each time step on a 15-minute basis whether a vehicle is available for FCR deployment. For a better understanding, the results look like showed in figure 22: Per 15-minute timestep is specified, weather an EV is available (=at home, plugged in, not charging) or not available (=either out of home or at home, plugged in but charging).

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1														
2	Time as integer	Date	Time	HH04	HH07	HH10	HH11	HH16	HH22	HH43	HH53	HH54	HH55	HH73
3	1609714800	Montag, 4. Januar 2021	00:00:00	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome
4	1609715700	Montag, 4. Januar 2021	00:15:00	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome
5	1609716600	Montag, 4. Januar 2021	00:30:00	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome
6	1609717500	Montag, 4. Januar 2021	00:45:00	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome
7	1609718400	Montag, 4. Januar 2021	01:00:00	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome
8	1609719300	Montag, 4. Januar 2021	01:15:00	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome
9	1609720200	Montag, 4. Januar 2021	01:30:00	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome
10	1609721100	Montag, 4. Januar 2021	01:45:00	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome
11	1609722000	Montag, 4. Januar 2021	02:00:00	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome
12	1609722900	Montag, 4. Januar 2021	02:15:00	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome
13	1609723800	Montag, 4. Januar 2021	02:30:00	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome
14	1609724700	Montag, 4. Januar 2021	02:45:00	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome
15	1609725600	Montag, 4. Januar 2021	03:00:00	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome
16	1609726500	Montag, 4. Januar 2021	03:15:00	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome
17	1609727400	Montag, 4. Januar 2021	03:30:00	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome
18	1609728300	Montag, 4. Januar 2021	03:45:00	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome
19	1609729200	Montag, 4. Januar 2021	04:00:00	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome
20	1609730100	Montag, 4. Januar 2021	04:15:00	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome
21	1609731000	Montag, 4. Januar 2021	04:30:00	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome
22	1609731900	Montag, 4. Januar 2021	04:45:00	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome
23	1609732800	Montag, 4. Januar 2021	05:00:00	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome
24	1609733700	Montag, 4. Januar 2021	05:15:00	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome
25	1609734600	Montag, 4. Januar 2021	05:30:00	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome
26	1609735500	Montag, 4. Januar 2021	05:45:00	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome
27	1609736400	Montag, 4. Januar 2021	06:00:00	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome
28	1609737300	Montag, 4. Januar 2021	06:15:00	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome
29	1609738200	Montag, 4. Januar 2021	06:30:00	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome
30	1609739100	Montag, 4. Januar 2021	06:45:00	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome
31	1609740000	Montag, 4. Januar 2021	07:00:00	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome
32	1609740900	Montag, 4. Januar 2021	07:15:00	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome
33	1609741800	Montag, 4. Januar 2021	07:30:00	notHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome
34	1609742700	Montag, 4. Januar 2021	07:45:00	notHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome	atHome
35	1609743600	Montag, 4. Januar 2021	08:00:00	notHome	notHome	atHome	atHome	notHome	atHome	atHome	atHome	atHome	atHome	atHome
36	1609744500	Montag, 4. Januar 2021	08:15:00	notHome	notHome	atHome	atHome	notHome	atHome	notHome	atHome	notHome	atHome	atHome
37	1609745400	Montag, 4. Januar 2021	08:30:00	notHome	notHome	atHome	atHome	notHome	atHome	notHome	notHome	notHome	atHome	atHome
38	1609746300	Montag, 4. Januar 2021	08:45:00	notHome	notHome	notHome	notHome	notHome	atHome	notHome	notHome	notHome	atHome	atHome
39	1609747200	Montag, 4. Januar 2021	09:00:00	notHome	notHome	notHome	notHome	notHome	atHome	notHome	notHome	notHome	notHome	atHome

Figure 22 result sheet of the Excel file output_planned_charging.csv after using different macros for formatting (Source: own illustration).

The functionality of the macros and formatting is described in the following and can be found in detail in the digital appendix in the *neuCPGeM* folder in file *output_planned_charging.xlsm*.

The file contains six workbooks: *description and macros, output, outputResult, HomeAndNotCharging, Results and SOC.* Firstly, the csv file *output* in the folder *csv_output* is loaded into an empty spreadsheet. Then, the macros are executed in sequence, and the remaining empty worksheets are filled automatically. An overview of the macros is illustrated in figure 23.

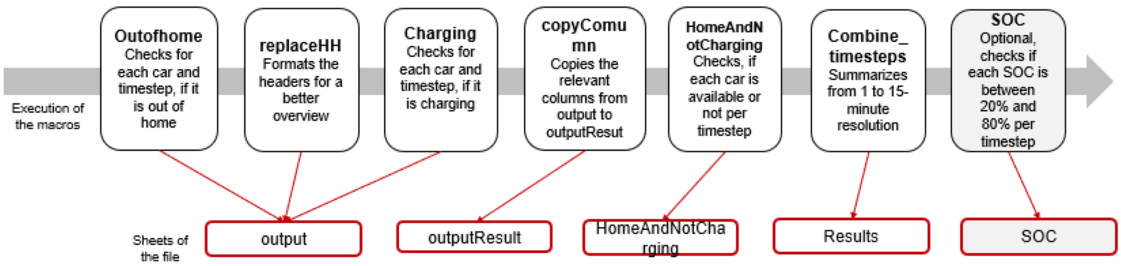

figure 23 overview of the macros and sheets in the file output_planned_charging.xlsm to format the file (Source: own illustration).

The worksheet *output* is exported from *GPGeM* and contains all households in the simulation. Column 1 contains the timestep as an integer. Column 2 contains the household number. Each household is described in 7 columns. They show the household number, when an out-of-home activity takes place, the charging power and the SOC.

The macro *outofhome* formats the columns in the *output* sheet, so that it is determined, at which timesteps exactly an EV is out of home.

Currently, the household number is only listed in the rows but not in the column headers. The macro *replaceHH* writes the household number in the respective column header for the sake of clarity in the output sheet.

The macro *charging* blocks 65 timesteps (1.1 hours) before the next out-of-home activity. This means that in column 5, which already indicates whether the EV is out-of-home, it also shows when the EV is being charged.

Now, the *outputResult* sheet is created. For each household, columns *charging/outof-home, charging power and SOC* are taken and copied to the new sheet by *copyColumn* macro.

The macro *HomeAndNotCharging* fills the *HomeAndNotCharging* sheet. The household numbers and timesteps are taken from the *outputResults* sheet. Then it checks whether a vehicle is available or not.

In the *15 Min resolution* sheet, the previous minute-by-minute resolution is summarized into a 15-minute resolution by *combine_timesteps* macro.

The *SOC* macro is optional and serves to check whether the SOC is between 20% & 80%. Since the charging behavior is planned so that the vehicle charges directly upon arrival to 60% and can only be used for FCR after that, this case should not occur and is only for checking. Since the case has never occurred in the simulations for computational capacity reasons, the macro can be optionally ignored, but is included for completeness.

3.3.6 Results SF

The script *Calculation_of_SF* determines the simultaneity factor at which the 100 EVs are available for the provision of FCR for each 15-minute, 1-hour and 4-hour interval. For the 1- and 4-hour interval, the minimum value of the 15-minute interval is always decisive. Figure 24 shows an example of the data frame of the total power. The index shows the 15-minute time steps.

dfGesamtleistung - DataFrame

Time	SF	Pgesamt	Minimum4h	Minimum1h
2022-11-07 04:00:00	100	100	60	100
2022-11-07 04:15:00	100	100	60	100
2022-11-07 04:30:00	100	100	60	100
2022-11-07 04:45:00	100	100	60	100
2022-11-07 05:00:00	100	100	60	100
2022-11-07 05:15:00	100	100	60	100
2022-11-07 05:30:00	100	100	60	100
2022-11-07 05:45:00	100	100	60	100
2022-11-07 06:00:00	100	100	60	90
2022-11-07 06:15:00	90	90	60	90
2022-11-07 06:30:00	90	90	60	90
2022-11-07 06:45:00	90	90	60	90
2022-11-07 07:00:00	90	90	60	60
2022-11-07 07:15:00	90	90	60	60
2022-11-07 07:30:00	70	70	60	60
2022-11-07 07:45:00	60	60	60	60

Figure 24 Part of the Python simulation Calculation_of_SF to determine the minimum SF per interval (Source: own illustration).

The SF column contains the simultaneity factors on a 15-minute basis. The *Minimum4h* column contains the minimum value for the entire 4-hour interval. This means that only the value 60 is assigned to the entire interval. Similarly, the same applies to the *Minimum1h* column, which assigns the minimum value on a 15-minute basis to each 1-hour interval. The columns of the Dataframe with the respective time steps as the index are plotted in diagrams and exported.

The result of the simulation are simultaneity factors and stored automatically in an output file called *SF.xlsx.* These will be further analyzed and evaluated in the subsequent steps.

3.3.7 Evaluation of the results

The simulation provides the SF as a result on a 15-minute basis. For a simulation with 100 households over a year, the results are evaluated and analyzed as follows:

Simultaneity factor for each 15-Minutes: The SF results per 4-hour, 1-hour, and 15-minute time slots for the year 2022 are analyzed. The SF is used to determine when and how many vehicles can be used for FCR and serves as the basis for further analysis. To provide an overview, the SF for a year, a month, and a week are displayed in a graph. The SF plotting calculation is performed in the script *SF_Calculation.py.*

Uncertainties: The result of the SF table is divided into 3 sheets: 4-hour, 1-hour and 15-time increments. To determine the uncertainty, the values are analyzed and broken down on a weekly basis. To display the values on a weekly basis, the *Median_SF* Python file is first executed. This reads the *SF.xlsx* and adds new worksheets where the SF is broken down to a weekly basis (called *Average*). Then the Python file *Uncertainties.py* is executed. The newly generated SFs on a weekly basis are read in, and a median is calculated for each time step. In addition, the 50th and 25th percentiles are calculated for each time step. The results are displayed in a diagram.

Calculation of the necessary vehicles to provide FCR for one year: To calculate the required number of vehicles to provide FCR, the minimum SF value is determined, which represents the minimum number of vehicles available simultaneously for FCR.

Financial Analysis: Calculation of revenue in 2022 with different pool sizes. In chapter 3.2.2, it was shown how much revenue could have been generated per 4-hour interval in 2022 through the provision of FCR. The revenues were combined with the call probabilities.

Analysis of the time slices: 4h vs. 1h vs. 15 minutes: This analysis examines the impact of decreasing the offer time slots to 1 hour or 15 minutes.

Impact of charging pattern: So far, it has been assumed that the EVs are not available while charging. This applies to the time after it arrives home and is charged to 60%, as well as the time before departure to charge it to 100%. With an improved charging pattern, the time can also be used to charge the vehicle according to the availability for FCR. Therefore, the analysis investigates how an increase in availability affects the SF. For a better understanding, figure 25 illustrates such a charging behavior. When the vehicle finishes its ooha, it is available for FCR until it sets off again. In the process, it is charged in line with the grid. Nevertheless, only a 20% - 80% range is available. The formatting and calculation are analogous to the calculation of the SF before, in the file output_smart_charging.xlsm. A detailed description can be found in the digital attachment in the file *output_total_potential.xlsm.* For the analysis of the impact of the charging pattern, the test pool with 25 vehicles, described in chapter 3.2.1, is used.

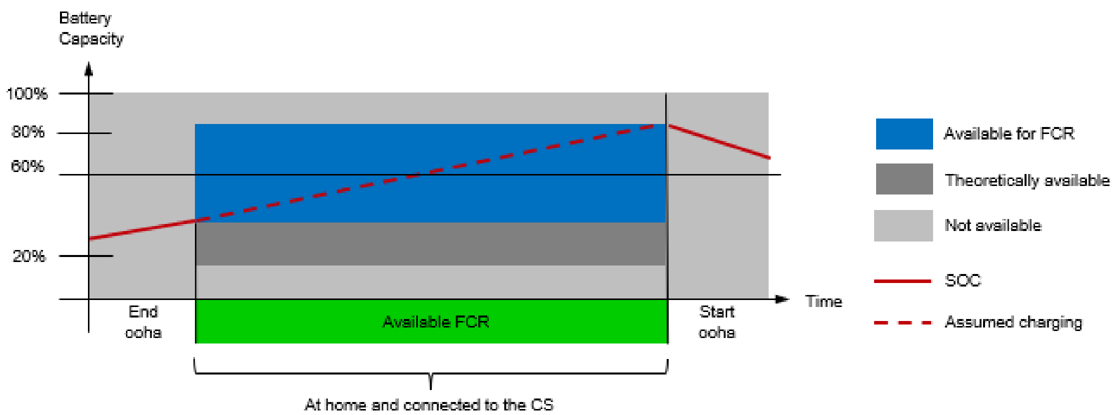

Figure 25 Schematic representation of the charging pattern from arrival at home, provision of FCR and departure with a modified charging pattern for an increased availability (Source: own illustration, based on [79])

4 Results and Discussion

In this chapter, the results are presented and discussed. First, the potential for private electric vehicles to provide FCR in Germany in 2022 was analyzed. Subsequently, these results were used to determine the potential revenue from providing FCR in the German market in 2022. An analysis of the reduction of time slots and changes in charging behavior was then conducted. Based on this analysis, a concept was developed for the economic, legal, and technical requirements under which private electric vehicles can offer FCR. Finally, the limitations of the study and the limits that have been reached are presented.

Out of the simulated 117 households, 100 households were used to represent coverage of small-town and rural areas. The simulation was conducted over 52 weeks (January 3, 2022 to January 1, 2023) from Monday to Sunday. The simulation using LPG included daylight saving time, which was not considered in the results, and the results were calculated for 52 weeks with 7 days and 24 hours each.

The simulation results are presented and analyzed here. The complete results can be found in the digital appendix in folder *Simulation 110 HH 1 year*. The data sets for 100 households and one year were too large for a single simulation, the steps were broken down into 2-month intervals for ten households each. Additionally, a test was conducted with 25 households. The results of this test can also be found in the digital appendix in folder *Simulation 25 HH 1 week.* Also, the whole simulation files, including the modified CPGeM can be found in the digital appendix in the folder *modifiedCPGeM.*

4.1 Potential analysis: Availability, revenues and uncertainty

In the following chapter, the theoretically available power based on the simultaneity factor is analyzed. As vehicles perform several out-of-home activities throughout the day, the available total pool power fluctuates.

4.1.1 SF 15-Minutes resolution for 1 year, 1 month and 1 week

For a first overview, Figure 26 shows the simultaneity factors of 100 households over one year, one month (January), and one week (January 3, 2022 to January 10, 2022). The resolution is done in 15-minute time steps.

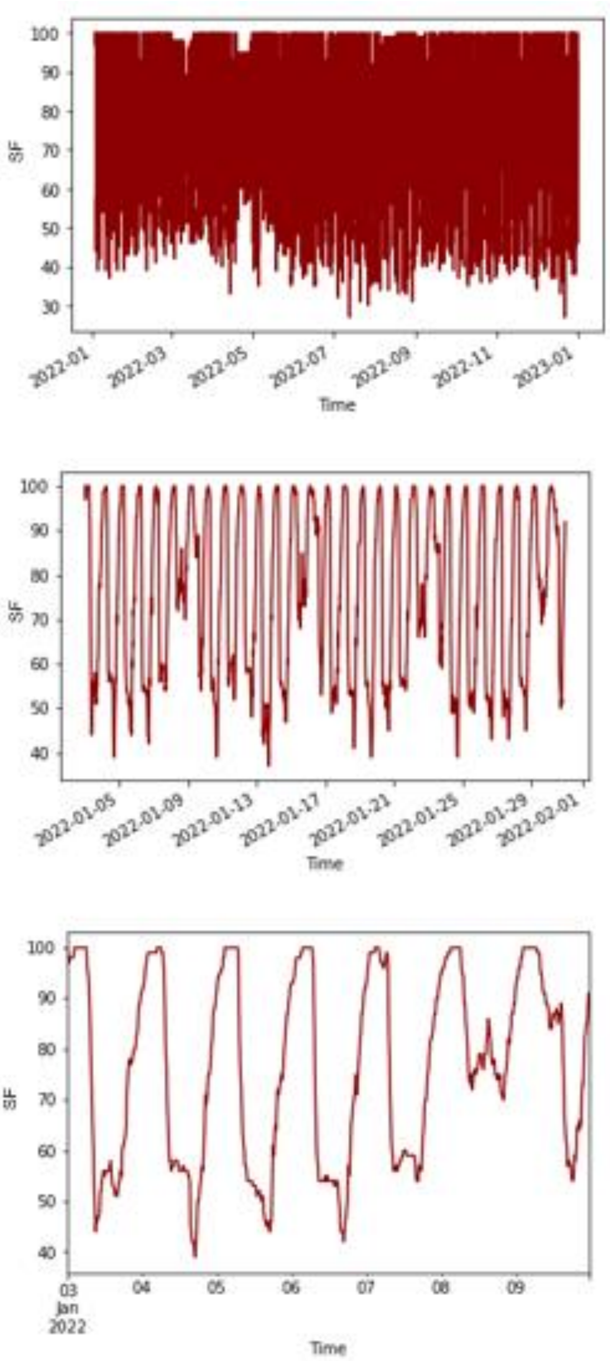

Figure 26 Overview of the SF in 15-Minutes resolution for 1 year, 1 month and 1 week (Source: own illustration).

Here, differences between weekends and weekdays as well as day and night can be observed. Over the course of the year, the nights (at the top of the diagram) are always covered with at least 95% availability. Throughout the day, minimum values of up to 24% are reached. A more detailed analysis is carried out in chapter 4.1.2.

The results can be found in the digital appendix, file *SF 100 HH 1 year.xlsm.*

4.1.2 Uncertainties: Days of the year over a period of one week

Figure 27 shows the days of the year (52 weeks) over a period of one week. The display starts at Monday 0:00 and ends on Sunday 23:59.

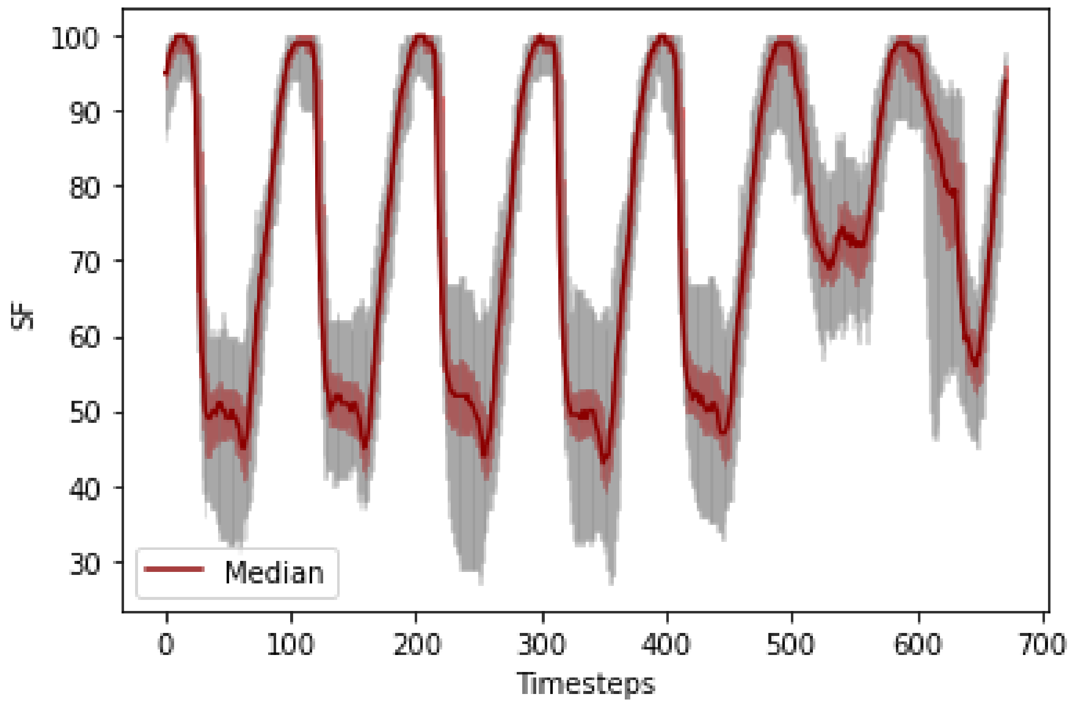

Figure 27 Graph of the simultaneity factors: 365 days of the year 2022 represented over a period of one week (Source: own illustration).

The dark red line in Figure 27 represents the median, and the light red shaded area shows the range where 50% of the values lie. The gray shaded area represents the full range of values. The availability fluctuates throughout the year, with a minimum SF of 24%. The median during the day on weekdays is around 50%, while the median during the day on weekends varies between 55% and 75%. The median during the night is around 95%. The SF is defined as the difference between the maximum and minimum SF within a certain period of time. Both profiles show higher uncertainty during the day than during the night.

As described in chapter 3.2.1 the household composition consists of households with only adults, as well as family households with children, young households, and households aged <65. These different household types exhibit different profiles. Nevertheless, many profiles represent household members working in a typical 9-5 job, which is indicated by the weekday spikes during the day. As the simulations cover complete years with the LPG, the deviations are relatively high. Many of the activities only occur several times a week, per month, or even only a few times a year. Thus, there are significant differences in the distribution. To mitigate the downward fluctuations, it is possible to selectively exclude vehicles with particularly high absence times. Due to the heterogeneous household profiles and different times, it is still possible to cover a large part.

The results can be found in the digital appendix and are called *Median 100 HH.xlsx.*

4.1.3 Calculation of the required vehicles to provide FCR

As the minimum number of available vehicles determines the total available power for FCR provision, the next step is to investigate how many vehicles are required in a pool to reliably provide the minimum offer size of 1.25 MW. The simulation with 100 vehicles was extrapolated for these calculations.

Scenario 1 describes being able to provide FCR all year, i.e., 8760 hours. Within this year, the minimum value reached is 24%. The required number $N_{required}$ of vehicles in the pool is calculated to have a sufficient amount of EVs at all the time. The power $P_{pool,100\%}$ must be high enough to ensure that 1.25 MW are still available at $P_{pool,24\%}$. The calculation is performed in equation 5.

$$
\begin{gathered}
N_{required} = \frac{P_{pool,100\%}}{P_{charging}} \\
To\ cover\ one\ year\ (8760h): \\
P_{pool,24\%} \geq 1{,}25\ MW \\
P_{pool,100\%} \geq 5{,}21\ MW \\
\text{with: } P_{charging} = 11\ kW = 0{,}011\ MW \\
N_{required} = \frac{5{,}21\ MW}{0{,}011\ MW} = 474
\end{gathered}
\tag{5}
$$

To ensure that 1.25 MW is still available at an SF of 24%, the total pool size must be able to provide 5.21 MW of power at 100%. With 11 kW per vehicle, this corresponds to a total pool of 474 vehicles. To provide a 10% buffer, this scenario would require 521 vehicles to reliably provide 1 MW of FCR throughout the year 2022. Figure 28 shows the SF over a year broken down into 4-hour intervals. The blue line represents the minimum of 24%.

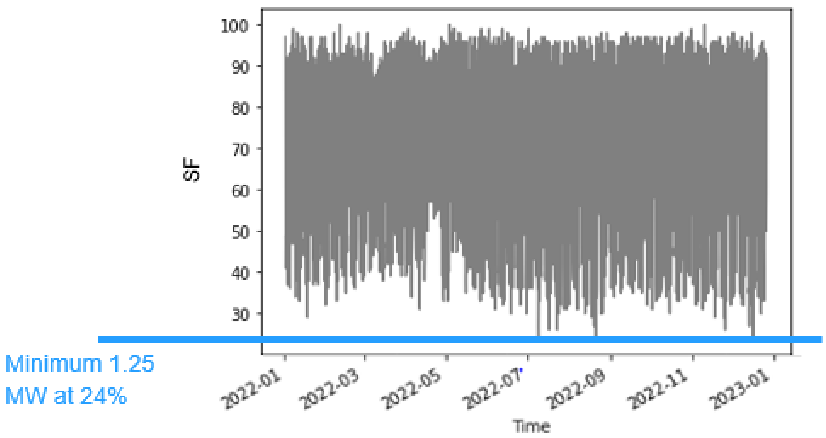

Figure 28 The SF in 4 Hour resolution over a year. The minimum simultaneity factor that is reached is marked (Source: own illustration).

The calculation is performed similarly to determine the number of vehicles the pool would need to offer 1 MW of power for 75% and 50% of the year 2022. The minimum required SF is calculated in the *Uncertainties* Python script by calculating the SF of the 50th and 25th percentiles (see digital appendix, *Uncertainties.py*).

Table 5 shows how many vehicles are needed for the full year, 75% of the year, and 50% of the year.

	100% of the year	**75% of the year**	**50% of the year**
Hours	8760h	6570h	4380h
Minimum SF	24%	45%	61%
$P_{100\%}$	5.21 MW	2.77 MW	2.05 MW
Vehicles required	474	251	187
Buffer included	521	277	205

table 5 difference between the required EVs, depending if 100%, 75% or 50% of the year 2020 are covered.

In summary, this means that with around 40% of the vehicles, 50% of the year can be covered. The calculation can be found in the digital appendix, file *Revenues 100 HH 2022.xlsx*

4.1.4 Economical analysis

In the next step, a theoretical pool of 500 vehicles is created. The 100 simulated vehicles are extrapolated to 500, and the potential revenues for 500 vehicles for the year 2022 are calculated. Figure 29 shows a section of the calculation, where the calculation of theoretical revenues for the 4-hour intervals in the year 2022 is determined.

Figure 29 shows the calculation of the revenues. The *Time* column lists the time from January 3, 2022, to January 1, 2023, in 4-hour intervals. The *Per4h* column contains the revenue values per 4-hour interval for FCR in Germany in 2022, taken from *re-sults2022.xlsx* [22]. The *SF* column contains the simultaneity factors per 4-hour interval per 100 vehicles. In the *Theoretical Power 500 EVs [MW]* column, the number of vehicles is multiplied by the power (11kW) and extrapolated to 500 vehicles. In the *Offering [MW]* column, the division by 1,25 takes place, to represent the necessary buffer of 25%. In the *Rounding [MW]* column, the values are rounded down to reflect the 1 MW bid sizes. Then, in the *Revenues* column, the MW offered are multiplied by the potential revenues. At the bottom of the sheet, the sums are formed, per year.

	A	B	C	D	E	F	G	H	I
1	Time	Per 4h	SF	Within 50%	Within 75%	Theoretical Power 500 Evs [MW]	Offering [MW]	Rounding [MW]	Revenues (€)
2	2022-01-03 00:00:00	122,20	97	122,2	122,2	5,335	4,268	4	488,8
3	2022-01-03 04:00:00	137,40	70	137,4	137,4	3,85	3,08	3	412,2
4	2022-01-03 08:00:00	110,67	41	0	0	2,255	1,804	1	110,67
5	2022-01-03 12:00:00	110,00	49	0	110	2,695	2,156	2	220
6	2022-01-03 16:00:00	82,00	46	0	0	2,53	2,024	2	164
7	2022-01-03 20:00:00	93,34	73	93,34	93,34	4,015	3,212	3	280,02
8	2022-01-04 00:00:00	89,50	92	89,5	89,5	5,06	4,048	4	358
9	2022-01-04 04:00:00	99,00	77	99	99	4,235	3,388	3	297
10	2022-01-04 08:00:00	52,40	52	0	52,4	2,86	2,288	2	104,8
11	2022-01-04 12:00:00	56,67	44	0	0	2,42	1,936	1	56,67
12	2022-01-04 16:00:00	55,60	37	0	0	2,035	1,628	1	55,6
13	2022-01-04 20:00:00	55,00	64	55	55	3,52	2,816	2	110
14	2022-01-05 00:00:00	101,60	92	101,6	101,6	5,06	4,048	4	406,4
15	2022-01-05 04:00:00	120,89	73	120,89	120,89	4,015	3,212	3	362,67
16	2022-01-05 08:00:00	53,17	52	0	53,17	2,86	2,288	2	106,34
17	2022-01-05 12:00:00	91,41	42	0	0	2,31	1,848	1	91,41
2183	2023-01-01 00:12:00	96,43	57	0	96,43	3,135	2,508	2	192,86
2184	2023-01-01 00:16:00	48,40	59	0	48,4	3,245	2,596	2	96,8
2185	2023-01-01 00:20:00	115,17	92	115,17	115,17	5,06	4,048	4	460,68
2186									
2187	renenues/a [€]	201504		94111	141127				450283
2188	number vehicles			229	305				500
2189	revenue/vehicle[€]			411	463				900,57
2190	with probability 2,5 [€]			164,39	185,08				360,23

Figure 29 Extract from the table revenues 100 HH 2022.xlsm. Revenues per year and per vehicle are calculated (Source: own illustration).

The same calculation is performed for the 1-hour time slices and 15-minute time slices. However, in these cases, the revenue values of the 4-hour intervals are divided by four and 15, respectively, to determine the revenues on a 1-hour and 15-minute basis.

The theoretical revenue for 2022 is 450,283 € for a pool size of 500 vehicles and even distribution, assuming no revenue for the aggregator. This corresponds to about 900 € per vehicle. In chapter 1.2.3 it was shown that there are 2.5 times as many providers for FCR compared to the amount that is actually called. This value of 2.5 was considered as the probability of retrieval and it is also examined how the revenues behave with this probability of retrieval. Therefore, including the factor 2.5 of the call probability a potential revenue per vehicle of 360 € could have been reached.

Figure 30 shows the revenues over the year 2022. In blue, the revenues are shown that could potentially have been generated with the supply of 1 MW. The revenues that could potentially have been generated with 500 EVs are shown in gray. One can see that in most cases more than 1 MW can be offered. Revenues up to 1600€ per time slice could be reached.

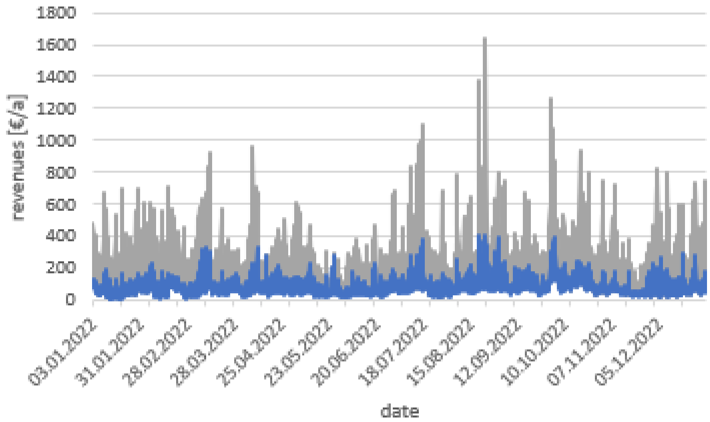

figure 30 Theoretical revenues in 2022 for 1 MW (blue) or a pool of 500 vehicles with up to 5 MW (gray) (Source: own illustration).

4.1.5 Analysis of the time slices

Currently, the supply size needs to be provided for 4-hour time slices. As the number of vehicles within the time slice varies greatly, the next step is to investigate how a reduction in time slices affects revenues. 1-hour time slices and 15-minute time slices are examined. Figure 31 shows the month of January 2022, and Figure 32 shows the first week of January.

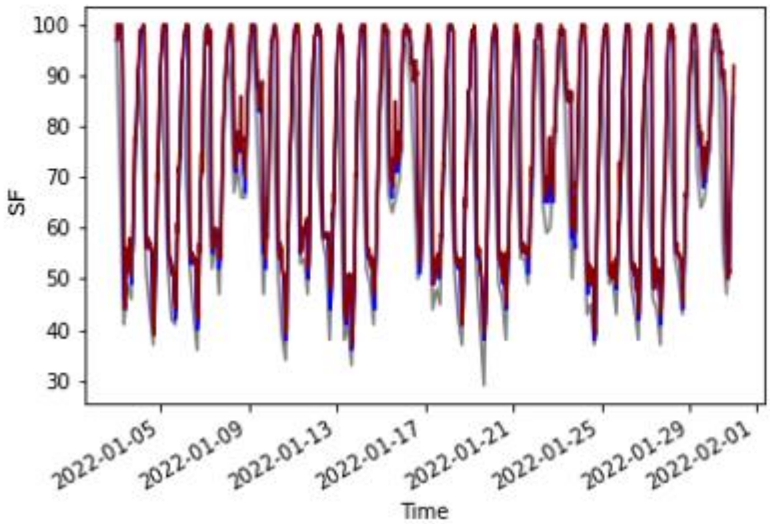

Figure 31 SF resolved the month January 2022 for 4h, 1h and 15 minute time slices.

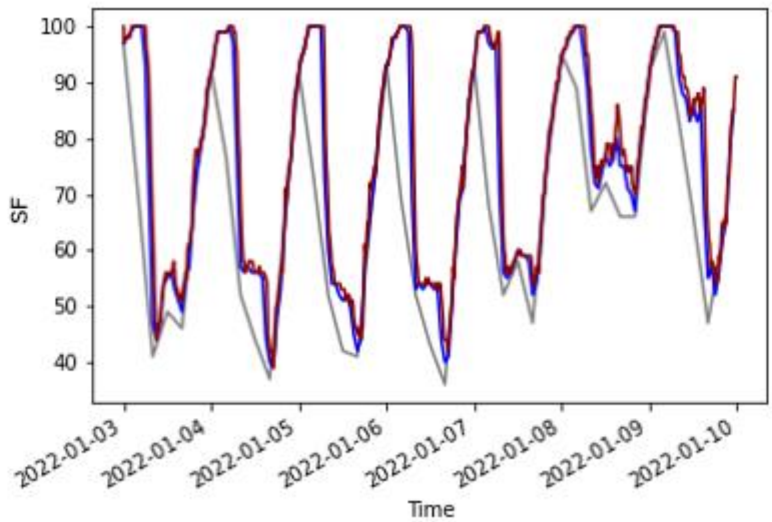

Figure 32 SF resolved over the first week of January 2022 for 4h, 1h and 15 minute time slices (Source: own illustration).

The red lines represent the SF on a 15-minute basis, the blue lines on an hourly basis, and the gray lines on a 4-hour basis. It is already evident that the simultaneous factors in the 4-hour interval are lower compared to the others. This is even more visible in Figure 33. Here, the gray blocks represent the 4h SF, while the blue blocks represent the 1h SF. It can be indicated that the minimum value of a 1h time slice determines the minimum value of the 4h time slice.

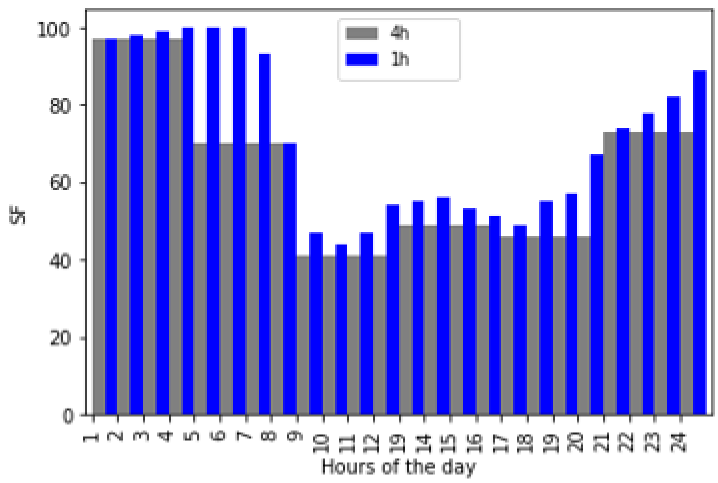

Figure 33 Influence of the reduction of time slices from 4h to 1h. Displayed over one day (Source: own illustration).

Similarly, in Figure 34, the 1h time slices are represented in blue, and the 15-minute time slices are represented in red.

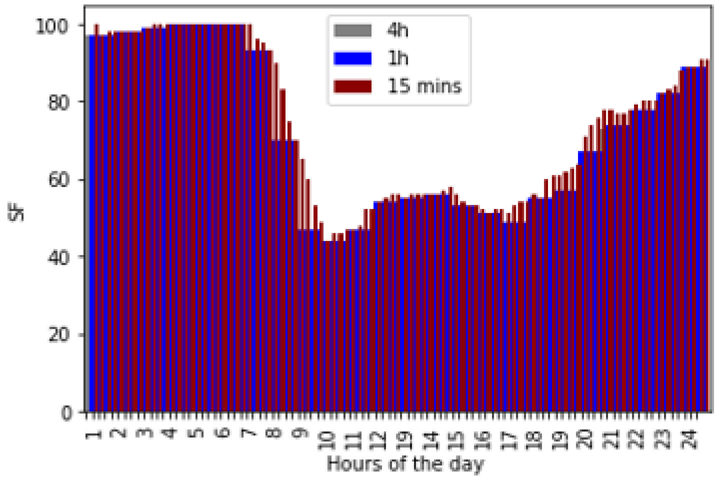

Figure 34 Influence of the reduction of time slices from 1h to 15 minutes. Displayed over one day (Source: own illustration).

The diagrams already show that reducing the time slices will increase the overall SF. This relationship is illustrated again in the following diagram, Figure 35.

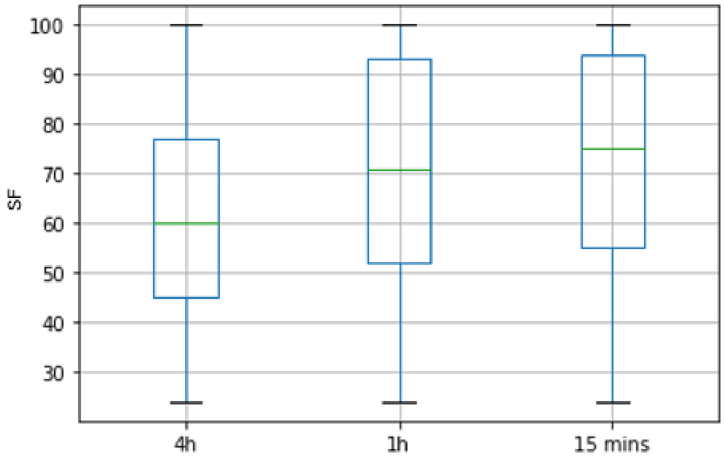

Figure 35 boxplot of the different time slices: 4h, 1h and 15 minutes and their impact on the SF and the median (Source: own illustration).

Figure 35 shows a box plot of the time slices. The boxes represent the interquartile range, which includes the middle 50% of the data. Here, for the 4-hour intervals, the interquartile range is between 45% and 86%. The median value is 60%. The lower and upper limits of the box represent the first and third quartiles. The maximum value for the 4-hour interval is 100% and the minimum is 24%. For the 1-hour interval, the upper limit of the interquartile range is 92% and the lower limit is 52%. The median is 71%, and the upper and lower values are equal. For the 15-minute intervals, the upper limit of the interquartile range is 93%, the lower limit is 55%, and the upper and lower values are the same. The median is 75%.

One can see that there are much smaller differences between the 1-hour and 15-minute intervals compared to the 4-hour and 1-hour intervals. The upper and lower extremes also remain the same, as the dataset contains the same values but in smaller intervals. Additionally, the median is higher for smaller time intervals.

These results show that the smaller the time slice offered, the more vehicles are available on average. This is because only the minimum pool size can be offered in the time slots. The analysis suggests that the smaller the time slice offered, the more profitable it is. Therefore, the next step is to analyze the revenue potential of the smaller time slices. The results can be found in table 7. The theoretical annual revenue increases from 4h to 1h by 75 €, while the revenue from one hour to 15 minutes only increases by 21 € per year and per vehicle.

	4h	**1h**	**15 min**
Revenues/a [€]	450,283	544,620	570,113
Revenues/EV max. [€]	900	1089	1140
Revenues/EV min. [€]	360	435	456

Table 6 Impact of the reduction of time slices on potential revenues in 2022.

4.1.6 Impact charging pattern

So far, it has been assumed that a vehicle is not available to provide FCR while charging. In chapter 3.1, the adaptation of the charging behavior was shown schematically. It is investigated how the total availability changes if the vehicle is always available when it is connected.

Figure 36 shows the first week of January in 2022 with a reduced pool of 25 vehicles. The previous charging behavior is shown in orange. There, the vehicle is only available when it is connected to the wallbox at home but not charging. The blue line shows the optimized charging behavior. Here it is assumed that the vehicle is always available when it is connected to the wallbox at home. The intelligent charging behavior assumes that charging is controlled in such a way that it is charged when FCR provision is not necessary.

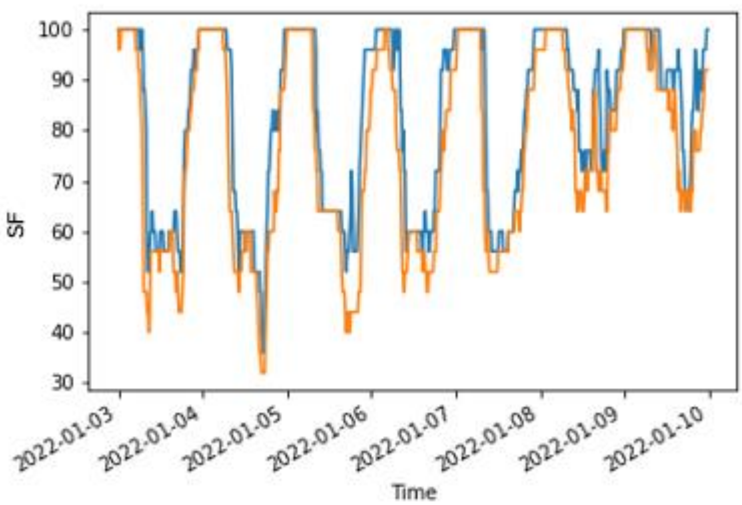

figure 36 impact of the changing of the charging pattern. Higher SF can be reached through the modification of the connection time. (Source: own illustration).

One can see that the availability increases during the day and the SF increases. The figures also confirm this statement. While an average SF of 68% was achieved with the *old* charging pattern during the week, it has increased to 76% with the *new* charging pattern.

It should be noted that this observation is only valid for an initial assessment since the pool of 25 vehicles is not representative. An extended simulation with 100 vehicles can determine the additional revenues due to the increased availability.

4.2 Discussion on future implementation concept

While the results of the simulation were described and explained before, the discussion takes place in the context of the implementation concept. Findings from literature research and simulation are combined and the technical, economic and legal prerequisites for the participation of private EVs in the FCR market in Germany are examined within the framework of an implementation concept.

4.2.1 Technical

As part of the master thesis, various actors and components were identified that must be present for the implementation of FCR through electric vehicles. These are schematically and exemplarily depicted in figure 37 and will be described subsequently. Since the principle is still quite new, there are many different approaches and providers to implement and link the components. The shown linkage of the components is an option, how such a concept can be built up. It is based on the results worked out in the literature recherche. Furthermore, several of the components can also be taken over by a provider or combined into one application, e.g. metering, the controlling platform and the VPP.

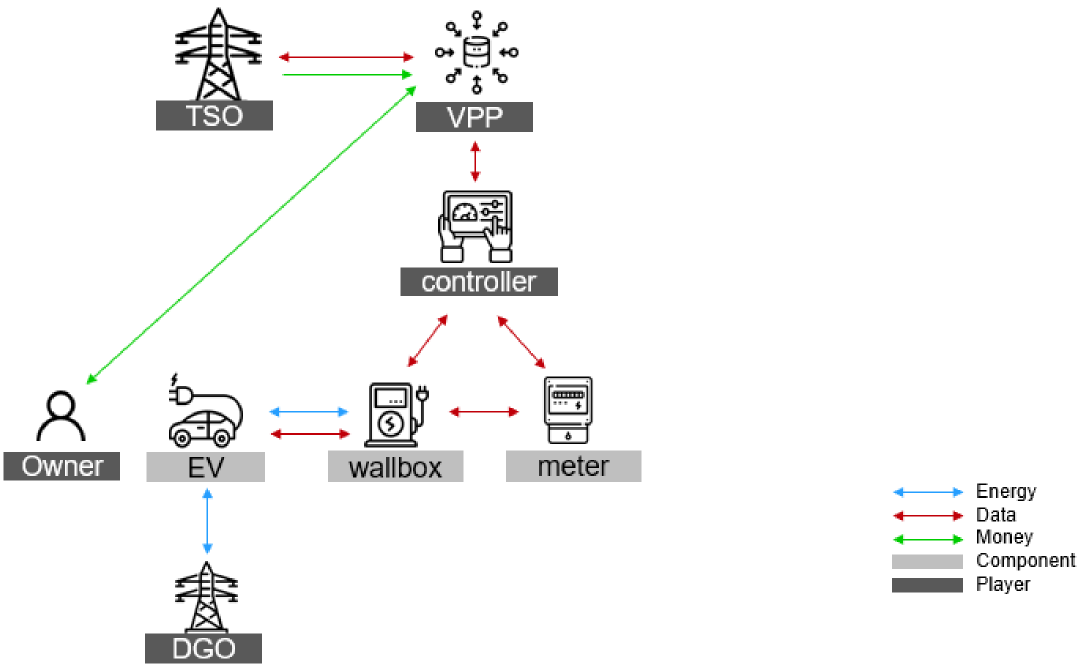

Figure 37 Overview of a concept for the implementation with consideration of technical components and players, payment flows and framework conditions DGO = Distribution Grid Operator (Source: own illustration).

Electric Vehicle and Wallbox: One necessary component for the implementation of FCR is the electric vehicle, which must be able to perform bidirectional charging. Additionally, a wallbox is also necessary, which in combination with the vehicle, allows bidirectional charging. The vehicle can be charged and discharged with either DC or AC. The exact difference between the two is explained in chapter 1.4.1. Currently, the number of EVs that support bidirectional charging is still limited, but more models are expected to be announced soon, as described in chapter 1.4.3. The availability of bidirectional wallboxes is also currently limited to a few models that are not yet available for purchase as of 02/2023, as described in chapter 1.4.1. However, based on many product announcements, their availability is expected soon.

Distribution Grid: As shown in chapter 1.1, the vehicle is connected to the distribution grid at the network level. It receives power from the grid and feeds it back into the grid.

Metering: For V2G, smart meter systems are needed for effective energy consumption and integration of flexible consumers and generators into the grid. They consist of a digital electricity meter and a smart meter gateway for data exchange with the smart grid. The rollout is currently slow. Detailed information can be found in chapter 1.4.5.

Controlling: To make the best use of the battery capacity, so that the driver and the TSO can benefit from the battery, some form of controlling and communication must be implemented. There are various approaches to this, as described in chapter 1.4.6, via integrated overall solutions or independent apps. Basically, however, information such as the charging behavior and status from the wallbox and the meter reading must be transmitted to the back end. There, an energy management system or an intelligent charging platform can be connected for control. In addition, the control system must be able to react automatically to frequency fluctuations [11].

Aggregator/VPP: A 1.25 MW minimum capacity is required to compete in the FCR tender [11]. It is required to combine electric vehicles because each one has no sufficient capacity. It needs an aggregator, such a virtual power plant (VPP), to manage, certify, and market them (see chapter 1.4.4).

TSO: the TSO prequalifies the pool. The aggregator is responsible for the prequalification process with the TSO for the entire pool of electric vehicles. The prequalification process is described in detail in chapter 1.3.

Communication Infrastructure: For a successful implementation, a standardized and functional communication between the components and actors is relevant. The following protocols for communication between vehicle and wallbox (ISO 15118, CHAdeMO), between wallbox and grid (IEC 61850), between wallbox and backend (OCPP, EEBus, Modbus-TCP) between backend and energy market (OpenADR) were identified in chapter 1.4.2 as particularly relevant for V2G and thus also for the integration of EVs into ancillary services [25, 40]. These are still being developed and implemented.

Implementation: Various pilot projects have demonstrated that the provision of electric vehicles is technically feasible. The necessary technical components are available, and prequalification for V2G services was successful in test cases. The simulation in the thesis confirms and expands upon the results found in the literature. In the simulation, a pool of 521 vehicles, was able to offer 1.25 MW of FCR be offered over a year, but the available power fluctuates over time due to the high variability of available vehicles. During the day, a median of 50% was reached for the weekdays, during the night a median up to 95%. Also, the battery SOC was identified as a critical factor, as FCR must be offered symmetrically [11], meaning that the SOC of the vehicle cannot be high or too low to be equally available in both directions. The losses incurred in providing available power were also analyzed, including time, transmission, and battery capacity that can be utilized. Time can be optimized by connecting the vehicle to the grid not only at home but also at other locations such as the workplace. The charging power can also be optimized both on the vehicle and wallbox sides. To increase the usable capacity, a larger battery capacity or a SOC of 50% would be a more sufficient choice. However, looking at the EVs announced to be bidirectional in the next few years, they mostly have at least a 60 kWh capacity. Furthermore a potential obstacle could be the 15-minute criteria, which requires that the same vehicles must be available in the pool for each 15 minutes call [11]. This would mean that vehicle owners would need to commit to having their vehicles connected for at least the specified time when in use or planned for use. Furthermore, in the literature was found that it is essential to ensure that both the driver's and the VPPs and TSOs needs are met. The driver wants to meet their mobility needs, while the VPP and TSO wants to utilize the battery capacity [62]. In the simulation, an average SOC of 60% was appropriate for a sufficient battery capacity for the EV owners' everyday activities while also allowing the VPP to have sufficient buffer to utilize the vehicle for FCR provision.

V2G is one of the main prerequisites for the use of EVs for providing FCR. Since the supply must be generated symmetrically, it is not possible to offer only unidirectional power. However, it would be possible to offer ancillary services in combination with stationary home storage, as *sonnen* does [55] (as mentioned in chapter 1.4.4). Thus, the part of the discharging process could be done via the EV and the part of the charging process via the home storage, as long as the bidirectionality is not yet given.

The availability of additional V2G-capable automobiles on the market is one of the most crucial requirements for the wide-scale implementation of V2G. With the estimation of [87], that 25% of EVs can charge in both directions by 2035 and an average of 40% of those vehicles are available for usage at the electricity market, the usable power will be 28 GW.

4.2.2 Economical

Today, the vehicle battery still accounts for about one third of the vehicle acquisition costs and is typically used for driving for less than 10% of the time. During periods of inactivity - given that the EV is connected to the power grid - the battery is ideal for providing short-term flexibility to the power system [26].

The thesis calculated the theoretical revenues that could be generated by a pool of 500 private EVs providing FCR while charging at home. Simulations were conducted to determine potential revenues for 2022 and found that a total of 900 € per EV and year could be earned, with each individual EV potentially earning a proportion of this revenue. As shown in Figure 37, the financial flows are channeled through the aggregator or VPP since individual vehicles cannot be directly connected. When a bid is accepted, the VPP receives the revenue for the offered power quantity, which is then distributed to individual EV owners according to the business model. The thesis assumed that all revenues would be distributed equally among EV owners, regardless of how much time their vehicles are actually connected and available. In this thesis revenues for the VPP and additional costs such as infrastructure, taxes and fees were not considered. In practice, however, a share of the proceeds for the VPP is conceivable. Therefore, these costs may further reduce potential revenues.

In addition, the thesis examined how to optimize the economic benefits. Currently, 4-hour time slots are required for FCR [11]. The simulation showed that it would be more profitable to sell in 1-hour increments and that the difference between 1h and 15 minutes is not as significant as between 4h and 1h. The average SF could be increased from 60% (4h) to 71% (1h) and to 75% (15 mins). While with 4-time slots, revenues of 900 € per vehicle and year could have been reached in the simulation, for 1-h time slots 1089 € would have been possible and up to 1140 € for the 15-minutes intervals.

The fewer vehicles participate, the less the revenue is divided. Therefore, it makes sense to include vehicles at night or for periods when the supply of flexibility is high. High penalties can be imposed for not meeting FCR requirements, so including battery storage for security could be beneficial. Optimizing the charging pattern could also lead to higher revenues. However, the commitment of EV owners is also of crucial importance in this regard. With a sufficiently large pool of EVs, availability can also be ensured. However, a smaller pool makes more sense to increase revenues per user. If users are willing to plan and communicate their travel times and SOC, revenues can be increased even further. Furthermore, pools can be selectively put together depending on household profiles, and vehicles with too low a utilization rate can be excluded. Up until now, an average value per EV owner has been calculated. A proportional compensation based on connection time is also conceivable.

The presented calculations were based on current result data from the tenders for FCR in Germany. Therefore, it is important to assess how prices will develop in the coming years to determine the future potential. In recent years, there has been a clear upward trend in the prices that can be achieved for FCR. The future price development has a significant influence on the resulting FCR revenues. In chapter 3.2.2, similar prices to those in 2022 were predicted for the year 2023 [86], which would also mean total potential revenues of around 900 € per year and EV, based on the simulation for 500 EVs.

Literature research has shown that user acceptance plays a significant role [67, 69, 71]. In chapter 1.4.7 the motivators of financial incentives and the limitations of range anxiety were highlighted the most. Therefore, in the next step, it needs to be investigated how high the incentive must be for users to be willing to not fully charge their EV (due to range anxiety), and how high the incentives must be for users to plug in their EV every time and make it available for the grid.

Currently, the unclear definition of energy storage systems still prevents the economic feasibility of electric vehicles. The double burden of energy storage systems in EVs with taxes, fees, charges, and surcharges does not make any economic sense.

4.2.3 Legal

In Germany, the development of vehicle-to-grid (V2G) charging infrastructure is subject to various legal requirements and obstacles, which must be carefully considered to ensure its successful implementation.

Firstly, regulations for the installation and operation of electric vehicle charging infrastructure must be observed. Charging infrastructure with a capacity of 3.6 kW or more must be reported to the grid operator, while charging systems with a capacity over 12 kW require prior approval [39].

Secondly, the implementation of intelligent metering systems, such as smart meters, is crucial for the effective integration of flexible consumers and generators into the energy system. However, the rollout of these systems has been slow so far. To address this issue, a new draft law by the German Federal Government aims to accelerate the rollout while ensuring data protection and IT security [60].

Thirdly, there is an unequal treatment of stationary and mobile storage in terms of energy surcharges, taxes, and levies, which leads to economic disadvantage for mobile storage. This issue creates a challenge for bidirectional EVs, which can offer system services both during controlled charging and during controlled vehicle discharge. To overcome this issue, the German Federal aims to improve the legal, technical, tax, and economic framework conditions to enable bidirectional charging without discrimination [18].

To conclude the legal aspects, the successful implementation of V2G charging infrastructure in Germany requires careful consideration of various legal requirements and obstacles, such as regulations for the installation and operation of charging infrastructure, metering concepts, and taxation. The German Federal Government aims to overcome these challenges and enable bidirectional charging without discrimination.

4.3 Limitations of the research

The aim of this work was to determine the potential and requirements for the integration of private electric vehicles into the balancing power market in Germany. The work is limited to the ancillary service FCR, as the simulation and analysis of other types would go beyond the scope.

Another research need arises from consideration of the costs incurred. The thesis does not include the revenue that the VPP receives for its service. Nor does it consider the costs, such as the cost of new wallboxes for EV owners or costs due to battery wear and tear.

The assumption that EVs are always plugged in at home is based on drivers' motivation to receive compensation for their willingness to do so. For this assumption to work in practice, there is a need for further research that examines the actual revenues after deducting costs and charges to the VPP in practice with potential users.

The reader should note that this work is based on a profile of 100 households. Due to the large amount of data and the high computational effort, 100 households were chosen as the maximum number. However, for an optimized simulation of the theoretical revenue with 500 EVs, an even higher number would be more sufficient.

5 Conclusion

This chapter includes a summary of the results as well as an outlook.

5.1 Summary

The aim of this thesis was to determine the potential and the requirements to integrate private electric vehicles into the balancing power market in Germany. The work is limited to the ancillary service FCR at the usage of the own wallbox at home. To this end, after a literature review, a simulation was developed and the theoretical potential based on the availability of EVs, i.e. connection to the home network, was determined with a simulated pool of 100 EVs. Furthermore, the technical, economic, and legal feasibility was examined.

To answer the research question, the following procedure was followed. The thesis builds on 2 existing tools, the Load Profile Generator (LPG) by Dr. Noah Pflugradt [7] and the Charge Profile Generator e-Mobility (CPGeM) by Marian Sprünken [8]. The CPGeM was further developed as part of the thesis. The input parameters were chosen based on the findings of the literature review. With these two tools, a pool of 117 representative households and corresponding charging profiles were simulated. Based on the simulated profiles, the availability is determined. Using simulation files developed with Python, Excel and VBA, it can be determined when household members are out of the house with their vehicles and when they are at home and available for PCR. The result is simultaneity factors for 15-minute time steps, which indicate how many vehicles per time step are available for PCR. Charging patterns are considered, which simulate the charging behavior to ensure sufficient SOC for mobility needs. From the results of the availability, the required pool size for providing the minimum offer amount was determined, taking into account the requirements and prequalification conditions of the German PCR market. In addition to the minimum offer amount, the uncertainty over one year was also simulated and presented. The economic feasibility was then examined, and the potential earnings that could have been achieved with a pool of 500 vehicles in 2022 were calculated. Furthermore, an analysis of the reduction of time windows and a different charging pattern was carried out. The simulation is based on the following framework conditions: It is assumed that the vehicles are connected to the network directly after arriving at home. Furthermore, it is assumed that the vehicles are available for FCR when they are at home but not charging. Charging and discharging are done with a charging power of 11 kW, and the EVs have an average battery capacity of 60 kWh.

To answer the research question to what extent private electric vehicles in Germany can be used for the provision of FCR, the literature review and the simulation based on it provide the following results. First, the overall potential is discussed, then the three sub-research questions on the technical, economic, and legal aspects are answered.

The high theoretical potential determined in the literature due to the long service life is partially confirmed in the simulation. The potential depends strongly on availability. Since only the wallbox and thus the usage time at home was considered, an average SF of 60% is achieved in 2022. The paper concludes that availability of the EVs fluctuates but can be increased by targeting specific time periods, such as nighttime hours. Accordingly, targeted coverage segments and area wide V2G are required for optimal utilization. Differences are observed between weekends and weekdays, as well as day and night. Nights were covered with at least 95% availability for the entire year 2022. During the day, minimum values of up to 24% are achieved. Availability fluctuates throughout the year. The median weekday daytime availability is about 50%, while the median weekend daytime availability varies between 55% and 75%. To ensure that sufficient vehicles are available throughout the year to always provide FCR, a pool size of 521 vehicles was determined with a minimum size of 1.25 MW. Optimization can also be achieved by extending the charging time, for example by integrating a different charging location or increasing the charging power.

The question, to what extent is implementation in Germany technically feasible at present and in the future can be answered as followed. From a technical perspective, the implementation of EVs for V2G services is technically feasible, with successful pilot projects and available technical components. These components include an electric vehicle that can be charged bidirectionally, a wallbox, a distribution grid, a smart meter, a back-end energy management system, and an aggregator or VPP. Communication between these components is critical, and new communication protocols are being developed to facilitate V2G implementation. Widespread deployment of bidirectional charging and ensuring that the needs of both EV owners and VPP or TSOs are met are important considerations for large-scale V2G deployment. In the simulation, an average SOC of 60% was sufficient to provide adequate battery capacity for EV owners' day-to-day activities while providing the VPP with a sufficient buffer to use the vehicle for FCR provisioning.

The question of how the economic implementation is currently and in the future regarding the market design can be answered as follows. The theoretical revenues for the year 2022 amount to 450,283 € with a pool size of 500 vehicles and even distribution, assuming no revenues for the aggregator. This translates to about 900 € per vehicle. With the call probability of 2.5%, this represents a potential revenue per vehicle of 360 €. Revenues could be optimized by the possibility of a smaller offer slice. Currently 4h must be offered. There are much smaller differences between the 1-hour and 15-minute intervals compared to the 4-hour and 1-hour intervals. Thus, the average SF can be increased from 60% (4h) to 71% (1h) and to 75% (15 mins). The potential revenues also increase. While with 4-time slots, revenues of 900 € per vehicle and year could have been reached in the simulation, for 1-h time slots 1089 € would have been possible and up to 1140 € for the 15-minutes intervals. By optimizing the charging behavior, the availability can be increased by up to 9%.

Furthermore, the question is answered, which legal and regulatory framework conditions are currently given, and which are necessary to provide FCR by private EVs in Germany. It was shown that V2G technology, which is essential for the provision of FCR, currently still faces obstacles in Germany. These are regulations for the installation and operation of charging infrastructure, the treatment of electric vehicles as consumption or generation units, and the unequal treatment of stationary and mobile storage in terms of energy surcharges, taxes and levies. The deployment of intelligent metering systems (iMSys) is necessary for effective energy consumption and smart grid applications but is slow. Clear legal definition and regulatory incentives are being called for by various initiatives to encourage the adoption of bidirectional charging, which is also being explored by the federal government.

The results of this thesis tie in with the literature reviewed in recent years on the provision of FCR. The study of the simultaneity factor and availability on a simulated private EV basis has not been done in this form in the literature, so it is difficult to compare these results directly with other studies. However, one result that is included in almost every study is the revenue per year per car. Since the studies examined on the provision of balancing power by electric vehicles were conducted in very different markets, at different years, and with different assumptions about driving pay, large differences in the results were therefore to be expected, and they have come to pass. The financial result is a higher value than in the other studies, which is due to the high FCR revenues in 2022.

In summary, it is not yet possible for private electric vehicles to be used to provide FCR in Germany. The technical framework is in place or mature, but the regulatory hurdles are still there. Nevertheless, there is great potential in terms of removing the hurdles. Sufficient availability of EVs could also be confirmed with the simulation. Due to the different household profiles, there are strong time-dependent fluctuations in the course of the day, week and year, but by selecting suitable supply slices, the time slices can be used when the availability becomes high. However, cooperation with the EV owner is important in this regard. With a sufficiently large pool, performance could be guaranteed even without planning and commitment from the EV owner. With a smaller pool, in order to increase economic efficiency, planning of the charging times by the EV owner is relevant. Furthermore, the commitment of the EV owner to plug in was identified as a critical success factor, as only then the EV can be used for the provision of ancillary services such as FCR.

5.2 Outlook

Even though the provision of FCR in Germany for private EVs is not yet possible, with the current market and policy developments, it is very likely that integration will be possible in the future. The increasing number of announced bidirectional EVs and charging stations suggest that the technology will also be available to private users in the coming years. V2G is also conceivable with regulatory adjustments.

The simulation showed that the potential is there, and high revenues can be achieved, but user acceptance and commitment to connect the vehicle to the grid are crucial factors. In terms of user acceptance and feasibility, as indicated by the limitations, it may be worthwhile to investigate this further. The thesis depends on the availability and willingness of the EV owner to plug in their EV, whenever they arrive at home. In this work, it was assumed that the revenue is high enough to make the contribution attractive to the EV owners. Accordingly, in a further step, it can be investigated to what extent the incentive of the revenue after deducting the costs and the flat VPP is interesting for potential users and how the connection times are realized in practice.

References

[1] Webseite der Bundesregierung, *Mehr Energie aus erneuerbaren Quellen.* [Online]. Available: https://www.bundesregierung.de/breg-de/themen/klimaschutz/energiewende-beschleunigen-2040310 (accessed: Feb. 15 2023).

[2] Webseite der Bundesregierung | Startseite, *Mehr E-Mobilität.* [Online]. Available: https://www.bundesregierung.de/breg-de/themen/klimaschutz/eenergie-und-mobilitaet/nachhaltige-mobilitaet-2044132 (accessed: Feb. 15 2023).

[3] P. Jochem, T. Kaschub, and W. Fichtner, "How to Integrate Electric Vehicles in the Future Energy System?," in *Lecture Notes in Mobility, Evolutionary paths towards the mobility patterns of the future*, M. Hülsmann and D. Fornahl, Eds., Heidelberg: Springer, 2014, pp. 243–246. Accessed: Feb. 15 2023.

[4] Nobis, Claudia und Kuhnimhof, and Tobias (2018), "Mobilität in Deutschland – MiD. Ergebnisbericht. BMVI, infas, DLR, IVT, infas 360. Bonn, Berlin (German)," (in German), p. 5,11. [Online]. Available: https://www.mobilitaet-in-deutschland.de/pdf/MiD2017_Ergebnisbericht.pdf

[5] regelleistung.net, *Markt für Regelreserve in Deutschland.* [Online]. Available: https://www.regelleistung.net/ext/static/market-information (accessed: Feb. 15 2023).

[6] regelleistung.net, *Präqualifizierte Leistung in Deutschland.* [Online]. Available: https://www.regelleistung.net/ext/download/pq_capacity (accessed: Oct. 27 2022).

[7] Dr. Noah Pflugradt, *LoadProfileGenerator.* [Online]. Available: https://www.loadprofilegenerator.de/ (accessed: Feb. 9 2023).

[8] Sprünken Marian, "Erzeugung synthetischer Ladeprofile für Elektrofahrzeuge synchron zu synthetischen Haushaltsprofilen," (in German), vol. 2022. [Online]. Available: http://www.100pro-erneuerbare.com/publikationen/2022-01-Spruenken-Ladeprofilgenerator/Spruenken-Ladeprofile_fuer_Elektrofahrzeuge-MA2022.pdf

[9] Thomas Bien, *Technische und wirtschaftliche Bewertung von Technologien für Regelenergie*. Stuttgart: Fraunhofer Verlag, 2019.

[10] Deutsche Energie-Agentur GmbH (dena), "dena-Studie Systemdienstleistungen 2030: Sicherheit und Zuverlässigkeit einer Stromversorgung mit hohem Anteil erneuerbarer Energien.," (in German), pp. 2–5, 2014. [Online]. Available: https://www.dena.de/fileadmin/dena/Dokumente/Pdf/9094_dena-Studie_Systemdienstleistungen_2030.pdf

[11] Präqualifikationsportal, *Prequalification Process for Balancing Service Providers (FCR, aFRR, mFRR) in Germany.* [Online]. Available: https://www.regelleistung.net/ext/download/PQ_Bedingungen_FCR_aFRR_mFRR_2022_en (accessed: Feb. 10 2023).

[12] ENTSO-E, *Member Companies.* [Online]. Available: https://www.entsoe.eu/about/inside-entsoe/members/ (accessed: Oct. 27 2022).

[13] consentec GmbH, “Beschreibung von Konzepten des Systemausgleichs und der Regelreservemärkte in Deutschland: Erläuterungsdokument im Rahmen der deutschen Übertragungsnetzbetreiber,” Aachen, 2022. [Online]. Available: https://www.regelleistung.net/ext/download/MARKTBESCHREIBUNG_CONS

[14] T. I. WAWER, *ELEKTRIZITATSWIRTSCHAFT: Eine praxisorientierte einfuhrung in strommarkte und stromhandel,* 1st ed. [S.l.]: SPRINGER GABLER, 2022. Accessed: Oct. 27 2022., pp.97-108. [Online]. Available: https://link.springer.com/content/pdf/10.1007/978-3-658-38418-0.pdf

[15] K. F. Schäfer, *Systemführung: Betrieb elektrischer Energieübertragungsnetze*. Wiesbaden, Heidelberg: Springer Vieweg, 2022. Accessed: Oct. 12 2022,p.163. [Online]. Available: https://link.springer.com/content/pdf/10.1007/978-3-658-36199-0.pdf

[16] ENTSO-E, “Load Frequency Control and Perfomance,” [Online]. Available: https://eepublicdownloads.entsoe.eu/clean-documents/pre2015/publications/entsoe/Operation_Handbook/Policy_1_Appendix%20_final.pdf

[17] Amprion, *Regelreserve in Deutschland.* [Online]. Available: https://www.amprion.net/Strommarkt/Marktplattform/Regelenergie/ (accessed: Oct. 27 2022).

[18] Forschungsprojekt Bidirektionales Lademanagement, “Bereitstellung von Systemdienstleistungen aus Elektrofahrzeugen mit bidirektionalem Lademanagement Ein BDL-Positionspapier zu Vehicle-to-Grid-Anwendungen,” 2022. Accessed: Feb. 15 2023. [Online]. Available: https://www.ffe.de/veroeffentlichungen/positionspapier-zur-bereitstellung-von-systemdienstleistungen-aus-elektrofahrzeugen-mit-bidirektionalem-lademanagement/

[19] regelleistung.net, *Minutenreserve.* [Online]. Available: https://www.regelleistung.net/ext/static/mrl (accessed: Feb. 15 2023).

[20] regelleistung.net, *Primärregelreserve.* [Online]. Available: https://www.regelleistung.net/ext/static/prl (accessed: Feb. 15 2023).

[21] regelleistung.net, *Sekundärregelreserve.* [Online]. Available: https://www.regelleistung.net/ext/static/srl (accessed: Feb. 15 2023).

[22] regelleistung.net, *Datacenter FCR/aFRR/mFRR.* [Online]. Available: https://www.regelleistung.net/apps/datacenter/tenders/?productTypes=PRL&markets=BALANCING_CAPACITY,BALANCING_ENERGY&date=2023-02-15&tenderTab=PRL$CAPACITY$1 (accessed: Feb. 15 2023).

[23] W. Kempton and J. Tomić, “Vehicle-to-grid power fundamentals: Calculating capacity and net revenue,” *Journal of Power Sources*, vol. 144, no. 1, pp. 268–279, 2005, doi: 10.1016/j.jpowsour.2004.12.025.

[24] K. M. Tan, V. K. Ramachandaramurthy, and J. Y. Yong, “Integration of electric vehicles in smart grid: A review on vehicle to grid technologies and optimization techniques,” *Renewable and Sustainable Energy Reviews*, vol. 53, pp. 720–732, 2016, doi: 10.1016/j.rser.2015.09.012.

[25] J. Liebl, Ed., *Der Antrieb von morgen 2021: Gemeinsam mit Grid Integration + Electrified Mobility,* 1st ed. Berlin: Springer Berlin; Springer Vieweg, 2021. Accessed: Jan. 3 2023.p.2-8 [Online]. Available: https://link.springer.com/content/pdf/10.1007/978-3-662-63403-5.pdf?pdf=button

[26] NPM, “Factstheet Vehicle to Grid,” Accessed: Nov. 24 2022. [Online]. Available: https://www.plattform-zukunft-mobilitaet.de/wp-content/uploads/2020/10/201012_NPM_AG5_V2G_final.pdf

[27] Helmut Tschöke, Peter Gutzmer, Thomas Pfund, *Elektrifizierung des Antriebsstrangs: Grundlagen - vom Mikro-Hybrid zum vollelektrischen Antrieb*: Springer Vieweg. Accessed: Jan. 3 2023. pp. 391-394.[Online]. Available: https://link.springer.com/content/pdf/10.1007/978-3-662-60356-7.pdf?pdf=button

[28] M. Linnemann, *ELEKTROMOBILITT UND DIE ROLLE DER ENERGIEWIRTSCHAFT: Rechte und pflichten eines… ladesulenbetreibers*. [S.l.]: MORGAN KAUFMANN, 2020. Accessed: Nov. 17 2022.p.10. [Online]. Available: https://link.springer.com/content/pdf/10.1007/978-3-658-30217-7.pdf

[29] ISO, *ISO 15118-20:2022.* [Online]. Available: https://www.iso.org/standard/77845.html (accessed: Feb. 15 2023).

[30] Texas Instruments, “Taking charge of electric vehicles – both in the vehicle and on the grid (Rev. A),” [Online]. Available: https://www.ti.com/lit/wp/szzy007a/szzy007a.pdf?ts=1676010726752&ref_url=https%253A%252F%252Fwww.google.com%252F

[31] S. S. Ravi and M. Aziz, “Utilization of Electric Vehicles for Vehicle-to-Grid Services: Progress and Perspectives,” *Energies*, vol. 15, no. 2, p. 589, 2022, doi: 10.3390/en15020589.

[32] Wallbox, *Wallbox Introduces Quasar 2 at CES 2022.* [Online]. Available: https://wallbox.com/en_us/newsroom/wallbox-introduces-quasar-2-at-ces-2022.html (accessed: Feb. 11 2023).

[33] Sono Motors, *Unsere bidirektionale Wallbox | Sono Motors.* [Online]. Available: https://sonomotors.com/de/bidirectional-wallbox/ (accessed: Feb. 11 2023).

[34] KOSTAL, *BDL Wallbox - Home.* [Online]. Available: https://www.kostal-industrie-elektrik.com/de-de/aktuelles/news/2021/ki-2021-07-13-bdl/ (accessed: Feb. 11 2023).

[35] EVtech, *sospeso&charge CHAdeMO und CCS V2X Wallbox - das Auto wird zum Energiespeicher fürs Haus.* [Online]. Available: https://www.evtec.ch/produkte/sospeso (accessed: Feb. 11 2023).

[36] ambibox, *ambiCHARGE.* [Online]. Available: https://ambibox.de/de/produkte/ambicharge (accessed: Feb. 11 2023).

[37] Honda.de, *Honda schließt Machbarkeitsprojekt erfolgreich ab.* [Online]. Available: https://www.honda.de/cars/world-of-honda/news-events/2022-11-21-honda-schliesst-machbarkeitsprojekt-erfolgreich-ab.html (accessed: Jan. 27 2023).

[38] B. Machalik and F.-H. Wehner, “Integrationsunterstützung von Ladeinfrastruktur für Elektromobilität durch Microgrids,” (in German), *Elektrotech. Inftech.*, pp. 1–2, 2022, doi: 10.1007/s00502-022-01082-5.

[39] VDE|FNN, “FNN-Hinweis Netzintegration Elektromobilität,” (in German), pp. 26–33. [Online]. Available: https://www.vde.com/resource/blob/1896384/8dc2a98adff3baa259dbe98ec2800bd4/fnn-hinweis--netzintegration-e-mobilitaet-data.pdf

[40] Vadi, Bayindir, Colak, and Hossain, “A Review on Communication Standards and Charging Topologies of V2G and V2H Operation Strategies,” *Energies*, vol. 12, no. 19, pp. 14–18, 2019, doi: 10.3390/en12193748.

[41] Nissan Deutschland, *V2G-Projekt i-rEzEPT überzeugt mit erster Zwischenbilanz.* [Online]. Available: https://germany.nissannews.com/de-DE/releases/release-95049f6c395212ac6d0ccf726f034c47-v2g-projekt-i-rezept-uberzeugt-mit-erster-zwischenbilanz (accessed: Feb. 12 2023).

[42] Media Stellantis, *CITROËN OLI [all-ë]: INNOVATIVER, VERANTWORTUNGS-VOLLER UND OPTIMISTISCHER ANSATZ INITIIERT MUTIGE ZUKUNFT DER MARKE.* [Online]. Available: https://www.media.stellantis.com/de-de/citroen/press/Citroen-oli_all-e_Innovativer-verantwortungsvoller-und-optimistischer-Ansatz-initiiert-mutige-Zukunft-der-Marke (accessed: Feb. 12 2023).

[43] Media Stellantis, *The Vehicle-to-Grid pilot project has been inaugurated at Mirafiori.* [Online]. Available: https://www.media.stellantis.com/em-en/e-mobility/press/the-vehicle-to-grid-pilot-project-has-been-inaugurated-at-mirafiori (accessed: Feb. 12 2023).

[44] Mercedes Benz Group Media, *Mercedes-EQ, EQS, V 297, 2021 - Mercedes-Benz Group Media.* [Online]. Available: https://group-media.mercedes-benz.com/marsMediaSite/de/instance/picture/Mercedes-EQ-EQS-V-297-2021.xhtml?oid=49620087 (accessed: Feb. 12 2023).

[45] Renault Deutschland AG, “Klimaneutralität: Renault entwickelt „Smarte Gebiete“,” *Renault Deutschland AG*, 09 Nov., 2021. https://blog.renault.de/neues-von-renault-elektromobilitaets-projekt-renault-treibt-energiewende-voran/ (accessed: Feb. 12 2023).

[46] P. Schäfer, “Renault Mégane E-Tech Electric ermöglicht bidirektionales Laden,” *springerprofessional.de*, 14 Sep., 2021. https://www.springerprofessional.de/crossover-fahrzeuge/batterie/renault-m%C3%A9gane-e-tech-electric-ermoeglicht-bidirektionales-laden/19656462 (accessed: Feb. 12 2023).

[47] BMW Group, *Bidirektionales Lademanagement – BDL – Pilotprojekt startet die wichtigste Phase: Kunden testen erste Elektrofahrzeuge, die ihren Strom zurückspeisen können.* [Online]. Available: https://www.press.bmwgroup.com/deutschland/article/detail/T0338036DE/bidirektionales-lademanagement-%E2%80%93-bdl-%E2%80%93-pilotprojekt-startet-die-wichtigste-phase:-kunden-testen-erste-elektrofahrzeuge-die-ihren-strom-zurueckspeisen-koennen?language=de (accessed: Feb. 12 2023).

[48] Hyundainews.de, *Hyundai entwickelt V2X-Technologie zur Stabilisierung des Stromnetzes.* [Online]. Available: https://www.hyundai.news/de/articles/press-releases/hyundai-entwickelt-v2x-technologie-zur-stabilisierung-des-stromnetzes.html (accessed: Feb. 12 2023).

[49] Volkswagen Newsroom, *Komfortabel, vernetzt und nachhaltig: neue Lösungen für das Laden der elektrischen Volkswagen Modelle.* [Online]. Available: https://www.volkswagen-newsroom.com/de/pressemitteilungen/komfortabel-vernetzt-und-nachhaltig-neue-loesungen-fuer-das-laden-der-elektrischen-volkswagen-modelle-7695 (accessed: Feb. 12 2023).

[50] ACAC, *Ford F-150 Lightning.* [Online]. Available: https://www.adac.de/rund-ums-fahrzeug/autokatalog/marken-modelle/ford/ford-f-150-lightning/ (accessed: Feb. 12 2023).

[51] C. Quinn, D. Zimmerle, and T. H. Bradley, "The effect of communication architecture on the availability, reliability, and economics of plug-in hybrid electric vehicle-to-grid ancillary services," *Journal of Power Sources*, vol. 195, no. 5, pp. 1500–1509, 2010, doi: 10.1016/j.jpowsour.2009.08.075.

[52] Next Kraftwerke, "Was ist ein Virtuelles Kraftwerk? | Definition," https://www.next-kraftwerke.de/wissen/virtuelles-kraftwerk (accessed: Feb. 20 2023).

[53] Next Kraftwerke, *Ein Virtuelles Kraftwerk für die Stromvermarktung.* [Online]. Available: https://www.next-kraftwerke.de/virtuelles-kraftwerk (accessed: Feb. 12 2023).

[54] The Mobility House, *The Mobility House handelt Elektroautobatterien an der EPEX SPOT SE.* [Online]. Available: https://www.mobilityhouse.com/de_de/magazin/pressemeldungen/the-mobility-house-handelt-elektroautobatterien-an-der-europaeischen-stromboerse-epex-spot-se.html (accessed: Feb. 11 2023).

[55] sonnen.de, *Häufig gestellte Fragen | sonnenVPP | sonnen.* [Online]. Available: https://sonnen.de/haeufig-gestellte-fragen/sonnenvpp/ (accessed: Feb. 20 2023).

[56] Next Kraftwerke, *Batteriespeicher im Virtuellen Kraftwerk | Regelenergie.* [Online]. Available: https://www.next-kraftwerke.de/virtuelles-kraftwerk/batteriespeicher (accessed: Feb. 20 2023).

[57] D. Göhlich and A. F. Raab, Eds., *Mobility2Grid - Sektorenübergreifende Energie- und Verkehrswende*. Berlin, Heidelberg: Springer Vieweg, 2021. p.1-24. Accessed: Oct. 12 2022.

[58] BMWK, "entwurf-eines-gesetzes-zum-neustart-der-digitalisierung-der-energiewende," (in German). [Online]. Available: https://www.bmwk.de/Redaktion/DE/Downloads/Gesetz/entwurf-eines-gesetzes-zum-neustart-der-digitalisierung-der-energiewende.pdf?__blob=publicationFile&v=6

[59] T. Kimpel, "Initiative Bidirektionales Laden Positionspapier März 2022," (in German). [Online]. Available: https://ceco.de/user/pages/downloads/14.bidirektionales-laden-von-eautos-als-schlussel-zur-flexibilisierung-des-energiesystems/Initiative%20Bidirektionales%20Laden%20Positionspapier%20M%C3%A4rz%202022.pdf

[60] Bundesministerium für Digitales und Verkehr (BMDV), “Masterplan Ladeinfrastruktur II der Bundesregierung,” (in German). [Online]. Available: https://bmdv.bund.de/SharedDocs/DE/Anlage/G/masterplan-ladeinfrastruktur-2.pdf?__blob=publicationFile

[61] J. A. P. Lopes, F. J. Soares, and P. M. R. Almeida, “Integration of Electric Vehicles in the Electric Power System,” *Proc. IEEE*, vol. 99, no. 1, pp. 168–183, 2011, doi: 10.1109/JPROC.2010.2066250.

[62] Willett Kempton and Steven E. Letendre, “Electric Vehicles as a New Power Source for Electric Utilities,” [Online]. Available: http://www.civil.ist.utl.pt/~martinez/PDF/ELECTRICMOVE/Paper18.pdf

[63] Jedlix, *Smart Charging Home Page - Jedlix.* [Online]. Available: https://www.jedlix.com/ (accessed: Feb. 21 2023).

[64] Transnet BW GmbH, *Große Fortschritte bei künftiger Netzstabilisierung durch E-Autos.* [Online]. Available: https://www.transnetbw.de/de/newsroom/presseinformationen/grosse-fortschritte-bei-kuenftiger-netzstabilisierung-durch-e-autos (accessed: Jan. 27 2023).

[65] N. Bañol Arias, S. Hashemi, P. B. Andersen, C. Træholt, and R. Romero, “Assessment of economic benefits for EV owners participating in the primary frequency regulation markets,” *International Journal of Electrical Power & Energy Systems*, vol. 120, p. 105985, 2020, doi: 10.1016/j.ijepes.2020.105985.

[66] J. Aengenvoort, “What's the business model of a Virtual Power Plant (VPP)?,” https://www.next-kraftwerke.com/energy-blog/business-model-virtual-power-plant-vpp (accessed: Feb. 21 2023).

[67] B. K. Sovacool, L. Noel, J. Axsen, and W. Kempton, “The neglected social dimensions to a vehicle-to-grid (V2G) transition: a critical and systematic review,” *Environ. Res. Lett.*, vol. 13, no. 1, p. 13001, 2018, doi: 10.1088/1748-9326/aa9c6d.

[68] D. Johnsen *et al., Gesteuertes Laden von Elekrofahrzeugen über Preisanreize*: TÜV Rheinland Consulting GmbH, 2020. [Online]. Available: https://publica.fraunhofer.de/entities/publication/9dc58373-f26a-4c2b-beb7-cbe496002946/details

[69] K. van Heuveln, R. Ghotge, J. A. Annema, E. van Bergen, B. van Wee, and U. Pesch, “Factors influencing consumer acceptance of vehicle-to-grid by electric vehicle drivers in the Netherlands,” *Travel Behaviour and Society*, vol. 24, pp. 34–45, 2021, doi: 10.1016/j.tbs.2020.12.008.

[70] Fraunhofer IWES, LichtBlick SE, SMA Solar Technology AG, Volkswagen AG, “IntelligenteNetzanbindung von Elektrofahrzeugen zur Eerbringung von Systemdienstleistungen- INEES,” (in German). [Online]. Available: https://www.erneuerbar-mobil.de/sites/default/files/2016-09/INEES_Abschlussbericht.pdf

[71] Aline Scherrer, Uta Burghard, martin Wietschel, Elisabeth Dütschke, *Early Adopter von E-Fahrzeugen: Ladeleistungen, Eigenerzeugung und Einstellungen zum Lademanagement.* [Online]. Available: https://www.researchgate.net/publication/338764283_Early_Adopter_von_E-Fahrzeugen_Ladeleistungen_

Eigenerzeugung_und_Einstellungen_zum_Lademanagement (accessed: Feb. 21 2023).

[72] S.-L. Andersson *et al.,* “Plug-in hybrid electric vehicles as regulating power providers: Case studies of Sweden and Germany,” *Energy Policy*, vol. 38, no. 6, pp. 2751–2762, 2010, doi: 10.1016/j.enpol.2010.01.006.

[73] A. Schuller and F. Rieger, “Assessing the Economic Potential of Electric Vehicles to Provide Ancillary Services: The Case of Germany,” (in En;en), *Z Energiewirtsch*, vol. 37, no. 3, pp. 177–194, 2013, doi: 10.1007/s12398-013-0112-x.

[74] J. Jargstorf and M. Wickert, “Offer of secondary reserve with a pool of electric vehicles on the German market,” *Energy Policy*, vol. 62, pp. 185–195, 2013, doi: 10.1016/j.enpol.2013.06.088.

[75] infas Institut für Sozialwissenschaft, *Mobility in Germany 20008 – Pulikationen (German).* [Online]. Available: https://www.mobilitaet-in-deutschland.de/mid2008-publikationen.html (accessed: Feb. 9 2023).

[76] T. W. Hoogvliet, G. Litjens, and W. van Sark, “Provision of regulating- and reserve power by electric vehicle owners in the Dutch market,” *Applied Energy*, vol. 190, C, pp. 1008–1019, 2017. [Online]. Available: https://econpapers.repec.org/article/eeeappene/v_3a190_3ay_3a2017_3ai_3ac_3ap_3a1008-1019.htm

[77] Tilman Huhne, Julian Schultheiß, Magnus Wobben, Patrick Wörner, and Oliver Wohak, “Optimale Erbringung von Systemdienstleistungen mittels Vehicle-to-Grid,” (in German), *ET. Energiewirtschaftliche Tagesfragen*, vol. 70, no. 10, pp. 59–62, 2020. [Online]. Available: https://www.researchgate.net/publication/346016926_Optimale_Erbringung_von_Systemdienstleistungen_mittels_Vehicle-to-Grid

[78] Ivan Pavic, Hrvoje Pandzic, and Tomislav Capuder, “Electric Vehicles as Frequency Containment Reserve Providers,” in *2020 6th IEEE International Energy Conference (ENERGYCon)*, 2020, pp. 911–917. [Online]. Available: https://www.researchgate.net/publication/346565553_Electric_Vehicles_as_Frequency_Containment_Reserve_Providers

[79] J. Figgener *et al.,* “The influence of frequency containment reserve flexibilization on the economics of electric vehicle fleet operation,” *Journal of Energy Storage*, vol. 53, p. 105138, 2022, doi: 10.1016/j.est.2022.105138.

[80] W.-P. Schill, M. Niemeyer, A. Zerrahn, and J. Diekmann, “Bereitstellung von Regelleistung durch Elektrofahrzeuge: Modellrechnungen für Deutschland im Jahr 2035,” (in German), *Z Energiewirtsch*, vol. 40, no. 2, pp. 73–87, 2016, doi: 10.1007/s12398-016-0174-7.

[81] N. Kraftwerke, *Hyundai Motor Group, LG und Next Kraftwerke liefern Re-gelleistung aus E-Autos im Netzgebiet von Amprion.* [Online]. Available: https://www.next-kraftwerke.de/neues/regelleistung-hyundai-lg (accessed: Feb. 16 2023).

[82] Porsche Newsroom, *Geben und Nehmen: Der Taycan als Pufferspeicher für das Stromnetz.* [Online]. Available: https://newsroom.porsche.com/de/2022/produkte/

porsche-taycan-pufferspeicher-stromnetz-vehicle-to-grid-anwendungen-27527.html (accessed: Feb. 16 2023).

[83] TenneT, *E-Autos als Stromspeicher: sonnen und TenneT gelingt erstmals Einbindung von Elektroautos in das Stromnetz.* [Online]. Available: https://www.tennet.eu/de/news/e-autos-als-stromspeicher-sonnen-und-tennet-gelingt-erstmals-einbindung-von-elektroautos-das (accessed: Feb. 20 2023).

[84] M. Doppelbauer, “Energiespeicher,” in *Grundlagen der Elektromobilität*: Springer Vieweg, Wiesbaden, 2020, pp. 129–184. [Online]. Available: https://link.springer.com/chapter/10.1007/978-3-658-29730-5_6

[85] Volkswagen Deutschland, *Hochvoltbatterie: Garantie und Pflege.* [Online]. Available: https://www.volkswagen.de/de/elektrofahrzeuge/id-technologie/batteriegarantie-und-pflege.html (accessed: Feb. 17 2023).

[86] Regelleistung-Online, *Analysen - Regelleistung-Online.* [Online]. Available: https://www.regelleistung-online.de/analysen/ (accessed: Feb. 17 2023).

[87] Agora Energiewende, Prognos, Consentec, “Klimaneutrales Stromsystem 2035. Wie der deutsche Stromsektor bis zum Jahr 2035 klimaneutral werden kann.,” (in German). [Online]. Available: www.agora-energiewende.de

Appendix

The digital appendix contains the following folders and files:

- Master Thesis
  - *Master_Thesis_Lea_Kern.docx*
  - *Master_Thesis_Lea_Kern.pdf*
- Literature as PDF
- *Figures, Illustrations and Diagrams.pptx*
- *Simulation instruction.xlsx*
- Simulation Data
  - *reslutsFCR2021.xlsx* & *resultsFCR2022.xlsx*: Economical input data
  - modifiedCPGeM: folder with the modified CPGeM
  - Simulation 100 HH 1 year: results of the simulation of 100 households for one year
  - Simulation 25 HH 1 week: results of the simulation of 25 households for one week