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Bachelorarbeit

Simulation of charging types and rates for Vehicle-to-Grid (V2G)

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Abstract

Electric vehicles have become increasingly popular in recent years and are a significant step towards sustainability and climate protection. This thesis deals with vehicle to grid (V2G) capable vehicles and examines the services for their potential to generate profit and stabilise the electricity grid. The main task of this thesis is to compare the typical charging rates of 2.3kW, 11kW and 22kW and to investigate them in the light of battery degradation and potential profit. Specifically, we propose a calculation model to find the profit of each charging rate's best possible charging periods and calculate the profitability. Our evaluation analyses the profit with and without degradation. Results show that at higher charging rates, battery degradation costs almost balance out.

Kurzfassung

Elektrofahrzeuge haben sich in den letzten Jahren immer mehr etabliert und sind ein bedeutender Schritt in Richtung Nachhaltigkeit und Klimaschutz. Diese Arbeit beschäftigt sich mit V2G fähigen Fahrzeugen und untersucht die Services auf ihr Potential, Profit zu generieren und das Stromnetz zu stabilsieren. Die Hauptaufgabe dieser Arbeit ist es, die gängigen Laderaten von 2.3kW, 11kW und 22kW zu vergleichen und diese im Anbetracht der Batterie degradation sowie dem möglichen Gewinn zu untersuchen. Im Einzelnen schlagen wir eine Berechnungsmodell vor, mit dem wir den Gewinn der einzelnen Laderaten die bestmöglichen Ladezeiträume findet und die Profabilität berechnen können. Unsere Bewertung analysiert den Gewinn mit und ohne Degradation. Ergebnisse zeigen, dass bei höheren Laderaten die Kosten der Batteriedegradation sich beinahe ausgleichen.

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Acronyms

AC alternating current. 22

BEV battery electric vehicle. 19

CCCV constant current constant voltage. 25

DBMS database management system. 28

DC direct current. 22

DOD depth of discharge. 30

EV electric vehicle. 17

EVSE electric vehicle supply equipment. 23

FCE fuel cell electric vehicle. 19

HEV hybrid electric vehicle. 21

ICE internal combustion engines. 19

LFP lithium iron phosphate. 20

LMO lithium manganese oxide. 20

NCA nickel cobalt aluminum oxide. 20

NMC nickel manganese cobalt. 9

PHEV plugin hybrid electric vehicle. 11

SOC state of charge. 22

SOH state of health. 27

SQL structured query language. 28

V2G vehicle to grid. 5

1 Introduction

The Paris Agreement, which was adopted at the end of 2015, aims to limit the increase in global average temperature to below 2°C. By 2025, industrialised countries are committed to spend 100 billion U.S. dollars annually on climate protection. In the transport sector greenhouse gas emissions are to be reduced and the use of renewable energy sources is to be encouraged. The car industry has specialised in producing more electric vehicle (EV) to achieve this goal. Smart grids have been introduced to improve the utilisation of the existing infrastructure. One part of this is the bidirectional V2G concept. Here the EV is designed to store electric energy when there is a surplus of power available in the electrical grid. It allows a draw from the battery and feed it back to the grid when there is a shortage of electrical power. Storing electrical energy can be particularly helpful when energy from renewable sources does not deliver consistent electricity, but fluctuations in the power grid are expected. Here, the V2G method can provide compensation and thus a more stable electricity network. Not only for the storage of the public but also of the own produced electricity for example a photovoltaic system can be realised by the electric car. Also, through smart charging, the private individual can profit by selling the electricity when demand is high and the market price is expensive, and by buying the electricity from the market when the price is cheap. According to the Electric Vehicle Outlook from BloombegrNEF, 116 million EVs are expected to be on the market by 2030 [MIO+22]. With battery sizes ranging from 16.7 kwh to 118 KWh [22], if the V2G principle is installed in the vehicles, it can play a significant role in how the energy market operates.

1.1 Problem statement and research question

Problem Statement

With 103 projects in 24 countries, V2G is a hot topic with promising benefits. However, few car manufacturers have electric cars on the market that are V2G capable. One reason is that the market always reflects the interest of customers. Buyers may be concerned about the extra costs if they want to use V2G privately. Also, the principle is not widely known, so few know the pros and cons. Another reason may be the impact on daily life. Since the vehicle is still accessible at all times, the fear of not being able to use the car for emergencies or spontaneous trips can arise. Due to the extra cycles and the resulting battery degradation, the advantage of V2G is doubted. Studies looking at the feasibility of V2G have focused on the following fields:

Battery degradation During charging and driving, the battery life is affected. Research by [JGZ+18; PAW10; XOU+18] deals with the degradation of the batteries concerning the charging and discharging processes that additionally arise with V2G.

Smart charging To achieve the greatest profit in charging and discharging with V2G, intelligent algorithms are needed. These were researched and analysed in [FBBG21; HKR15; SDFW14].

Renewable Energies The connection between V2G and renewable energies from wind and solar is researched in [BBC12; KK16; SLZL20]. They focussed on working with mostly smaller domains to reduce costs via renewable energy storage.

Ancillary services and grid stability In order to ensure a constant main voltage and a continuous flow of electricity, ancillary services are needed for a stable grid. Frequency regulation and peak load shavings are examined in [SBD+14; Wir19; ZXH+20].

Since there are different types of charging on the vehicle, the question arises for each owner what is the best variant for him, with which he has both his car at selected times ready to drive and that the vehicle battery lives as long as possible. Owners of V2G capable vehicles who are unaware of the advantages and disadvantages could be deterred because there are more charging cycles than a conventional electric car has. Another reason is the extra cost of installing a charger in the home that supports V2G.

Research Question

- How will the battery life of an EV be affected when it's charged with 2.3kW, 11kW and 22kW charger?
- How many charge/discharge cycles will be accomplished in the V2G window when using the three types of charging and which charging duration is beneficial?
- Will it be beneficial for V2G users to own a Type 2 Charger in terms of charging rate (C-rate)?
- Will fast-charging maximise the possible amount of energy to the degradation cost ratio?

1.2 Contributions

This research aims to develop a price model that includes an optimal C-rate for EVs. Explicitly, focusing on EVs which use the vehicle to grid method. Therefore, deriving a model that can be used for suggestions on the battery type and EV. Hence, the model uses different parameters to minimise the ratio between battery degradation costs and profit gained by providing electricity to the grid. The model was created in the programming language python 3.

1.3 Document Structure

Chapter 2 begins with background information and explains important principles to understand the concept discussed in this work. Chapter 3 provides information to recent work Chapter 4 explains the concept idea of the simulation and the Chapter 5 will explain the implementation process and Chapter 6 compares the results from the simulation And finally, in chapter 7, we will reach our conclusion and final thoughts for future work and improvements

2 Background and Motivation

In Germany, a greenhouse gas reduction of 95% shall be achieved. [BBH+16] In order to do that, it is recommended that in the car industry internal combustion engines (ICE)s should only be built till 2030 and after that only battery electric vehicle (BEV) or fuel cell electric vehicle (FCE) shall come onto the market. [Bie21] To support large fleets of EVs, a correspondingly large amount of electricity is needed. To meet the demand and at the same time protect the climate the longer-term trend in gross electricity production tends toward a decrease in coal and nuclear energy and the further expansion of renewable energies. In Germany, 534 billion kilowatt hours of electricity were produced in 2019. 42% of this came from renewable energies, such as wind power and photovoltaic plants. In 2020 the installed capacity of onshore wind turbines was 54.4 gigawatts and offshore 7.75 gigawatts. According to the Renewable Energy Law, powerplants with 71 GW on land and 20 GW are to be expanded to reach a capacity at sea.

Photovoltaic systems are also a cost-effective way to obtain renewable electricity. At the end of 2019, more than 1.6 million plants generated about 47.5 GW of power, making it the second largest power generation system. Although the development of new power generators is progressing, people need more and more electricity. This demand is due to a growing population, new economic developments in developing countries, and more and more electronic devices in everyday life.

One problem with renewable energies is that electricity production is not linear but rather fluctuating. For example, the first quarter of 2020 was very windy, so more electricity from renewable energy sources was fed into the network for the first time than from conventional energy sources. [BMKS21]

Since the demand is needed to work with more current, such imbalances need to find a way to store the electricity in times of surplus to feed it back when needed. The storage also brings several advantages in the event of short-term network fluctuations. The storage units can balance the network and eliminate short-term power failures, voltage drops or surges. Also, plants that are only partially utilised to cover the needed electricity in case of a sudden demand and possible electricity emergencies and to prevent the failure of generation or transmission units could be eliminated or reduced. For minute-hour peaks in the daily demand curve, the storage facilities can accommodate the necessary power for the network. There are two main memory types for storage. [KBJ+14] They are either electrical or thermal. Thermal energy storage systems use heating or cooling liquids to store energy and later use it for power generation.

2.1 Energy Storage systems

In this work, we want to focus on electrical energy storage systems. More information about thermal energy storage can be found in the book from Dincer and Rosen [DR21]. They provide additional background on thermal energy storage systems and their applications. A battery energy storage system uses electrochemical reactions to deliver electric energy. It consists of single or multiple cells. They are connected in series, in parallel or both depending on the cell type. The battery consists of two electrodes and an electrolyte, which transfer electrons from one electrode to another by applying an electrical voltage. This process discharges the battery through an external circuit. By application of an external voltage, it will reverse the process and the battery charges. The most common battery models used in energy storage applications include lead acid battery, nickel-based, lithium-based and sodium sulfur batteries [KBJ+14].

2.1.1 Lithium based batteries

Lithium-based batteries are the oldest type of battery worldwide. They are a very cheap solution because of their favourable manufacturing technology and high power output capability. A disadvantage is their build-up with acid, which is dangerous for humans and the battery has a very high atomic weight. The Nickel-Cadmium batteries are also heavy but have more harmful effects on the environment and human health. The advantage here is the battery's high lifespan in charge and discharge cycles. Lithium-ion batteries can store a large amount of energy and weigh comparatively little, but they have the potential to overheat, have more costs and have a limited life cycle. A related method is the lithium-ion polymer type which provides a more significant life cycle than the classical battery. However, it has problems when overcharging or the charge value falls below a particular value [MM15].

The industry has specialised in lithium-ion-based batteries because in comparison to the previously mentioned types, they do not exhibit a memory effect, the self-discharge rate is significantly lower, the lifetime is longer than ten years, it is smaller weight and size [AHK10].

Chemistry types for electric batteries

For pure EV, there are four different chemistry types for lithium batteries: lithium iron phosphate (LFP), NMC, nickel cobalt aluminum oxide (NCA) and lithium manganese oxide (LMO). [CSV+12] Batteries made by Tesla Motors rely on NCA due to their excellent electrical properties, and their insensitivity to process fluctuations and humidity. The high price results from the restricted occurrence of cobalt. LMO batteries are found in the Think and Nissan-Leaf models. It benefits from the low prices; manganese can be found in the environment and the low toxicity to the environment. Although it has good rate capability and excellent cycle Lifetime at ambient temperature, Since manganese dissolves in the electrolyte due to elevated temperatures, it has a higher capacity loss compared to NCA and LMO. It also has a lower capacity, which it makes up for with an outstanding ambient temperature life and a reasonable rate capability. Based on phosphate, LFP batteries have an excellent temperature range. Also, the characteristic can withstand oxidation and an acidic environment which improves the battery's performance. The Mitsubishi-iMiEV and the BYD-E6 are based on this technology. NMC batteries are sensitive but comparing the previously mentioned battery types many benefits. It has the highest capacity per mAh/g [TKS08] ***

2.1.2 Vehicle status

Around 67,7 million vehicles are registered in Germany. The most common are fuel types, with 31 million gasoline and 14,8 diesel cars. Although the share of electric cars is still low, there is growth in the car industry. In 2.1 is observable that the percentage from EV in 2022 is at 1,3% so the stock has doubled compared to the previous year. [KBA22]

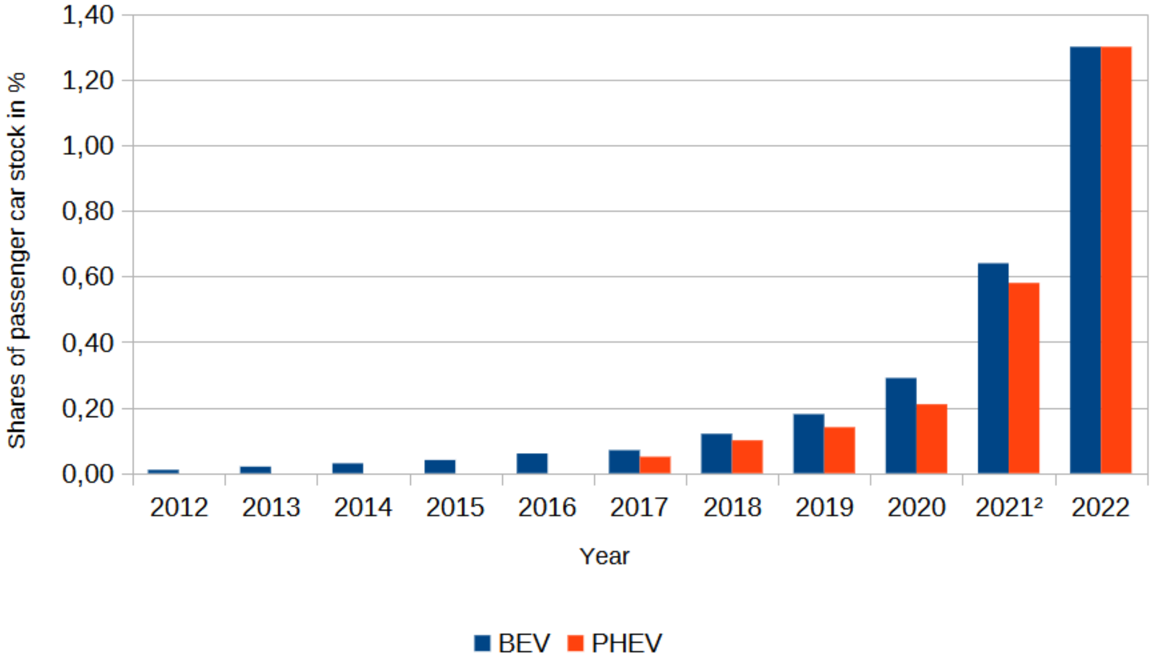


Figure 2.1: Market share of electric cars in the passenger car fleet in Germany by 2022

2.1.3 Electric vehicle

An EV is powered by a battery and uses one or more electric motors for propulsion. According to the International Council on Clean Transportation, they have a 66%-69% lower emissions life cycle, lower costs and higher efficiency compared to ICE.

An EV uses the electricity from a battery as motive power. A hybrid electric vehicle (HEV) consists of a small battery, an electric motor and an internal combustion engine. They use the electricity to accelerate the car, e.g. from a standstill and switch to the gasoline engine at a certain point. The battery is charged here by recuperating. Every time the car brakes, the kinetic energy can be used to operate a generator, which produces electricity through the electromotive resistor and load the battery.

Vehicles using an external plug to charge the battery are called PHEV. They also have an electric motor and a fuel-based ICE. Compared to HEV they can travel decent distances, usually around 20 to 30 kilometres with the electric power alone. BEV are pure EVs with one or more electric motors using the energy stored in a battery. Most of them are using fixed-ratio gearboxes and have no clutch. The batteries can be recharged using grid electricity, power sockets, and non-grid sources such as solar panels. This is the designation from the raw material of the individual vehicles to the part considered for fuel up to the vehicle's movement.

Advantages BEV

While ICE vehicles have pipeline emissions and pollute the environment when burning the fuels, electricity used to charge the EVs can be completely green. Even if the electricity comes from a CO_2-emitting source we have around half to one-third less CO_2-emission compared to the IC vehicles. Gases and oil need to be replaced in cars after a particular time to allow them to run smoothly. Due to their design, EVs do not need this. The acceleration runs smoothly and instantly because they have no transition and the electrical power goes directly to the wheels. The BEV also has an advantage on various inclines because, for example, it does not have to be shifted into another gear to have torque. Charging the EV full costs less compared to a conventional car running on gasoline. [Can22]

With 59-62% of the electrical energy supplied by the grid being converted into kinetic energy EVs have a 40% better use than a normal gasoline vehicle which can only use 17-21% of the energy generated.

Disadvantages BEV

The cost in the production of an EV is more expensive than that of IC engine. The travel distance from an EV is also shorter. Typical ranges are 600 and 1200 km in an ICE. EVs can reach between 300 and 450 Kilometers depending on the driving style. Refuelling is also time-consuming depending on the kind of charger. While gasoline cars can refuel in minutes, with a standard home charger, times up to 14h can be achieved. At fast-charge stations, in about 30 minutes, the car can be fully charged. Furthermore, battery packs are hefty and also expensive. The state of charge (SOC) displays the current charge level. This is given as a percentage and lies between 0 and 100%. The SOC is essential for the grid as it is used as a regulating factor for the flow of energy and the total load requirements.

2.2 Charging

There exist two charging methods. The most common one is the alternating current (AC) method. It is cheap and the power that comes from the grid, which is AC is then converted inside the car to direct current (DC). Charging can be done at multiple locations for example, at home or official charging stations. Outputs depend on the converter's capabilities inside the cars and the output power of the charge point and it ranges between 6A (1.4 kW with 240V) and 63A (43.5 kW with 400V).

DC charging is more expensive and larger. Typically DC is to fast charge the EV. The AC from the grid is directly converted in the charger, which distinguishes those two types. Much power is needed from the grid, so the high-cost result from the production, installation and operation. Also, the tariffs are a bit higher than AC ones.

Depending on the direction of flow of the current, there are two types of chargers, unidirectional and bidirectional. Unidirectional-based chargers are easy to control, require less hardware and have lesser battery degradation issues. A bidirectional charging system supports both ways, charging the vehicle with energy from the grid and injecting it back into the grid. This bidirectional link to the power grid is called Vehicle-to-grid. The potential of V2G is concluded to offer the most storage for Europe compared to other standalone batteries. [Ric13]

2.2.1 Charging rate

The charging or discharging of a battery is specified as a function of time as the C-rate. To fully charge or drain a battery within one hour, 1C is required. The formula for this is:

$$C_{rate} = \frac{C_{out}}{B_{cap}} \tag{2.1}$$

2.2.2 Charger systems

An important role in the development of EVs are battery charger. They need to fulfill several requirements, such as high efficiency and reliability, high power density, and low volume and weight. Chargers are always connected to the specific characteristics of an ev and his battery type, which gives details about charging time and charging capacity.

2.2.3 Charger levels

To categorise the rated power, the current of the system and the voltage, there exists three levels:

Level 1

With 120 V/15 A (12 A usable) or with 20 A (16 A usable), level 1 charging is the slowest method. Based on the amperage, a power of 1.4-1.9 kW can be absorbed at the battery. [SIM16] Based on battery size and capacity, it takes 8 - 16 hours to charge an EV fully. The outlet is single-phase, and the method is also known as "Home Charging "as it is the cheapest and simplest charging form. This level, in general, is built-in the vehicle, with a small cost and no additional infrastructure is needed for the charging application.

Level 2

With a connection installation, it is possible to use Level 2 with 240 V and up to 80 A. They are often in the form of wall boxes and form a bridge between the vehicle and the power grid. They provide additional control and safety equipment, also known as electric vehicle supply equipment (EVSE). It can monitor the current charge and disconnect when fully loaded. Also, hardware faults or an external short-circuit fault can be detected. With its combination of an AC charge connector on top and a two-pin dc connector below, it benefits from both methods. Due to the faster loading speed compared to level 1, buyers tend to use level 2 stations.

Level 3

Often referred to as "fast charging", typically operating with 480 V or higher charge times in less than one h can be achieved. It utilises DC voltage directly from the cable’s connector inside the charging station and bypassed the EV ’s onboard charger.

2.2.4 Charging modes

Mode-1

Connected by a single cable to the socket without in-cable control and protection, this mode is very unsafe and not recommended. It uses the normal AC charging with a regular household outlet or a one or three-phase industrial outlet. Usually, this mode is for light EVs, with a built-in residual current device. [Ele21] Light EVs are, for example, e-bikes, e-scooters and other land vehicles powered by an electric motor, using a battery or fuel cell and weighing less than 100 kg. [Ben21]

Mode-2

Also with AC charging which is plugged in the regular outlet the second mode is limited to 3.7 kW in residential use or 7.4 kW for industrial use. Here the cable has an in-cable-control-and-protection device. It protects in case of an electric shock by isolation errors, when the owner tries to plug it into an outlet which was not intended to function as an EV charging station.

Mode-3

Inside the EVSE the voltage is controlled and communicated with AC charging and a wider range from 3.7kW to 43kW. Often there is also a charging line permanently connected to the charging station. The connectors on both sides of the charging cable are locked to prevent them from being pulled out under load.

Mode-4

In this mode, direct charging with dc chargers is possible. Also, special chargers can reach up to 150kW. Here the charging line is always permanently connected to the charging station and similar locked like in mode 3.

While modes 2,3 and 4 have a low level of communication, which is used to exchange basic information about the operating conditions, modes 3 optional and 4 have a combined charging system and a high-level communication is needed. Also higher safety standards for electrical safety and protection in the event of overcurrent has to be met for those two modes.

2.2.5 Charger types

Charger types are divided into AC connectors and DC connectors

AC connectors

Type 1 is single phase coupler, Type 2 and 3 consist of single and three-phase vehicle coupler,

DC connectors

In the Japanese market, the charger type is called CHAdeMO, and in the European market, the combined charging mode is the normalised standard. The company Tesla has built own connector which are both AC & DC [Pau19] [YK13] [KRK+21].

Battery charging methods

Typically Lithium Batteries are charged by the constant current constant voltage (CCCV) method consisting of two phases. The first constant current phase charges the battery with a constant current I_C until the voltage limit V_C, which is predetermined, is reached. The charge current is an essential factor for the battery as it can strongly influence the behaviour of the battery, so it is a great challenge to find the correct values for both the charging time and the capacity utilisation. After the voltage has been reached, the charger switches from constant current to constant voltage and keeps charging until the current drops to a low also predetermined value [LNL+20; Zha06]. A combination of several CCCV methods is called multi-stage constant-current charging. The current is progressively reduced when the terminal voltage reaches a certain voltage threshold. This will continue till the specific terminal condition of the battery is reached. CCCV and MCC are the efficient charging methods and the foundation for charging performance optimisation [Osm20].

Vehicle-to-Grid and Vehicle-to-Home

While EVs are charged by the grid, the batteries can also be used as storage for the electricity [KL97]. During low demand times, they can charge up their batteries and discharge the power to the grid in V2G or use it to power your home in the vehicle to home when needed. To work stable, the EV needs an EVSE which provides a logical connection or control to communicate with the network operator and monitors the vehicle itself. While vehicle to home is relatively simple, V2G needs a more complex control. The grid operator sends a request; this could be done either by a radio broadcast, direct Internet connection, power line carrier or cell phone network, for power to a large number of vehicles. This signal can be transmitted to the vehicle directly or to the supervisor, who controls the vehicle fleet in an area [KT05].

There are only a few V2G capable cars compared to pure electric cars. On the European market, these are the models from Mitsubishi, the Outlander and i-MiEV, and the models from Nissan, the Leaf and e-NV200. Since V2G vehicles use the ChAdeMO type, customers may be reluctant to use a type that is not common in Europe. However, research continues and companies are also working on more V2G capable vehicles. The Volkswagen Group has announced in the *Handelsblatt* that by 2022 every electric car they produce based on the modular e-drive system should be V2G capable [Men21].

Model / Manufacturer	Sales in thousand units	Battery type	Size
Nissan Leaf	100.99	LMO	52 kWh / 75 kWh
Nissan e-NV2000	53.04	LMO	58 kWh / 77 kWh
Mitsubishi Outlander	45.69	LMO-NMC	41 kWh
Mitsubishi i-MiEV	38.31	LMO-NMC	52 kWh / 77 kWh

Table 2.1: PHEV V2G Vehicles

RTE

The round trip efficiency is the ratio of the energy recovered from the battery and the energy charged into it, this is given in %. The higher the percentage, the less energy is lost, for example in the form of heat loss. Lithium-ion batteries have the highest round-trip efficiency compared to other storage technologies.

Charging and Discharging efficiency

The efficiencies (losses) at a given point and storage level in the charge and discharge cycle are the charging/discharging efficiency. These efficiencies vary depending on the size of the battery, the crate and the type of storage.

Manufacturer / Model	Sales in thousand units	Battery type	Size
Tesla Model 3	100.99	NMC	52 kWh / 75 kWh
Volkswagen ID.3	53.04	NCA	58 kWh / 77 kWh
Renault Zoe	45.69	NCA	41 kWh
Volkswagen ID.4	38.31	NCA	52 kWh / 77 kWh
Ford Kuga PHEV	36.19	NCA	14,4 kWh
Kia Niro EV	33.93	NCA	64 kWh
Hyundai Kona Electric	32.3	NCA	64 kWh
Volvo XC40	31.74	NCA	10.7 kWh
Fiat 500	30.92	NCA	42 kWh
BMW 330e (PHEV)	29.85	NCA	11,2 kWh

Table 2.2: PHEV Vehicle and Manufacturer sorted by sales in Europe

Cycle number counting

One complete discharge from 100% to 0% and back full describes one cycle. Counting these cycles creates a simple and direct way to observe the life of a battery. Manufacturers provide information about the estimated total life cycle number and the cycles counted so far give a rough overview of the current battery status. Usually, the information about life cycles is found in small devices such as laptops, mobile phones or similar devices. Apple users, for example, can find the number of cycles in the system settings.

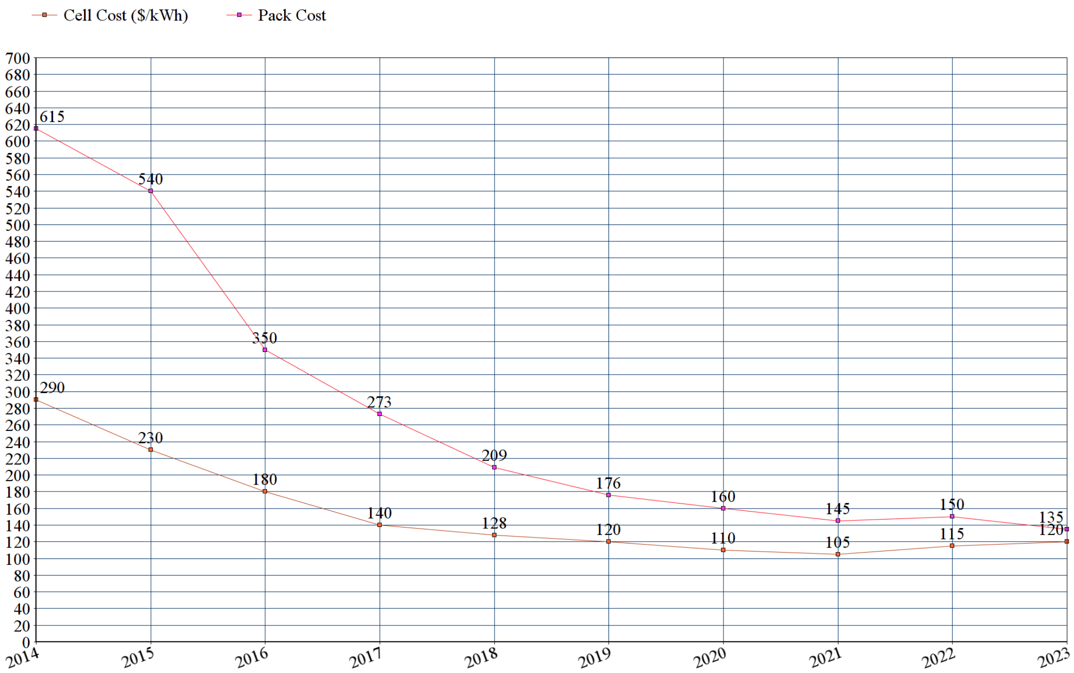


Figure 2.2: "The price per kilowatt-hour of lithium-ion battery cells with NMC cathodes. Prices for 2022-2023 are estimates."[ISE]

In EVs the state of health (SOH) is an essential factor in determining the degradation of the battery so possible failures can be detected and prevented early. [BGV+16] If the lithium content in the active carbon of the batteries decreases, this will lead to self-discharge and the capacity decreases as well. Under low temperatures and high currents or both, the metal plating from lithium itself leads to a faster ageing and efficiency loss. [JGF20; VNW+05]

Metal plating is an unwanted side effect from the battery where ions reduce to metallic lithium instead of embedding them into the anode crystal structure. The ageing effect of the graphite also affects the cathode, leading to modified properties of the electrode after time and use. These unavoidable changes in the graphite particles occur in each charge and discharge cycle, which affects the electrode's impedance and increases it slightly. Lifetime effects which can occur while storing the energy affect the calendar life of the battery; this can include self-discharge or impedance rise.

[XOU+18]

2.3 Database

A database system is needed to store and evaluate the simulated data. Depending on the database size, smaller ones are stored on a file system, while cloud storage and computer clusters need more extensive databases.

To organise a database, one needs a database management system (DBMS). A DBMS serves as an interface between users or programs and the database, so that data can be easily accessed, modified, controlled and organised [Ora22]. The DBMS is installed on the system and located on a workstation like a computer or a server, depending on the application. Using a specific language like structured query language (SQL) allows us to communicate with the database. There are several forms of databases [Ora22].

A survey conducted in 2020 shows multiple DBMSs, and on top, we have MySQL with the largest share of users of DBMSs. For this work, we use a minor database system, namely SQLite. The advantage of this is that the database needs no server. SQLite is a relational database storing data in tables with rows and columns. Tables can be linked to each other via entities. This is done by means of so-called foreign keys. Linked tables have stronger data integrity, lower data redundancy and the data is easier to analyse. A one-to-one relationship is a direct link between exactly one entry in one table and one entry in the other table. Similarly, a one to many relationship has exactly one entry in one table and several in the linked one. SQLite library is smaller, making it easy to copy data from different devices. MYSQL supports multi-user access while SQLite is more for single-user as it does not have any specific user management functionality. Since the database does not get too big and does not need multiple users, SQLite is sufficient in this case. Also SQLite is easy to set up and does not require many configurations compared to MySQL.

3 Related Work

3.1 Battery health issues and challenges

3.1.1 Battery aging

The individual components of the batteries undergo ageing processes during their service life, which cannot be reversed. These changes are reflected in the structure of the components, the anode and cathode, as well as in the characteristics of the electrolytes [RLCL14].

Degradation of the battery

To estimate a battery's life cycle, the critical factor influencing the battery degradation and the ageing mechanism is essential. It is difficult to determine the actual state of the battery because there is no direct measurement for the state of the battery, so the commonly known methods estimate the current SOH. The SOH is the available unit to measure the ageing level of batteries. The condition of a battery is described in percentage. While 100% is known as a fresh new battery, a depleted battery only has 80% of its initial capacity and should be replaced. [VNW+05] The SOH estimation is either model-based or calculated by experimental methods. Barre et al. [BDG+13] analyzed existing models and came up with the following five categories:

1) **Electrochemical model** It relies on theory understanding to predict the physical and chemical reactions causing the battery to degrade

2) **Statistical approach** The model mainly based on data, without scientific background knowledge

3) **Analytical models** Measurements estimate the ageing parameters often combined with empirical fitting

4) **Performances-based model** Physical equations model the battery ageing

5) **Equivalent circuit based models**

Each of the methods mentioned has its advantages and disadvantages. Since both capacity fade and resistance rise greatly influence the battery's ageing, both factors must be taken into account in the modelling. In many studies, only one factor is taken into account. Statistical methods require large data sets to account for all the factors influencing the battery. Chemical studies can work precisely on the selected battery model, but they are not applicable as they depend on their design and technology. A significant factor in this is the battery's ageing over time. A battery must have aged over a longer time to examine the effects more closely. Purely electric cars have not existed for very long, so the data is also limited. It is possible to age the battery faster to get results,

Sources / Year	Stress factors considered	Type of aging considered	Battery type	Model Output
J. Wang et al. [WLH+11] 2011	Temperature, C-rate, charge throughput	Cycle aging,	NMC, LMO	Remaining capacity
Xu et al. / 2013 [Xu+13]	DOD, SOC, C-rate, Temperature, Time	Cycle and calender aging	LMO	Remaining capacity
Gao et al. / 2017 [GJZ+17]	C-rate, cycles, Temperature	Cycle aging	NMC	Capacity compared to cycles
Lunz et. al / [LYGS12]	Charging Power, SOC, c-rate	Cycle and calender aging	NMC - LFP	Estimated cycle lifetime
Bishop et al. / 2013 [BAB+13]	Temperature, SOC, Voltage, Ah, DOD, fixed C-rate	Cycle and calender aging	18650	Estimated lifetime in years
Uddin et al. / 2017 [UJW+17]	Temperature, SOC, fixed Charge Rate, two discharge Rate, DOD	Cycle and calender aging	NCA	Remaining capacity
Petit et al. / 2016 [PPS16]	SOC, Temperature, C-rates	Cycle and calender aging	LFP- NCA	Remaining Capacity
D. Wang et al./ 2016 [WCZ+16]	Temperature, C-rate, Ah,	Cycle and calender aging	NMC - LMO	Capacity loss

Table 3.1: V2G battery degradation models

but these values do not correspond precisely to those that would have had an impact in the real world[BDG+13]. Also, due to the rapid charging and discharging, the time the energy is stored is significantly shorter than in real life.

Most processes occur at similar times, so the individual processes cannot be studied in isolation. Experimental methods directly test the batteries in a laboratory environment to measure the capacity, impedance and other factors. [XOU+18] Analysing data based on real-time events and processing it is the indirect experimental method. Extending this indirect method with intelligent algorithms or filtering and identifying the main characteristic parameters will create the SOH from a model-based estimation.

Causes

Charging Rate With higher charging rates, the battery degradation is more significant compared to a lower charger rate. [WLH+11]

temperature It influences chemical reactions as well as ionic conductivities of electrodes and electrolytes

SEI formation On the negative electrode of Li-ion batteries a solid electrolyte interphase(SEI) is formed. This protecting layer guarantees a long life for the battery as it prevents further electrolyte degradation and allows continued electrochemical reactions. The creation of the SEI takes place in the first charging/discharging processes, and it will reduce the graphite surface, leading to the battery's degradation. [WKL+18]

Lithium deposition Overcharging a battery or charging at low temperatures will lead to lithium deposition. This leads to capacity fade and can even lead to internal short [LHY+14].

DOD Like the charging rate, with a higher depth of discharge (DOD) the cells will degrade faster. It is recommended that the DOD should not exceed 60% [Som04].

SOC If the battery is kept at high SOCs, the battery degradation increases according to Bashash et al. [BMFF11]

Abdullah. et al [AS18] analyzed the requirements to make the V2G cost-effective and beneficial to EV owners, utilities and system operators. Masoum et al. [MDMA10] studied the impact of different charging strategies on the smart grid to analyse potential performance issues. The three different charging rates were standard charge at 2.4 kW, medium at 3.6kW and quick charging at 11.4 kW. By creating a V2G system model to determine the profit, an owner of an EV can make, Malya et al. [MFRA21] investigated the factors that played a role in V2G. Their model did not consider the dependence of different C rates concerning the degradation of the battery. Bhagavathy et al. [MBSM21] examined the existing literature on the various charging rates of common electric cars and their effects on EV battery life. They concluded that NMC batteries with a charge rate of more than 1C have a more significant impact on battery degradation than LFP batteries, which are not seriously affected by rates up to 4C. Table 3.1 lists further V2G models.

4 Modeling Techniques

The mobility in Germany (MiD) collects data on everyday mobility. This study was conducted at several-year intervals, most recently in 2017, in which approximately 70,000 people from 35,000 private households were asked. [Dig22] Data based on the results of this study describe the behaviour of car owners with EVs to build the model for the simulation. There are two types of measurements for data collection. On the one hand, all persons are included in the statistics in order to obtain an average value for the general public. The second measurement includes only mobile persons, i.e. people who go out of the house at least once a day. The daily average travelling distance per person is 39 km. For mobile persons, it is 46 km, which is the value being used for the daily consumption of the EV [CT18]. The results report of the MiD showed that 92% of all EV owner park their vehicle at home. They are either in a garage, a carport or a private parking space. It follows that 8% of EVs are charged either at public charging points or at charging stations at the workplace. These high numbers are due to the interest in having a private charging facility at home.

To find a benchmark for the daily driving distance, one must first look at the driving behaviour of electric cars. Although the operating costs are meager, the driving performance of EVs tends to fall below average. This factor could be explained by the fact that electric cars are used for shorter distances, a proportionally more minor part of the total mileage than comparatively long trips. The estimated annual mileage is 13000km.

V2G Profile

We use the data we have previously mentioned to create profiles for EV users. We have divided these into the following three profiles:

V2G0: No V2G during charging. As shown in 4.1 the electric vehicle is only charged when connected to a charging station.

V2G1 : While the vehicle is connected at work, it can access the V2G function. The vehicle is connected to the charger from 8 am to 5 pm as shown in 4.2

V2G2 : As in V2G1, the vehicle is connected during working hours, but the vehicle can also charge on V2G when arriving home at 6pm. This process goes from 6pm to 7am and can be seen in 4.3

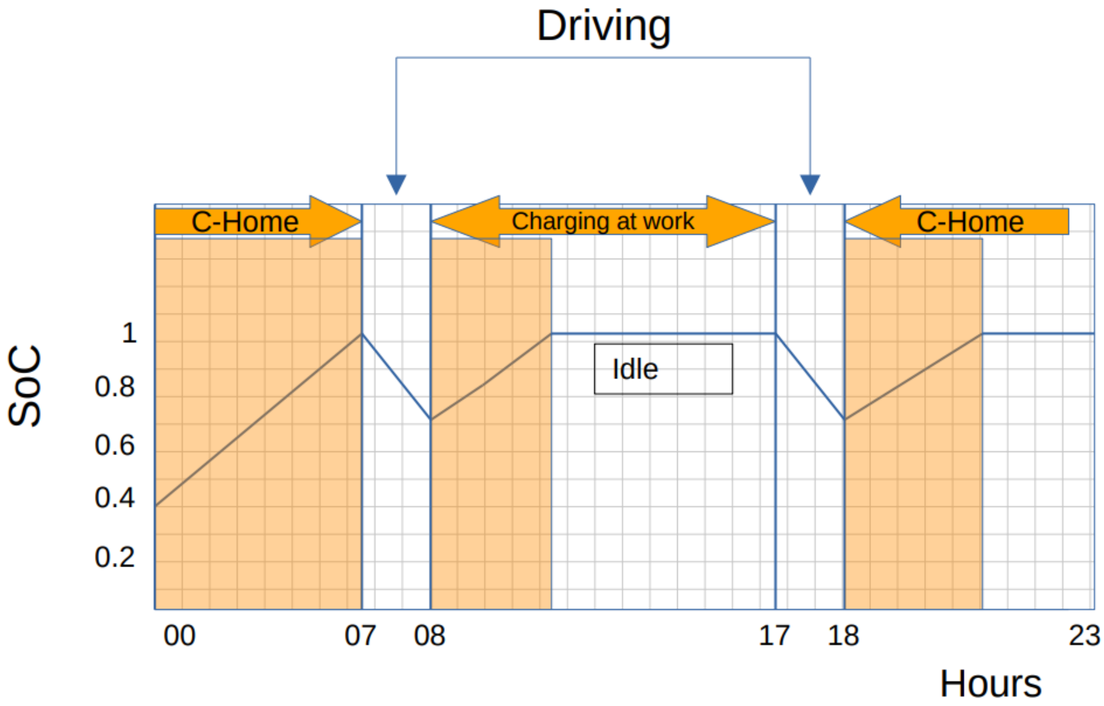


Figure 4.1: Driving pattern without V2G

4.0.1 Conceptual framework

To create a suitable model, data from the top ten best-selling pure electric cars in Germany were used as a basis. Each vehicle has a certain battery type, an average consumption as well as restrictions in the charging behavior differentiated in under load and maximum charging speed and capacity. The models are independent of each other in the simulation and the effects of simultaneous charging on the power network are not taken into account. Based on the individual model types and the law of large numbers, multiple vehicles will be simulated. Each vehicle has its own current SOC, battery usage, here estimated life cycles from the manufacturer of the battery will be calculated into % of lifetime.

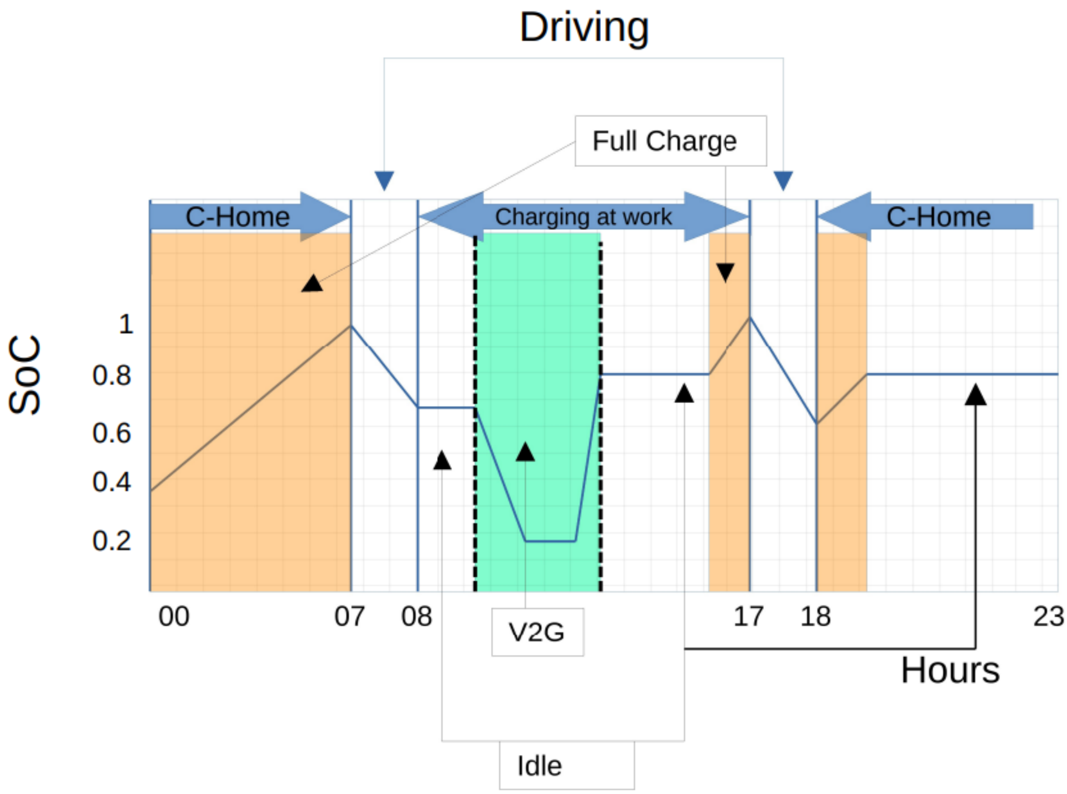


Figure 4.2: Driving pattern with V2G possibility at work

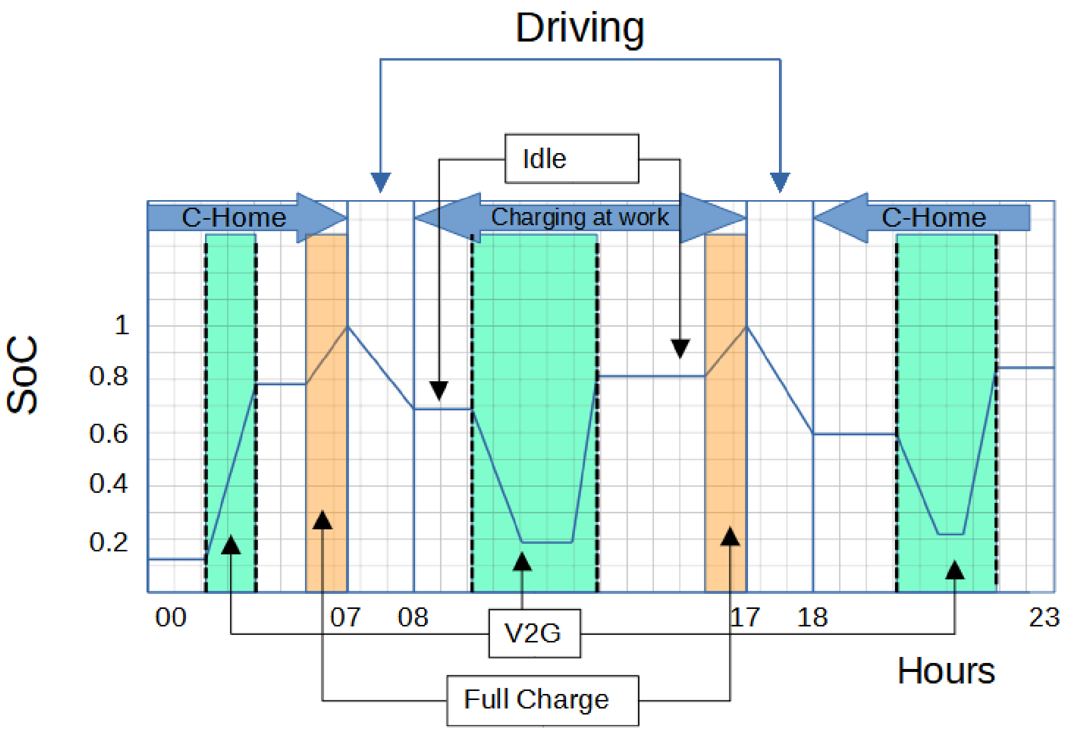


Figure 4.3: Multiple V2G events at work and home

5 Implementation

There were two programs to choose from for the simulation. On the one hand, it was Matlab with Simulink. On the other is the pure programming language Python. Simulink is a block diagramming environment for designing systems with mutli-domain models, simulating and deploying the system without programming effort. It has an event dispatcher that can be used for asynchronous networking or multi-agent systems. Both programs provide excellent tools for simulation and modelling. We decided to go with Python because it is free and open-source software, so future work can also be done without owning a license like in MATLAB. Also, for each additional toolbox they wish to install, users must pay extra in MATLAB. In comparison, Python offers hundreds of thousands of free packages to include in the program. Source code can also be modified and ported to other operating platforms.

5.1 Law of large numbers

In probability theory, there is the law of large numbers. It states that the more frequently a random experiment is carried out, the more the result of the random event, i.e. the empirical probability, approaches the theoretical probability. This approach will not be monotonic since outliers of the measurement still exist in a higher number of repetitions, but the relative distance between the measurement results decreases. Based on this law, the simulations of a large number of days will provide an approximate prediction of the battery level and impact on the EV over the simulated period. Unpredictable events on individual vehicles cannot be taken into account as these are lost in the calculation of the average values.

5.2 Profit calculation

The amount obtained from the sale of electricity to the grid is called revenue. To determine the profit, it is necessary to deduct all the costs incurred in purchasing electricity from the revenue. The degradation of the battery and its replacement cost must also be subtracted.

$$Profit = Revenue - (C_{replacement} + C_{electricity})$$

Revenue: To calculate the revenue, the following values must be taken into account:

$T_{\text{charge:}}$ Time while the vehicle is charging the grid
$T_{\text{price:}}$ Electricity price in kW at the time
kW: Number of kW which is charged
RTE: Effective current being charged

(5.1) $\text{Revenue} = \text{kw} * T_{\text{price}}$

(5.2) $\text{kW} = \text{SOC}_{t_0} - \text{SOC}_{t_1} * \text{RTE}$

5.3 Cost Optimization

The energy prices in the grid also reflect the demand on the market. Thus, when there is a surplus of energy, the price is relatively low, whereas the price is high when there is a shortage. In order to charge the vehicle at optimal times, the charge control unit must know what the prices in the network will be. For this, the day-ahead price from the grid operator is used.

Electric energy is traded on the power exchange. The principle is similar to that of a securities exchange. The smallest possible trading unit is 1 MW. Exchange trading takes place between 8 a.m. and 6 p.m. (CET). The day ahead price describes the trading of electricity for the following day. Negative electricity prices can occur when demand is lower than production. Typically, negative prices occur when there is a high feed-in of electricity from wind and solar power or low electricity consumption [Gmb21]. Negative electricity prices occur most frequently between 0 and 7 a.m. and between 2 and 4 p.m. and are most common in the winter months between December and February [Car22]. Since the storage capacities are not yet sufficient to completely absorb fluctuations between supply and demand, one is paid for electricity which is bought at negative electricity prices on the electricity exchange. Power plants that participate in the balancing energy market are legally obligated to produce a conventional minimum generation and cannot further down-regulate even in times of too much electricity [Gmb21]. For other market participants it is also not easy to completely stop the production.

The optimal price behavior of the market would be if the daily market price would resemble several sine curves. In this way, it would always be possible to load and unload in the same periods. In reality, the period is not evenly distributed and an algorithm is needed which calculates the minimums and maximums and thus concludes the number of charging events.

Various charging and discharging schemes were analyzed by [DSKS18; HKR15; SDFW14; SE11]. Factors such as grid power, load power demand, coordinated and uncoordinated strategies of charging/discharging were investigated in order to maximize profit and also to consider the mains voltage and effects of the charging schemes on it.

The prices of a sample day of simulation are in graph 5.1. Prices per MWh are shown here depending on the time points. Day-ahead prices are always given for a full hour, which leads to the staircase-shaped graph.

As seen in graph 5.2 depending on the charge time, the average price varies. Each step represents the average price for the period of the given hours. For example, if the vehicle has a charge period of 15 hours, the graph shows the possible charging time points that do not exceed the total charging time duration. For charging at time $t = 8$ with a charging time of 1h, the price per MWh is -48.93 €

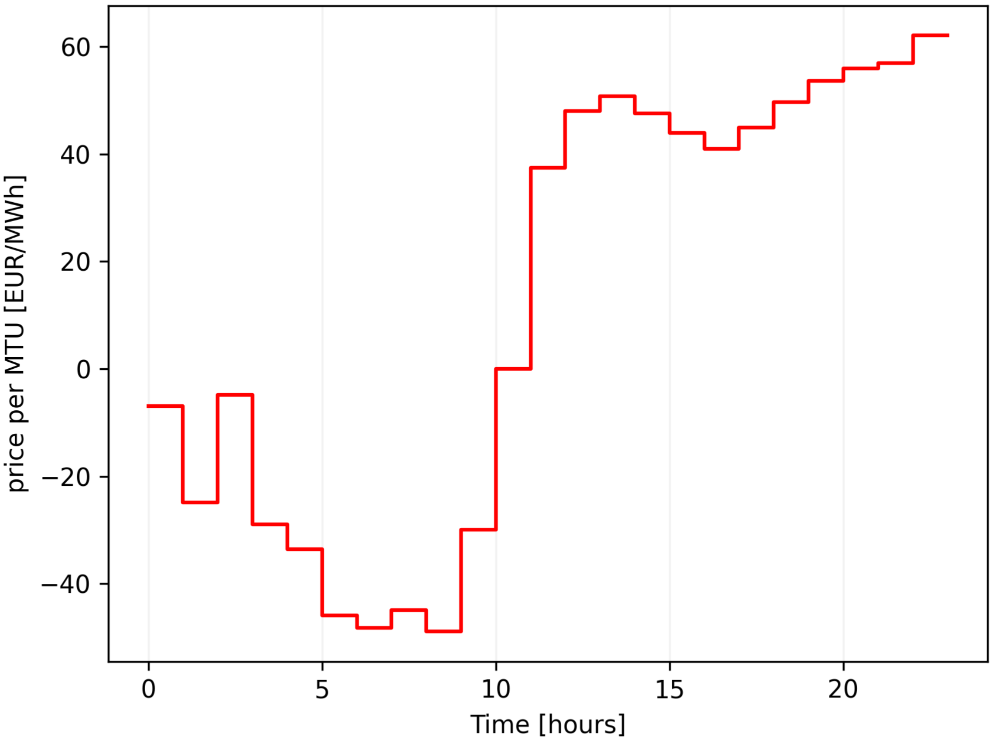


Figure 5.1: Prices per MWh in euros for each time point for one day

and therefore the lowest. If the vehicle is charged with a slow charger that takes four h, the price for $t = 8$ drops to -10.36 €. A better price per MWh will be obtained if the vehicle is charged for four h at $t = 5$, since the average value is -47.03 € per MWh.

Costs incurred when charging at home

In our simulation, we assume that a charging station is available at work that supports 11kW, 22kW and 50kW charging types. When charging at home, there are several costs for the owner. These consist of the price of the wall box, the cost of installation and the running costs for operation. Since a wall box with a charging power of more than 11 kW requires a permit, it costs extra. Since the prices vary depending on the manufacturer and the installation cost for unidirectional wall boxes is set at 1025 € for 11 kW and 2625 € for 22 kW wall boxes in a sample calculation. Bidirectional wall boxes are significantly higher than typical wall boxes. Prices here start at 4000€ and go up to 21000€ []. Since various companies are working on V2G vehicles and thus also V2G and V2H charging stations, more favorable prices can be expected in the future. For an 11kW wall box, a price of 10000€ is calculated in the simulation.

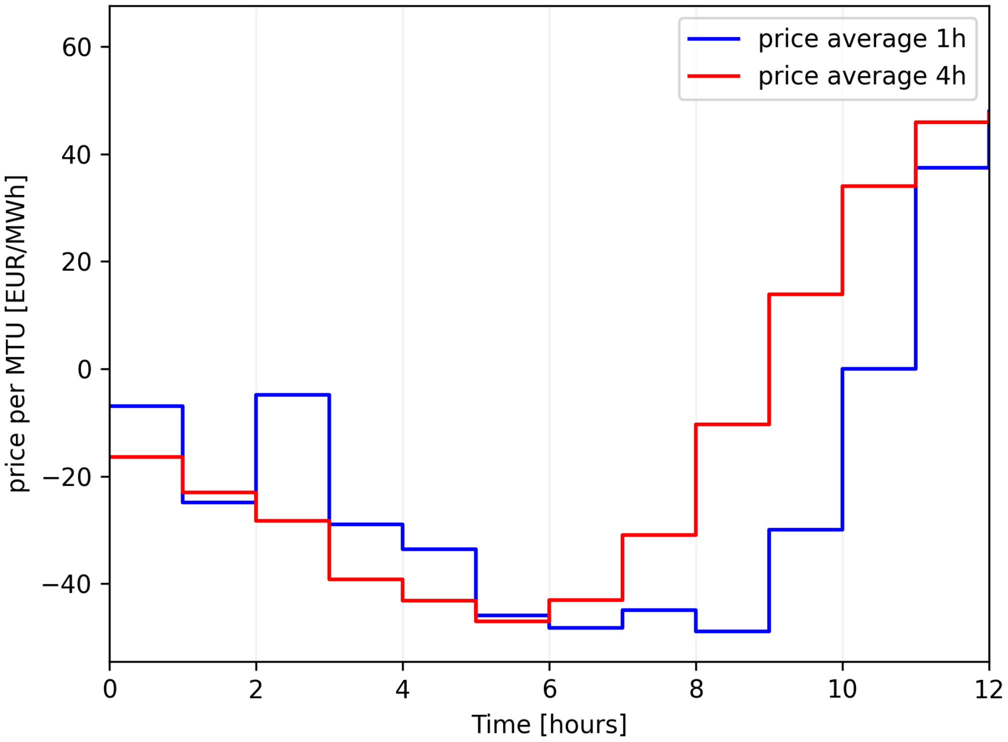


Figure 5.2: Average prices for different time periods depending on charge time

5.3.1 Algorithm

The charging period is limited because the vehicle is also needed for driving. The algorithm must adapt the charging and discharge depending on the charging time. It is assumed that the owner specifies until which time the vehicle is parked when it is plugged into the charging station. The duration of charging or discharging depends on the SOC, DOD and C-rate. Should the battery be below 10%, the vehicle will be charged above the percentage to guarantee enough driving range in case of emergency travel.

If the vehicle uses V2G and the charge time is comparably low, it will lead to only one charging or discharging process. To calculate the maximum revenue, we divide the charging time window in smaller subwindows based on the minimum charging time. The average price is calculated for each charging window and then sorted by size. The algorithm always starts with unloading. This leads to looking for the most significant value to make the best profit. To create a big difference, the price at the unloading hour must be a small value. It can be loaded if the difference between the two values is greater than x. During the calculation, the different loading times must not overlap. If this happens, compare the next min or max value until a time window for both is found. If no comparison is found over the whole period, t+1 becomes the new t, and the algorithm starts again.

If there are values between minimum and maximum, they will be ignored for further calculation. After all time windows have been found, the time is reserved for the best one, and the V2G event can start. After the V2G window, the car charges up to the desired charge level. 5.1

Algorithm 5.1 Calculate charge time

```
procedure CHARGE TIME
    Initialise input parameters.
    $T_{V2g} \leftarrow T_{end} - (T_{start} + T_{state})$
    while $x < T_{V2G}$ do
        $max, T_{max} \leftarrow$ Calculate max as per Algorithm
        $min, T_{min} \leftarrow$ Calculate min as per Algorithm
        if $max - min > 0.05ct$ then
            Set start and end time for loading process $x$
        else
            $max \leftarrow min$
        end if
    end while
    $x \leftarrow x + 1$
end procedure
```

5.4 Battery ageing estimation methods

To find a selection for the best battery degradation model, the following factors should be considered as input data: time, temperature, soc, charge/discharge rate, DOD and cycle number. Finding the right battery degradation model is difficult because existing models can quickly differ despite similar characteristics. For the work in this thesis, the battery type for the model will be the one most commonly used for electric cars in the current market. It is also important that the C-rate is taken into account in the cycle aging parameters.

The model we have used to calculate the battery degradation is that of Wang et. al. [WCZ+16]. It takes into account the temperature, the depth of discharge and different C-rates as well as the calculation of cycle and calendar aging. Unfortunately, it does not take into account the SOC in the calendar cycling, which we have to accept due to the limited research.

In 5.3 the calender life is calculated

$$Q_{loss,\%} = A * exp(-E_a/RT)^{0.5} \tag{5.3}$$

A = pre-exponential factor
E_a = activation energy in Jmol^{-1}
R = gas constant
T = absolute temperature in Kelvin

For the cycle life the function 5.4 is used

$$Q_{loss,\%} = B_1 * exp(B_2 * rate) * Ah_{throughput} \tag{5.4}$$

Coefficient	Value
a	0.00000861
b	-0.00513
c	0.76
d	-0.0067
e	2.35
f	14876

Table 5.1: Constant coefficient of the Wang battery model [WCZ+16]

B_1 = pre-exponential factor
B_2 = exponential factor

The final equation of both calender and cycle life function is in 5.5

$$(5.5)\quad Q_{loss,\%} = (a*T^2+b*T+c)epx[(d*T+e)*C_{rate}]*Ah_{throughput}+f*t^{0.5}*exp[-E_a/RT]$$

a, b, c, d, e, f = Constant coefficient
t = Days

5.4.1 Final Algorithm

Algorithm 5.2 Final Algorithm

```
procedure CHARGE TIME
    Initialize input parameters.
    while $day$ <= 30 do
        Get prices from the day
        Get driving pattern for one model
        Simulate one day of driving and charging
        Calculate battery degradation
        Calculate Profit made
        Save data
        $day \leftarrow day + 1$
    end while
    Compare results
end procedure
```

EV Type for Simulation

The Nissan Leaf was used for the simulation of this work. Due to the high sales figures and also because it is one of the first EVs on the market, most of the data is available here.

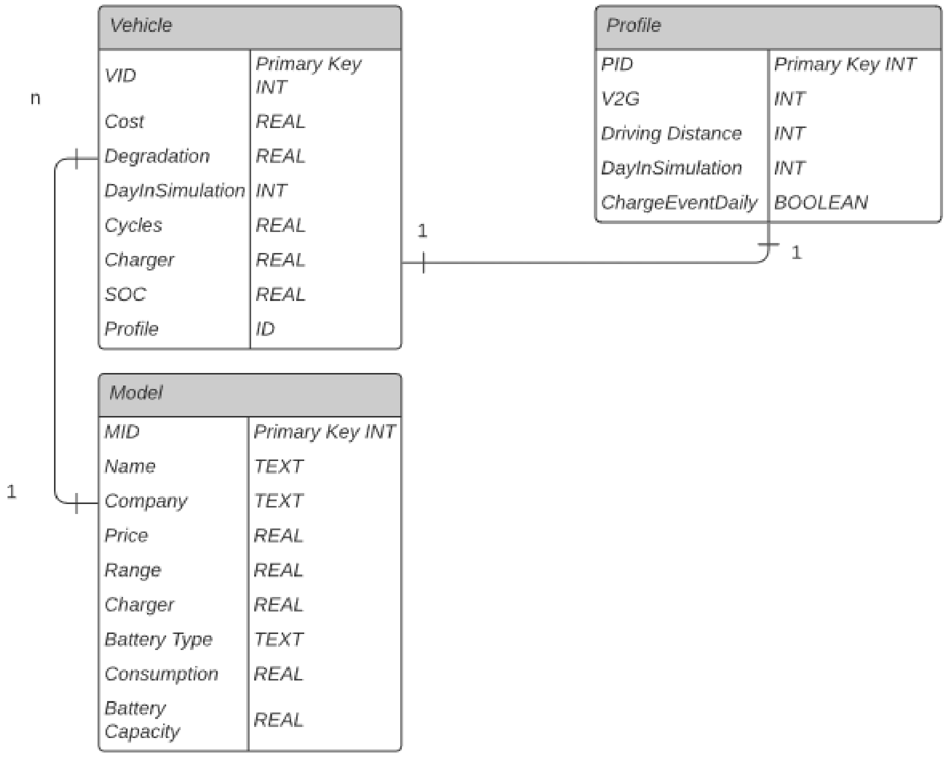
So the inputs for the simulation are listed below.

1. Battery capacity: 39kW

2. Range: 235km
3. Daily travel distance: 46km (24km for one way)
4. Charging limit in V2G window: 80%
5. Battery discharge threshold: 15%
6. Charging types: 3.6kW, 11kW or 22kW
7. Time for charging/discharging At work: 9hours, At home: 12hours
8. Battery Replacement cost: 6450€ [Wit22]

Database for Simulation

The figure 5.3 shows the individual tables of the database. In the Model table, all manufacturer specifications that are important for the simulation are stored. In the Profile table, the individual differences are listed that will be needed later for evaluation. The vehicles are generated on the basis of the Model and Profile table.



Vehicle	
VID	*Primary Key INT*
Cost	*REAL*
Degradation	*REAL*
DayInSimulation	*INT*
Cycles	*REAL*
Charger	*REAL*
SOC	*REAL*
Profile	*ID*

Profile	
PID	*Primary Key INT*
V2G	*INT*
Driving Distance	*INT*
DayInSimulation	*INT*
ChargeEventDaily	*BOOLEAN*

Model	
MID	*Primary Key INT*
Name	*TEXT*
Company	*TEXT*
Price	*REAL*
Range	*REAL*
Charger	*REAL*
Battery Type	*TEXT*
Consumption	*REAL*
Battery Capacity	*REAL*

Figure 5.3: Database model for the simulation

6 Results and Observations

Results

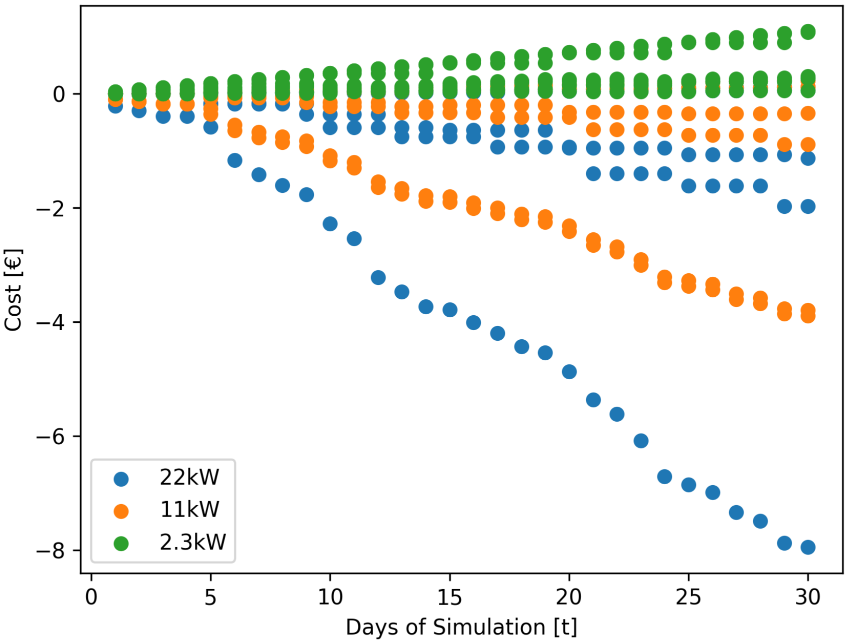


Figure 6.1: Possible costs for electricity for a simulation of 30 days

As can be seen in graphic 6.1, due to the different loading rates, the profit is analogously higher the faster the loading rate. The graph shows a rough distribution of all three types of charging and indicates lower costs for faster charges. This result is conclusive because the faster the vehicle charges/discharges, the more kW can be bought at a lower price or sold at a higher price. The non-linearity of the graph can be explained by the days of the simulation, as they do not follow the same price trend every day. To compare V2G1 and V2G2, let's take a closer look at 6.2. At lower charging rates, the functions are close together. If you compare the two values, you pay 47 cents for 30 days with 2.3 kW with V2G1 and receive 1.00 € with V2G2. The gain for the same time duration is comparatively greater with a charger with 22kW. Here we have get 7.93€ for V2G1 and 21.89€ for V2G2.

Almost analogous to the cost graph is the graph of the number of cycles. 6.3 shows that with a 22kW charger, the battery has to go through up to 40 cycles within a month, and after 100 days we have more than twice as many cycles compared to the V2G1. Although the charging efficiency

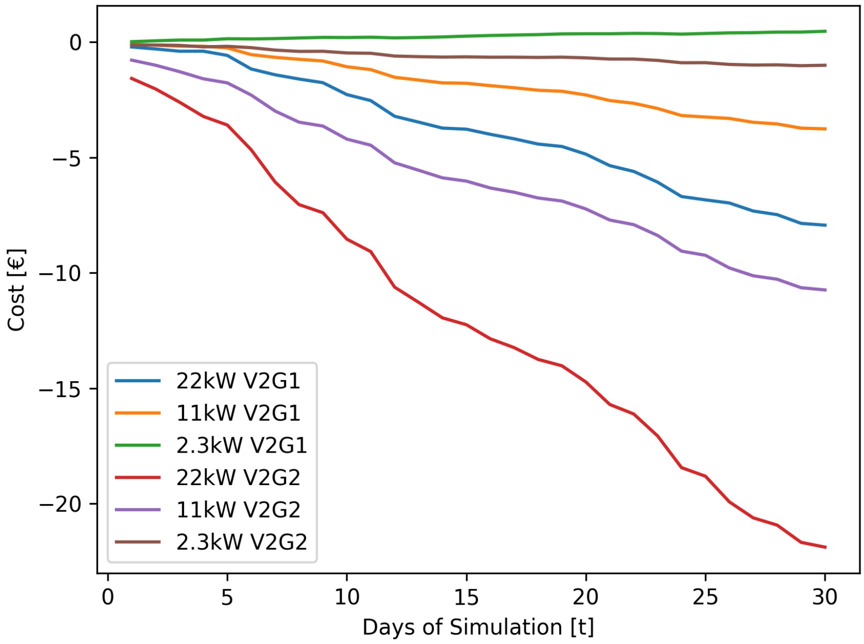


Figure 6.2: Comparison of V2G1 and V2G2 costs without degradation

decreases as the C-rate increases, we can observe in 6.4 the degradation at 100 days is 0.2050% at 22kW and for the 0.1565% for the 11kW and 0.0872% for the the 2.3kW charger. If we include the degradation of the battery in our profit calculation, we obtain for:

22kW Profit made: -65.44€ + Battery degradation cost: 66.62€ = 1.18€

11kW Profit made: -31.10€ + Battery degradation cost: 50.86€ = 19.76€

2.3kW Profit made: 0.06€ + Battery degradation cost: 28.34€ = 28.40€

The aim of this work was to provide EV owners participating in V2G services with information on which type of charging station they can use to ensure both the longevity of their vehicle and the potential profit. Our results show the V2G2 profile with 22kW will generate the most profit. However, it must also be considered that the battery must run through twice as many cycles. If you should decide on a V2G-capable charging station for your home, it is noticeable that the higher the charging rate, the more profit is possible. By comparing both 2.3kW chargers, it is observable that charging cycles and the capacity loss are very close to each other.

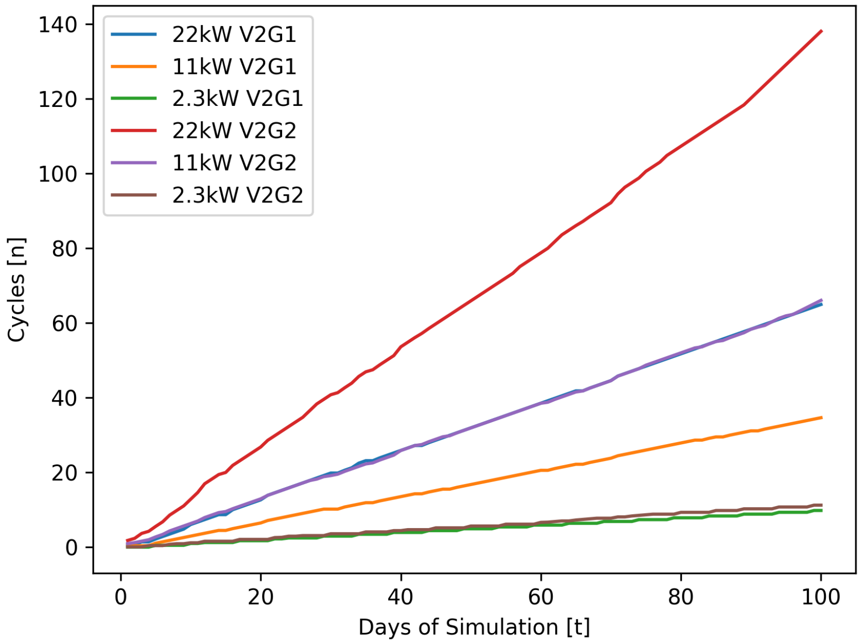


Figure 6.3: Comparison of V2G1 and V2G2 charging cycles

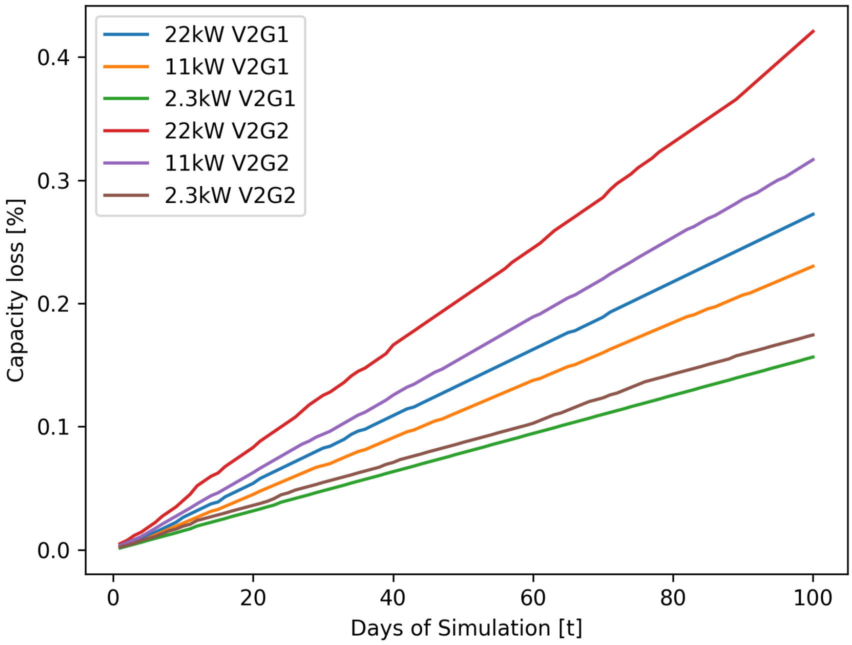


Figure 6.4: Comparison of V2G1 and V2G2 capacity loss

7 Conclusion and Outlook

7.1 Conclusion

The aim of this work was to provide EV owners participating in V2G services with information on which type of charging station they can use to ensure both the longevity of their vehicle and the potential profit. Our results show the V2G2 profile with 22kW will generate the most profit. However, it must also be considered that the battery must run through twice as many cycles. If you should decide on a V2G-capable charging station for your home, it is noticeable that the higher the charging rate, the more profit is possible. By comparing both 2.3kW chargers, it is observable that charging cycles and the capacity loss are very close to each other.

7.2 Outlook

The database used for the price ahead market is from 2019. As the website to this date only released the data for the year 2020 and 2021 for viewing, but not for downloading, the model's statement is limited to the year 2019. Therefore, the model should be tested with new data. The calculation of the time windows is also recalculated for each vehicle; a direct calculation at the beginning of each day would lead to a faster running time of the code.

8 Appendix

Extracting Day-ahead price signals for the german market

The day ahead price is taken from the website Energy-Charts (`https://www.energy-charts.info/index.html?l=en&c=DE`). To get the data follow the steps below.

- select in the menu the item ’Prices’
- in the submenu select ˵Spot Market Prices″
- set the time interval to either ‘month’ or ‘week’.
- under the point ‘export’ the data can be downloaded directly.

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