

EV to grid - Basic modeling and simulation

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Abstract

This paper's main point of focus is the vehicle-to-grid (V2G) system, more specifically examining the conditions of use and participation from the perspective of the owners of electric vehicles (EVs) for the region of Baden-Württemberg, Germany. A short introduction to the V2G system is presented, explaining the general ideas and benefits behind the system as well as potential downsides after which the focus is put on exploring one such downside in further detail. That potential downside could render the whole V2G system pointless and unused, raising the question of whether there exists an incentive for EV owners to participate in the system. To find definitive answers all the needed data is gathered, explained and put together to form the numbers needed. Both fixed prices and variable prices are considered and as such this paper is split into two main parts that complement each other. In the first part all the data is gathered and theoretical calculations are done with regards to fixed prices. In the second part the grid with V2G is modeled, implemented and simulated with variable prices for more practical insights into the V2G use. The simulations' setups and results are explained and in the end a conclusion is reached by analyzing the results and further speculating the possibilities.

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1 Introduction

As seen in the report [1], the world energy consumption keeps increasing prompting the world to find new ways of generating and using electricity. Reasons aren't limited to only generating the required need, as the main fossil fuels used for the generation are depleting as well as causing serious environmental damage the more it is used. Renewable energy sources (RES) are seen as the solution, however they are still unable to cover the world's electricity need fully. One of the main reasons is that they are too dependent on weather conditions making it hard to provide a constant amount. A possible idea for aiding the grid is the use of the V2G system. The V2G system connects the EVs with the grid, providing the possibility of temporarily storing electricity in their batteries. The main idea sees the role of the EVs as a storage helping the distribution system operators (DSOs) balance the electricity by storing it when more than needed is being produced, either by the power plants or the RES, to then be able to provide that stored electricity at later times when the production of power plants or the RES is too low, effectively filling in the gaps.

While this may sound like a promising solution there are downsides to it that could render this method unusable, with the main downside being the economic worth. EV batteries degrade over use, creating the need to eventually replace them. Replacement costs are not a minor amount and anything that accelerates the time until replacement is necessary would need to be worth it for the EV owners to want to subject their batteries to it. Hence this paper will focus less on the V2G system itself, but more on the personal view of an EV owner, intending to discover if the V2G use can be feasible and if so which conditions need to be fulfilled for this feasibility to be reached.

2 Economic feasibility for EV owners under fixed prices

An economic feasibility counts as a worthwhile participation in the V2G system with monetary gain instead of loss. In order to make any statements about the feasibility, sufficient data has to be gathered to calculate what exactly the gains and losses here represent. The V2G system works by charging and discharging electricity on the EV battery, hence the main data to find are:

1. How much money is needed to charge electricity?
2. How often is the EV not in use, ie. connected to a charging station?
3. How often can an EV battery be used before needing replacement?
4. How expensive is the replacement of an EV battery?
5. How much money is gained by discharging electricity?

There are two ways to consider the price for the EV electricity: fixed price and variable price. A fixed price ensures the price doesn't change regardless of when the EV battery is charged, while variable price would make every hour important in determining whether charging the battery is a worthwhile action or not. This paper will consider both options and accordingly split up the work into two main parts, one for each option.

In order to find a fixed price a region has to be selected due to prices depending on location. This paper will focus on Germany, more precisely the region of Baden-Württemberg, so the prices listed will

Tariff	AC	DC	Extra costs
Standard	39 ct/kWh	49 ct/kWh	None
Viellader	29 ct/kWh	39 ct/kWh	5€ per month
Vorteil	29 ct/kWh	39 ct/kWh	Prerequisite of being a customer

Table 1: Prices of charging an electric vehicle of the main electricity provider of Baden-Württemberg enBW [2].

be in Cents or Euro (€) depending on the use case. [Table 1] shows the, at the time of writing this document, current fixed prices of charging an EV in Baden-Württemberg. There are 3 different tariffs to choose between and the prices for AC and DC charging are different. All 3 options will be included in the calculations. According to [3] on average vehicles are parked and unused for 23 hours of the day. This provides for more than plenty enough opportunities for the EV to react to the grid’s needs via the V2G connection, so that aspect should generally not be a big issue.

2.1 EV lifetime performance

Next the mechanical specifics of the EV battery itself must be considered. [Table 2] shows many of the common market EVs which all have battery capacity somewhere between 4kWh and 90kWh. The size of the battery increases the range of the EV when driving as well as how much energy can be supplied to the V2G system when in demand, but with the size another thing that increases is the production costs and eventual replacement costs. Every EV battery has a limited lifetime as well as a performance that changes during that lifetime. Most commonly the lifetime of an EV is measured in the number of charging and discharging cycles it can go through until the battery starts to get negatively affected by it, to the point that replacing the battery becomes necessary. The exact number of cycles an EV battery can last is not a fixed amount but rather it depends on many conditions related to the charging.

Electric currents come in two forms, as alternating current (AC) and direct current (DC) [4], both of which can be used for charging the battery. When using AC, an onboard charger of the EV is used that transforms the incoming AC into DC, which then gets sent to the EV battery. Each EV has its own onboard charger which can take a maximum of energy at a time to convert, which makes the onboard charger the important difference for AC charging as it determines the charging amount and thus speed as well. DC charging means that the AC is transformed into DC before being sent to the vehicle. However unlike AC charging DC charging can only be done at specialized DC charging stations which are less available than charging places for AC charging. DC charging is usually a lot faster than AC charging, which is useful for cases when a lot of electricity is needed fast, but DC should generally be avoided for the V2G. Ultra-fast charging can impact the cycle number negatively, especially if used very often for the charging process which would be the case in a permanent V2G connection, so the slower AC charging is the better alternative for extending battery life. Other factors influencing the cycle numbers, with V2G use in mind, are state of charge (SoC), depth of discharge (DoD) and temperature during charging and using the EV [5]. SoC and DoD are percentage values showing how high the battery is charged until charging is stopped and how low the battery depletes before being charged. As such the values impacting the cycle number negatively are an SoC above 80%, DoD below 20%, and a temperature that is as close to room temperature as possible due to both very high and very low temperature reducing the capacity over time.

Model	Battery	Charge Times (%)
Toyota Prius PHEV	4.4kWh Li-ion, 18km all-electric range	3h at 115VAC 15A
Chevy Volt PHEV	16kWh, Li-manganese/NMC, liquid cooled, 181kg, all electric range 64km	10h at 115VAC 15A
Mitsubishi iMiEV	16kWh, 88 cells, 4-cell modules; Li-ion; 109Wh/kg; 330V, range 128km	13h at 115VAC 15A
Smart Fortwo ED	16.5kWh; 18650 Li-ion, driving range 136km	8h at 115VAC 15A
BMW i3 Curb 1,365kg	42kWh, LMO/NMC, large 60A prismatic cells, battery weighs 270kg, driving range: EPA 246; NEDC 345km; WLTP 285	11kW on-board AC charger
Nissan Leaf	30kWh; Li-manganese, 192 cells; air cooled; 272kg, driving range up to 250km	8h at 230VAC, 15A
Tesla S Curb 2,100kg	70kWh and 90kWh, 18650 NCA cells of 3.4Ah; liquid cooled; 90kWh pack has 7,616 cells; battery weighs 540kg; S 85 has up to 424km range	9h with 10kW charger
Tesla 3 Curb 1,872kg	75kWh battery, driving range 496km; 346hp engine, energy consumption 15kWh/100km	11.5kW on-board AC charger
Chevy Bolt Curb 1,616kg	60kWh; 288 cells in 96s3p format, EPA driving rate 383km; liquid cooled; 200hp electric motor(150kW)	40h at 115VAC 15A

Table 2: Table of common eVs with battery and charge times [6].

Generally, the efficiency of the battery is at above 95% at a temperature of 40°C, between 93-95% at around 25°C and between 89-92% at 10°C. [Figure 1] shows the proportional effect of the charging habit on the battery capacity. A 100-25% SoC describes a charging and discharging habit of always charging the EV battery at 25% all the way until it is fully charged. The worst charging habit is charging from low capacity to maximum capacity, so the higher the battery when the charging starts and the lower the maximum at which the battery stops charging the better the battery lifetime overall.

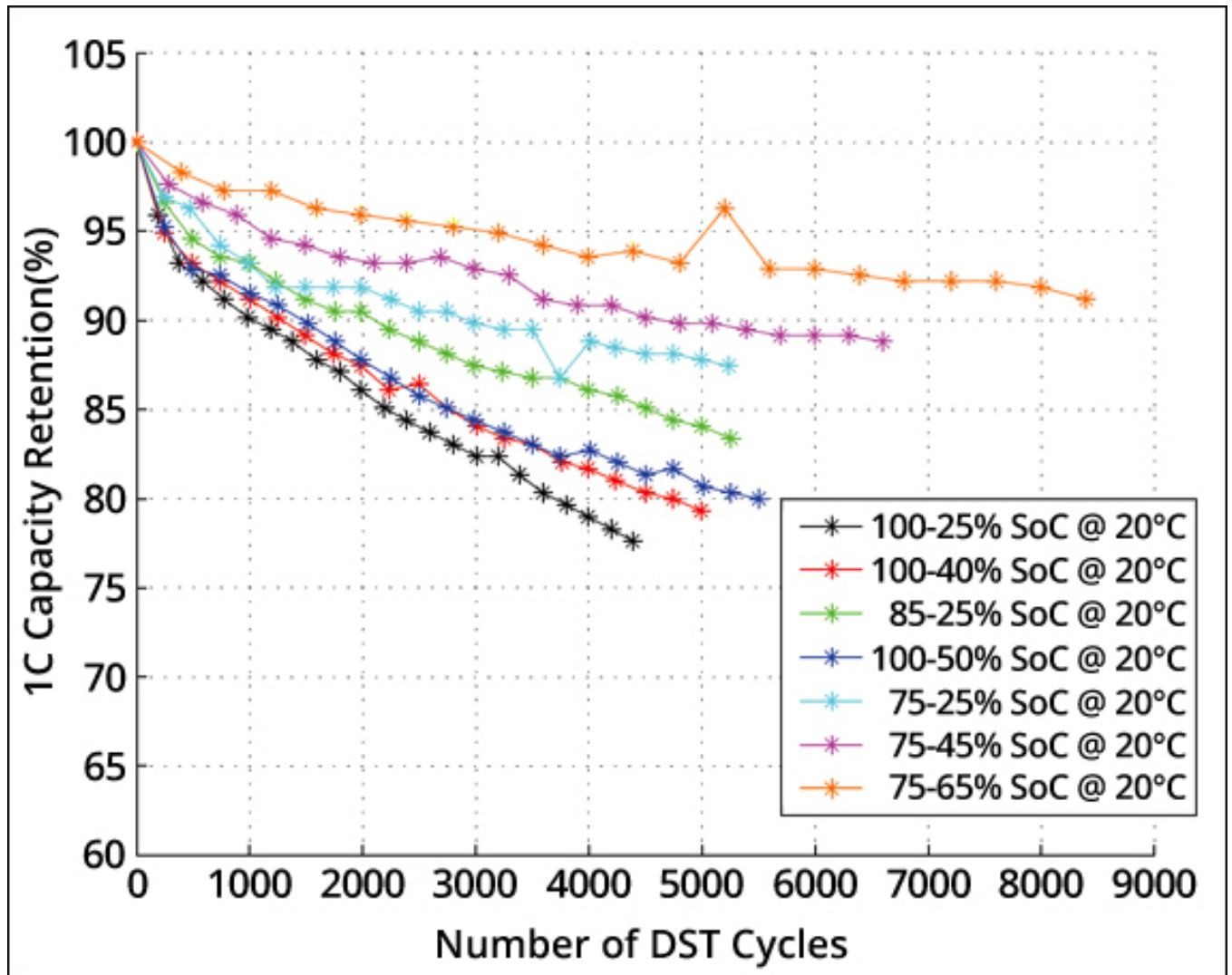


Figure 1: Battery capacity loss over different charging cycles [7].

With all this in mind a table can be set up featuring expected cycle numbers at certain SoC and DoD. [Table 3] shows a table that helps compare these values. Always charging from 65% to 75% is very good for the number of cycles, allowing for up to 12,000 cycles until battery capacity drops significantly. However, that is not a realistic amount to expect from an EV user or even a good amount to have, as an effective 10% usage is rarely enough for driving or for the V2G model benefit even with very large battery capacity of 90kWh. A more average estimate would be the 4,500-7,100 cycles between 25% and 75% or 85%, as it gives a decent amount of battery between 50% and 60% while also having a large expected cycle count.

Charging Parameters and total battery percentage	B for E of Standard-Tariff of 39ct/kWh	B for E of Viellader-Tariff of 29ct/kWh*	B for E of Vorteil-Tariff of 29ct/kWh (%)
100% - 25% (75% total battery)	2,010	60,300 kWh	1,507.5 kWh
100% - 40% (60% total battery)	2,800	67,200 kWh	1,680 kWh
100% - 50% (50% total battery)	2,800	56,000 kWh	1,400 kWh
85% - 25% (60% total battery)	4,500	108,000 kWh	2,700 kWh
75% - 25% (50% total battery)	7,100	142,000 kWh	3,550 kWh
75% - 45% (30% total battery)	10,000	120,000 kWh	3,000 kWh
75% - 65% (10% total battery)	12,000	48,000 kWh	1,200 kWh

Table 3: The effect of charging on the cycle number. First column are the charging parameters with % total available battery included. Second column shows total number of charging cycles before reduction to 85% of maximum battery. Third column shows how much kWh would be available in total during the lifetime of a 40kWh battery. Fourth column shows that same example but for 1kWh, multiplicable by the kWh battery amount of any EV [8].

However, the 12,000 cycles with 10% total battery are not the same energy amount as the 2,010 cycles with 75% total battery. This means that the number of cycles themselves is not a reliable meaningful number, since a bigger amount of cycles isn't necessarily better. The third column in Table 2 gives an example in kWh based on a battery size of 40kWh. This shows that the best charging habit for the EV in terms of energy available to the owner until it needs replacement is the 75% - 25% charging habit with 50% of the EV battery available. The fourth column shows the same amount but for just 1 kWh, multipliable for any final battery size that can be used for later calculations.

2.2 EV battery cost

There's not a lot of information available on EV battery replacements and costs, considering that most sold EVs haven't been in use long enough to need replacing, hence the battery replacement is seen more as a rare case unlike how much more common it would become with the V2G system widely used. Currently most EV manufacturers offer a battery warranty of 8 years/100,000 miles, or 160,934.4 kilometers [9]. For some the warranty includes only outright failure of the battery, while most will replace the battery if it drops below roughly 70% capacity within that time or mileage. So far, their warranty doesn't expect their customers using the battery for other non-driving related uses, like the V2G system from which the battery could likely drop below the 70% capacity threshold within the 8 years of warranty(whether this is true will be seen later in the simulations). When the V2G system becomes widespread their warranty will certainly change to reflect that, so this study will ignore the warranty as a means of replacing the battery free of cost as that would certainly make the V2G system a profitable prospect, but the warranties would most likely either be changed fast before they can be made use of to such an extent or would deny the warranty claim. So far only Nissan has issues comments related to this and said that the V2G technology would not void their warranty [10].

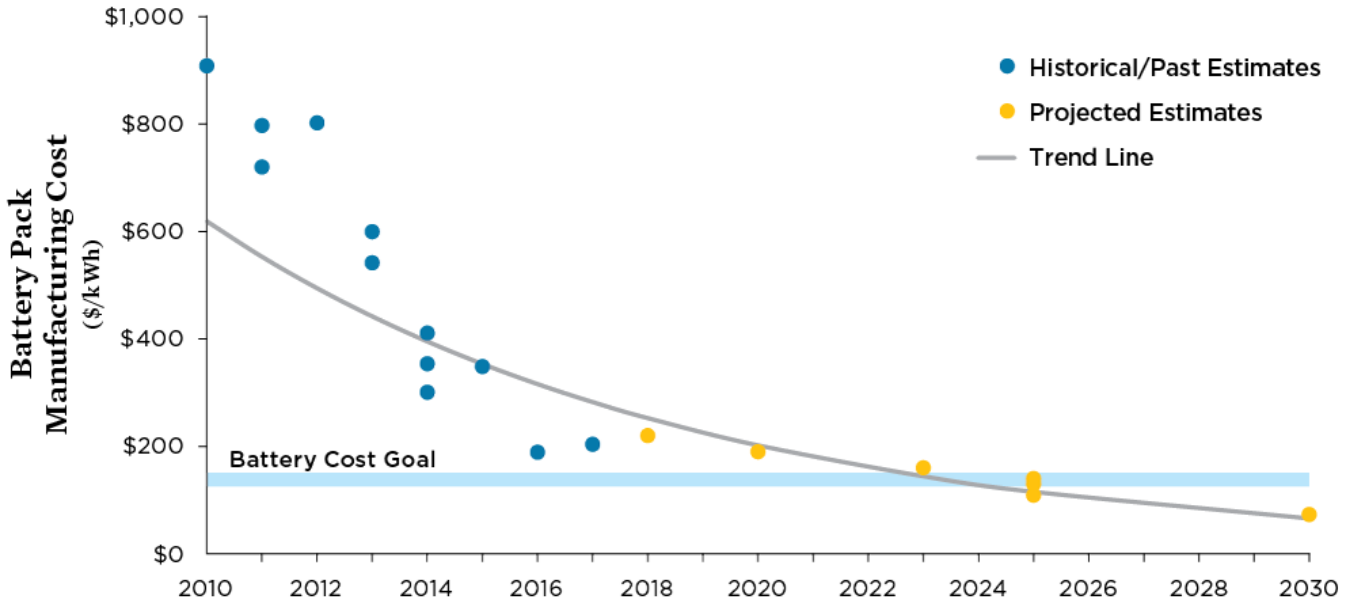


Figure 2: Manufacturing costs for EV batteries so far, and expected future values [11].

[Figure 2] shows a graphical representation of battery manufacturing costs, in \$ per kWh. At the beginning they were an expensive 1,000 \$/kWh, but that price has been falling with each year, with the current estimate today to be at 190\$/kWh. As the prices continue to fall it will be more affordable for consumers to buy EVs leading to a big increase of EVs used worldwide, as well as a reduced cost for battery replacement due to cheaper manufacturing. This will make the V2G system more affordable in the future than it is now. As for now, most EV manufacturers never stated the full price of a battery replacement for their vehicles. A known value by Nissan is 5,499\$ to replace the old 24kWh battery [12], although with labor costs of replacement itself the suggested retail price goes up to 6,499\$. This means a price of roughly 270\$/kWh. Replacement prices of the newer Nissan models of 30kWh and 40kWh battery size isn't known at this time, nor for most current and common EVs. Due to the unknown price factor and difference in price for each EV manufacturer a general average price tag can't be determined for this paper, so for battery replacement costs we will consider the current manufacturing costs of 190\$/kWh, which is roughly 172€.

2.3 Calculation of feasibility

From the previous list of 5 points showing the needed data to calculate feasibility, we determined 4. The last one, the price for selling electricity, is the least straightforward one as there is no information available about how much money the energy sold and discharged from the EV battery would be. There are several ways to continue, such as assuming a price for selling, but the one shown here will be the calculation of a "break-even" point, which is symbolized with a **B**. The break-even point shows what the selling price per kWh needs to be to at least break even with the costs of upkeep of the V2G system, meaning no profits exist but neither do losses. The general formula for B is:

$$B = \frac{L}{T} \quad (1)$$

- **B** is in *ct/kWh*.
- **L** is the total loss of money over the course of using 1 EV battery until replacement, in *cent*.
- **T** is the total amount of kWh the EV battery can charge and discharge during its lifetime, in *kWh*.

T is calculated as follows:

$$T = P \cdot C \cdot S \quad (2)$$

- **P** is the percentage of total battery availability dependent on the charging parameters, as seen in the first column of Figure 2. Since it is a percentage calculating value, between 0.1 and 0.75, it has *no units*.
- **C** is the expected number of charging cycles, dependent on the percentage P. Since it is just the number of cycles it has *no units*.
- **S** is the total size of the EV battery in *kWh*.

L is calculated as follows:

$$L = (E \cdot T) + R \quad (3)$$

- **E** is the cost of buying energy in *ct/kWh*.
- **T** is the same value as in the previous formula for B, in *no units*.
- **R** is the replacement cost of the EV battery.

There are 2 ways to determine the R value. Either a fixed price per vehicle or a calculated price of 172€/kWh of original battery size:

$$R = 172e/kWh \cdot S = 17,200ct/kWh \cdot S \quad (4)$$

- 172€/kWh changed into 17,200ct/kWh for the sake of later calculations.
- **S** is the same value as in the previous formula for T, in *kWh*.

We will consider only the calculated replacement price of 17,200ct/kWh to keep the results more general and less focused on the type of car and manufacturer, as well as due to the unavailability of those statistics for many of the EV brands. To create the final formula of B we insert the formula of L into the first formula for B, then insert the formula of T:

$$B = \frac{(E \cdot T) + R}{T} = \frac{E \cdot \cancel{T}}{\cancel{T}} + \frac{R}{T} = E + \frac{17,200ct/kWh \cdot \cancel{S}}{P \cdot C \cdot \cancel{S}} = E + \frac{17,200ct/kWh}{P \cdot C} \quad (5)$$

This final B formula shows that B is independent of the EV battery size S, meaning that any battery size will perform equally well in V2G in terms of reaching the break-even point. This only holds if replacement of the EV battery is calculated with the per-kWh number, else the individual EV manufacturer's replacement prices must be considered for each vehicle to reach an assessment. [Table 4] shows a table of B values calculated for each energy plan and for different charging parameters.

Charging Parameters and total battery percentage	B for E of Standard-Tariff of 39ct/kWh	B for E of Viellader-Tariff of 29ct/kWh*	B for E of Vorteil-Tariff of 29ct/kWh (%)
100% - 25% (75% total battery)	50.4 ct/kWh	40.4 ct/kWh	40.4 ct/kWh
100% - 40% (60% total battery)	49.2 ct/kWh	39.2 ct/kWh	39.2 ct/kWh
100% - 50% (50% total battery)	51.3 ct/kWh	41.3 ct/kWh	41.3 ct/kWh
85% - 25% (60% total battery)	45.4 ct/kWh	35.4 ct/kWh	35.4 ct/kWh
75% - 25% (50% total battery)	43.8 ct/kWh	33.8 ct/kWh	33.8 ct/kWh
75% - 45% (30% total battery)	44.7 ct/kWh	34.7 ct/kWh	34.7 ct/kWh
75% - 65% (10% total battery)	53.3 ct/kWh	43.3 ct/kWh	43.3 ct/kWh

Table 4: Break-even point calculated for different Tariffs of E.

By comparing the numbers we can see that the lowest prices are on the Viellader-Tariff and the Vorteil-Tariff, so one of them would be the ideal one depending on whether the EV owner is an enBW customer or not. The higher the number of cycles available the lower the B value. Looking at the previously established best charging habit of 75% - 25%, with 50% battery availability in total, the necessary B to break even the wins and losses would be the possibility to sell the gained energy back for more than 33.8 ct/kWh. However just breaking even isn't enough to make EV owners want to participate in the V2G system, there needs to be a positive income from all this that is worthwhile their time. A selling price of 1 cent more than the break-even point would already mean 35.5€ increase for each kWh the battery has of the total profits at the end of the battery's lifetime. Which for a 40kWh battery is already a 1,420€ profit. Generally, $B > E$ must always hold, else the V2G system will never be in use. For the future, each cent of lower price E would lower the amount needed for the break-even point B for one cent. Inversely, a higher price for charging also increases the necessary price for discharging. Whether the E price or B price change is not something the EV owner can actively influence, however the T value is up to the EV owner and as established makes a big difference in the scale of profitability. Owners that take good care of their EV will have the most income from the V2G system, those that don't will either make losses or not make as much, depending on the selling price.

So far, the calculations were done with the assumption that the EV is mostly only for the V2G system, which is unlikely to ever be the case with an EV owner. The amount of energy the owner uses for personal reasons of driving will be energy that can't be sold, which means a lower amount of T. Taking into account the warranties of the EV manufacturers, the EV battery capacity should not significantly drop until 100.000 miles were passed, which are roughly 161.000km. According to a study [14], the average German drives 10.000 km per year. Each EV needs a different amount of kWh per 100km, but a good example is the Nissan Leaf with 22.1 kWh per 100km [15]. This would amount to 2210 kWh used per year on just driving. Thus for this Nissan Leaf example with 40 kWh battery, the driving of one year equates to roughly 1/50th of the total income the EV can provide you in the V2G system. However EV owners participating in V2G may be in the population group of people driving less frequently than that, or change their driving habits accordingly if possible.

Even though the battery size isn't included in the calculation for B there are still some benefits to have an EV with a larger battery over a smaller one. The P value in an owner's charging habits represents the percentage of the EV that he can use, so a bigger battery maximum means more usable energy both for personal driving and the amount of energy possible to be supplied to the grid during high demand. Similarly to Figure 3, [Figure 3] shows another overview of the EV Battery prices to be expected in the future. The amount used for R in the calculation was 190\$/kWh, but the prices are expected to keep dropping in the future. Furthermore, the future prices could be more relevant than current prices since it could take several years until the battery needs replacing, at which point the prices will be different. The following [Table 5] is the same table as Table 3 but considering the effect future changes of battery price have on the value of B. Considered are the 2024 estimate of 94\$/kWh(8,466ct/kWh) and the 2030 estimate



Figure 3: Another overview of past, current and future prices for batteries per kWh [13].

of 62\$/kWh(5,584ct/kWh).

Charging Parameters and total battery percentage	B for E of Standard-Tariff of 39ct/kWh	B for E of Viellader-Tariff of 29ct/kWh*	B for E of Vorteil-Tariff of 29ct/kWh (%)	
100% - 25% (75% total battery)	94\$/kWh	44.6 ct/kWh	34.6 ct/kWh	34.6 ct/kWh
100% - 40% (60% total battery)	94\$/kWh	44.0 ct/kWh	34.0 ct/kWh	34.0 ct/kWh
100% - 50% (50% total battery)	94\$/kWh	45.0 ct/kWh	35.0 ct/kWh	35.0 ct/kWh
85% - 25% (60% total battery)	94\$/kWh	42.1 ct/kWh	32.1 ct/kWh	32.1 ct/kWh
75% - 25% (50% total battery)	94\$/kWh	41.4 ct/kWh	31.4 ct/kWh	31.4 ct/kWh
75% - 45% (30% total battery)	94\$/kWh	41.8 ct/kWh	31.8 ct/kWh	31.8 ct/kWh
75% - 65% (10% total battery)	94\$/kWh	46.0 ct/kWh	36.0 ct/kWh	36.0 ct/kWh
100% - 25% (75% total battery)	62\$/kWh	42.7 ct/kWh	32.7 ct/kWh	32.7 ct/kWh
100% - 40% (60% total battery)	62\$/kWh	42.3 ct/kWh	32.3 ct/kWh	32.3 ct/kWh
100% - 50% (50% total battery)	62\$/kWh	43.0 ct/kWh	33.0 ct/kWh	33.0 ct/kWh
85% - 25% (60% total battery)	62\$/kWh	41.1 ct/kWh	31.1 ct/kWh	31.1 ct/kWh
75% - 25% (50% total battery)	62\$/kWh	40.6 ct/kWh	30.6 ct/kWh	30.6 ct/kWh
75% - 45% (30% total battery)	62\$/kWh	40.8 ct/kWh	40.8 ct/kWh	40.8 ct/kWh
75% - 65% (10% total battery)	62\$/kWh	43.6 ct/kWh	33.6 ct/kWh	33.6 ct/kWh

Table 5: Break-even point calculated for different Tariffs of E, under future price of EV battery per kWh.

In the future example it shows that for our previous general average with $T=3,550\text{kWh}$, the necessary B to break even the wins and losses would be the possibility to sell the gained energy back for more than 31.4ct/kWh in the year 2024 and 30.6ct/kWh in the year 2030. However this doesn't include other possible future changes like lower electricity cost E or battery improvements to last even longer in terms of cycles. Calculating future costs with one future value (replacement cost R) and one present value (energy price E) is unreliable as a future prediction but a viable measure for now. Another important information learned from this is the comparative rate between the buying price and break-even price. The electricity selling price must be bigger than the electricity buying price by at least 16.2068% in the present time, 8.2758% in 2024 and 5.51724% in 2030 for a break even point to be reached. These values will assist us in the next section.

3 Modeling and simulation

While the first part only considered a fixed price, the second part of the Thesis focuses on the V2G use with changing market prices for electricity. This includes EV-owners' participation in the Spot-Market, namely here "EPEX SPOT" [16] as it covers the area of Germany among other European countries. The SPOT-Market "provides a market place where exchange members send their orders to buy or sell electricity in determined delivery areas" [17], which allows for further examining of whether an individual EV-owner has an incentive for using his EV battery for the V2G system. The EPEX SPOT prices are determined by private calculations depending on several factors such as the individual country's prices, the continuous market trades of certain periods of time (such as 15 minutes, 30 minutes or 1 hour) and cross-border trades between countries [18]. In order to examine this, there is need for modeling the situation of V2G in the grid as well as simulating that model under certain conditions to retrieve and study its results.

3.1 Design

The electricity distribution system, more notably the smart grid design already exists making the core design of the needed model straightforward. [Figure 4] shows an overview of the grid with renewable energy sources (RES), EV charging stations and residential houses, which is a good model for what we need to do. The main regulator in this model is the distribution system operator (DSO) that ensures proper energy distribution and constant supply. The DSO needs to communicate with all grid participants by tracking the required energy of the residential houses, the production of RES providers while also accounting for the EV in a V2G system that would actively participate whenever the EV owner wants to and providing energy transport at the EPEX SPOT varying prices. To minimize cases of overproduction or underproduction the DSO has various tools at its disposal which help predict the RES production and the residential energy need per day and per hour. However the EV as an independent singular entity would be unpredictable at first so the EV and DSO interactions will be modeled as such. This gives the EV owners a lot of freedom and individuality in how and when they wish to participate which in turn should give a properly good insight into the feasibility of the whole process from the owner's perspective.

The EV owners have no need to interact with other grid participants like the RES and residential houses due to the DSO's functionality covering most interactions. The prices will be known to the DSO who can send the current offers to the EV owner, though whether the prices are communicated by the DSO or self-checked by the EV owner doesn't make a difference in the overall process logic. A UML design at [Figure 5] showcases the intended, most important functions. The 1 DSO Agent is connected to n EV Agents, n House Agents and n RES Agents. The House and RES Agents are similar in functionality, as they save their Load and Energy produced in a Double Array and have a TickerBehaviour() which makes certain actions happen periodically "on tick". For them that periodical action is sending the inform message to the DSO about their current Load and Energy. The EV Agents meanwhile have a more complicated structure. 3 Integers count the times the EV Agent charged, discharged or was idle, the battery Double is the EV battery amount, Money saves the money earned or lost during the interactions with the DSO, the parameter which is the charging parameter determining the kWh charge/discharge, bmax and bmin are the battery constraints and finally buyprice and sellprice are the accepted minimum prices for charging and discharging. EV Agents also have 3 main methods: a TickerBehaviour() that executes the price checking functions every simulated hour of time, the send(request) that sends requests to the DSO about price and decisions, and HourlyDecider() that will make the decision for the EV Agent about what to do. The DSO Agent stores the hourly kWh needed and produced in kwhhave and kwhneed Doubles, their difference

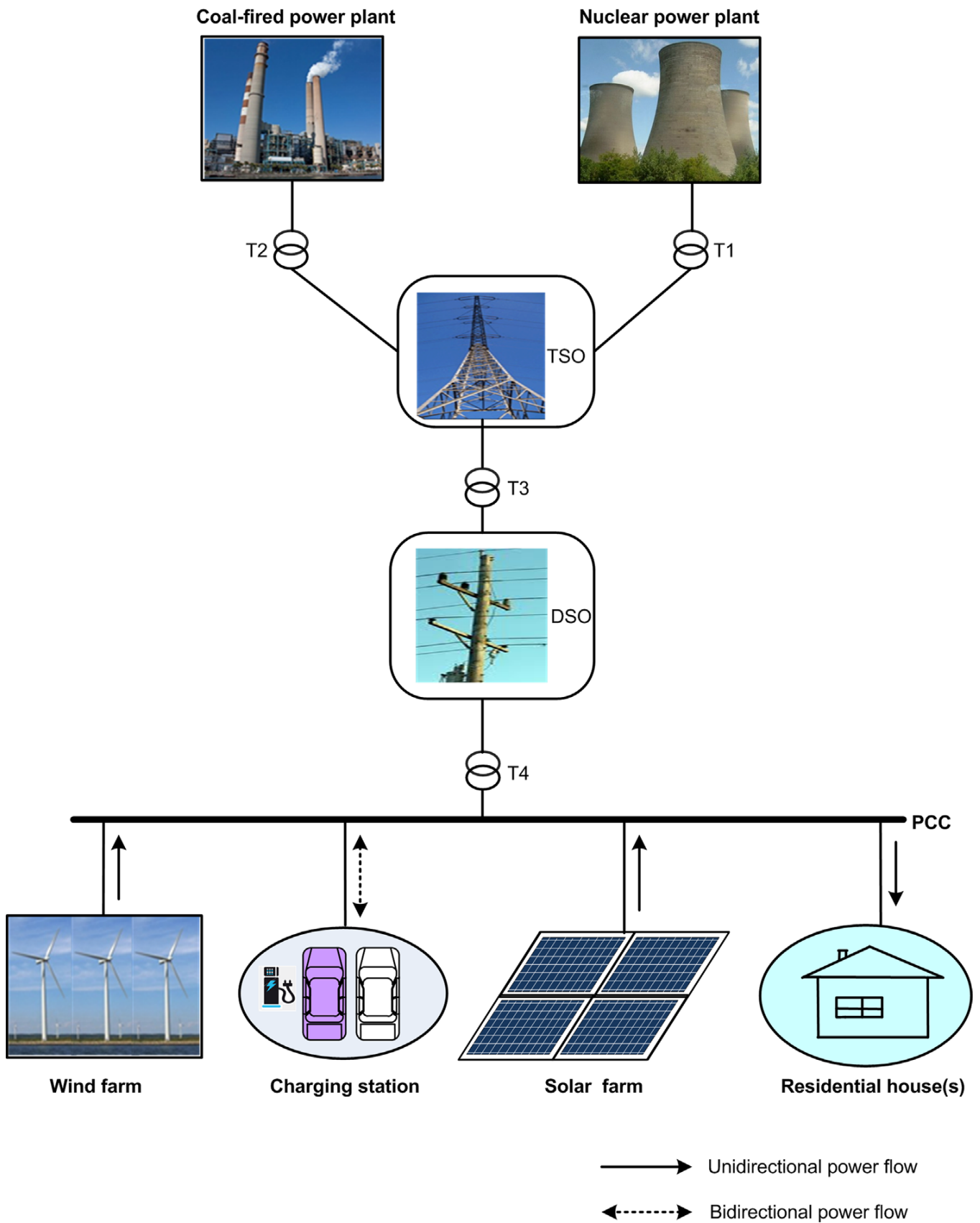


Figure 4: Simple overview of electric grid integration of all expected common participants [19].

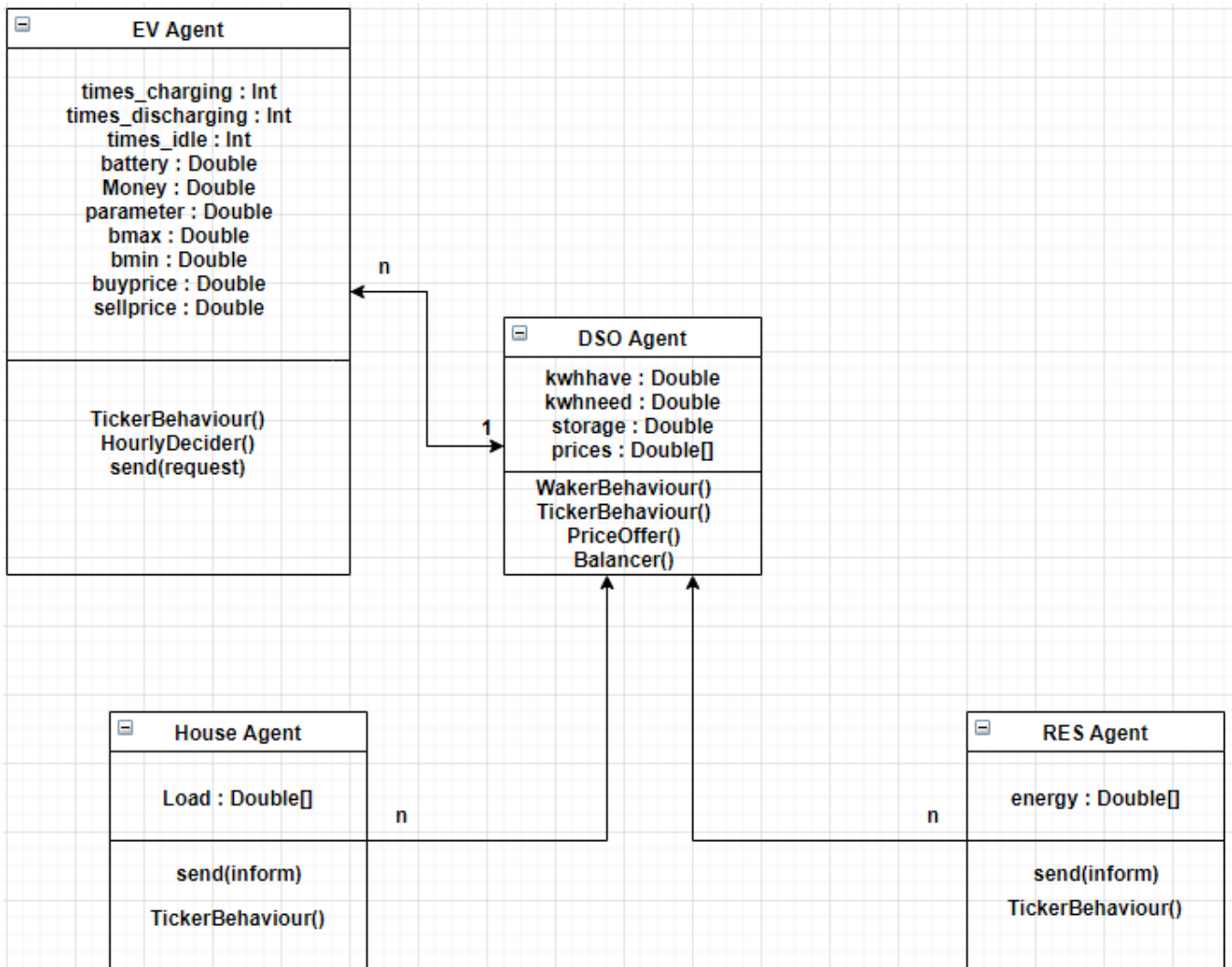


Figure 5: Self-made UML Model showcasing the basic structure and interactions in the desired system for simulating.

in a storage Double and the prices in a Double Array. Furthermore it needs a WakerBehaviour() to start after the other agents have done their actions, then a TickerBehaviour() to continue doing his actions after the other agents, a PriceOffer() that handles any incoming requests from the EV Agents, and a Balancer() to track everything related to the kWh in the system. This is a simplified and shortened outlook on the implementation itself, but still serves as a logical preview of all individual parts of the system and their interactions. More about the full Agent behaviours in the Setup.

3.2 Implementation

Now that the proper model is established that model must be put through a simulation to retrieve the needed data. To this end the model was implemented using the JAVA Agent DEvelopment Framework (JADE) [20]. Jade is a software framework written in Java which enables a simplified creation of a multi-agent system. The Agents can easily communicate with each other in many ways so that any complex

model can be implemented and put under simulations. The communications can be set to occur at certain program runtimes, when one or multiple conditions have been met or to communicate periodically. The functionality of each Agent can be split up into many "Behaviours" which like Methods execute when called, but unlike Methods the Behaviours have additional built-in properties that can be used according to the need of each Behaviour, as well as interconnected ways of calling and activating each other. This makes it possible to do a "behaviour-oriented" approach at modeling all participants of the system which ensures not missing any planned functionalities. A model created with Jade has a high degree of easy overview of all its components, which also aids in its property of being highly scalable. The same Agent class can be initialized many times, and with passing of command line arguments more individuality can be created while still only use one main Agent, to the point where multiple same Agent types can be started while they all aren't identical clones.

3.3 Experimentation

In the following paragraphs the parameters used for the simulation are further explained, the main points of interest tracked in the simulation are listed, the execution results of different simulations are listed and their details reviewed.

3.3.1 Setup

Following in the examples of the previous model, the main Agents required for the simulations are Agents for the DSO, EV-owners, residential homes and RES providers. Only 1 Jade platform is necessary for the Agent interactions and all Agents are on the same platform, simulating a small network of grid participants. The simulation time at base is 1 full day of 24 hours, where 1 hour is represented by 20 seconds runtime, needing 8 minutes to simulate a day and 56 minutes to simulate a week. The base number of agents used are 1 DSO Agent, 2 EV Agents, 1 RES Agent and 3 House Agents. Reason being that 1 DSO is enough to manage all other grid participants, while the 2 EV Agents, 1 RES Agent and 3 House Agents are picked in those numbers to make for a good grid balancing opportunity on the DSO. A short description on each Agent's functionality:

DSO Agent - The main Agent in terms of inter-Agent communication, communicating with all other existing Agents. He informs the EV Agents of the hourly prices (in €/kWh) and tracks their decisions, while also tracking the RES Agents electricity production and House Agents electricity need, all in kWh. Additionally the DSO balances the grid by ensuring the sent electricity is always equal to the required electricity, saving those values for each hour to later in the results see the effect of the EV on the balancing task. The only variable starting parameter that can be changed and affects results in the DSO Agent is the hourly price, which changes each simulated hour. Correct and appropriate values were chosen from the EPEX Spot Market prices, with the chosen price value to inspect being the Intraday Continuous Index Price.

EV Agent - The EV agents represent the EV owner as an active participant in the grid, and as such he makes his own decision what to do at which time. He only interacts with the DSO by checking the price and informing the DSO about the his action for that hour. In order to make that choice several starting parameters are set as constraints. The battery must be limited to charge no more than 75% and to discharge no less than 25%, operating with the ideal charging habit discussed previously, meaning only 50% of the battery are available without charging. This constraint is for posterity and in favor of the EV owner, and while it may reduce the income short-term the long-term income will be greater with more

Supply Type / Charger Rating		AC/DC	Rated power*	Time to charge 10kWh	Time to charge 30kWh
Regular electricity socket 13A	Slow	AC	3.0 kW	3 hours 20 mins	10 hours
Single phase 16A	Slow	AC	3.7 kW	2h 40 mins	8 hours
Single phase 32A	Fast	AC	7.4 kW	1h 20 mins	4 hours
3 phase, 16A per phase	Fast	AC	11 kW	55 mins	2 hours 45 mins
3 phase, 32A per phase	Fast	AC	22 kW	27 mins	1 hour 22 mins
3 phase, 60A per phase	Rapid	AC	43kW	14 mins	42 mins
3 phase, DC	Rapid	DC	50kW	12 mins	36 mins
3 phase, DC	Rapid	DC	120kW	5 mins	15 mins

Figure 6: Types of charging an EV. *Rated Power is a simplified value ignoring power correction that slightly changes the value but doesn't have a significant impact on the results [21].

years and cycles available to the EV battery without degradation. Additionally, the starting battery state could be of importance for the calculations and will thus also be a starting variable, possibly affecting the number of charges and discharges. Next the EV Agent must know which price is worth it for charging or discharging. For this a good assumption on discharging would be a statistical average of the common price range in the EPEX Spot Market, though this is for the likely case of the EV smart-charging on its own without needing the owner's permission, automating the process. As for charging, we will set the value to be several % lower than the discharging value, following the results of the first part to assist in reaching at least a break-even point. Finally the last necessary starting parameter is the rated charger power. This parameter determines how many kW can be charged or discharged per hour of time, see [Figure 6]. The Rapid and Fast charging are detrimental to the battery health and would wear out the battery too fast with how commonly charging would be necessary by using the V2G system, as well as not being home-applicable charging methods. The assumption for the tested parameters is that the on-board charger of the EV type supports that amount of charging. The end-values important for the results is the number of times the EV participated in the grid by charging/discharging and the money earned throughout the simulation.

RES Agent - The RES Agent represents an averagely sized solar panel for Germany, with estimated production between 3 and 10kWp [22]. The value of 1kWp represents an average of 1000kWh produced per year. In the simulations, testing different sizes doesn't impact the results tracked by this simulation, so an average 5kWp size is assumed. That is 5000kWh per year, or 14kWh per day. To accurately represent this in a 24-hour day in the simulation, these daily 14kWh are spread out among the 24 hours by correlating it to the solar production data of Germany on the same day as the EPEX SPOT market prices. This way the hour with the most % of production that day also has the same % amount of production with the RES

Agent. The DSO is informed of the production every hour.

House Agent - To aid the DSO or the service providers in predicting the electricity amount that must be sent out and available, they use *load profiles* [23]. A load profile shows expected energy needs at certain hours, which is either based on real amounts measured by an interval meter or a standard profile for the type of consumer such as residential area, office etc. Similarly to that the House Agent also needs a load profile to be used by the DSO as the house's hourly energy consumption. The House Agents inform the DSO of their hourly energy need for the DSO to provide to them, and with occasional producers like RES and EVs the DSO must balance out the electricity supply. Generally the electricity price is cheaper at late in the night after 01:00 when most people go to sleep, and rises during the day as people wake up, with an additional spike in the evening.

3.3.2 Measures

The following are the starting parameters, where some will vary across simulations:

- DSO Agent - A day or a week of simulation; EPEX SPOT prices for a certain time.
- EV Agent - Starting battery amount; Battery size; Charging parameter.
- RES Agent - Matching weather data for the same day as the DSO Agents' price parameter.
- House Agent - Load profiles.

Meanwhile, the results that will be tracked and listed at the end of simulations are:

- DSO Agent - Balancing parameters, where did the EV help the grid, how often and how much.
- EV Agent - Number of times the Agent participated in the grid during the simulation; Battery at the end of the simulation; Money that was gained or lost during the simulation.

3.3.3 Simulation Results

In the following section the variables for the simulations and the results of various simulations are listed. They will be further discussed and explained below. Prices used by the EV Agents and the DSO Agent for all the simulations were from the day of the 11.11.2019(Monday), deemed as a good representative for 1-Day simulations, and the week from the start of 11.11.2019(Monday) until the end of 17.11.2019(Sunday) for 1-Week simulations [24]. The variables, 24 for each hour of the day and in €, are:

Day 1 - 0.02861, 0.03259, 0.03357, 0.03046, 0.02916, 0.03006, 0.04298, 0.04234, 0.04858, 0.04698, 0.04985, 0.05201, 0.0487, 0.04762, 0.04738, 0.04784, 0.04843, 0.04989, 0.05203, 0.05018, 0.04461, 0.04015, 0.03995, 0.03473 .

Day 2 - 0.03123, 0.03126, 0.02931, 0.02951, 0.03227, 0.03282, 0.04169, 0.04445, 0.04351, 0.04367, 0.04128, 0.04136, 0.03939, 0.04071, 0.04471, 0.04707, 0.05026, 0.05447, 0.04602, 0.04297, 0.03878, 0.03806, 0.03656, 0.03325 .

Day 3 - 0.02901, 0.02984, 0.03128, 0.03226, 0.03250, 0.03536, 0.04595, 0.05329, 0.05370, 0.05348, 0.05081, 0.04808, 0.04714, 0.04783, 0.05101, 0.05195, 0.0555, 0.06103, 0.05298, 0.04772, 0.04085,

0.03818, 0.03701, 0.03442 .

Day 4 - 0.03881, 0.03729, 0.03667, 0.03602, 0.03751, 0.03837, 0.04728, 0.05228, 0.04785, 0.0424, 0.04174, 0.04198, 0.04218, 0.04427, 0.0458, 0.04818, 0.05351, 0.04695, 0.04275, 0.041, 0.03763, 0.0346, 0.03447, 0.03144 .

Day 5 - 0.03422, 0.03009, 0.02871, 0.0255, 0.02343, 0.02718, 0.03327, 0.03536, 0.03767, 0.03602, 0.03927, 0.0406, 0.04531, 0.04913, 0.05074, 0.05226, 0.05484, 0.06729, 0.06157, 0.05928, 0.05727, 0.05284, 0.04901, 0.04536 .

Day 6 - 0.03885, 0.03747, 0.03658, 0.03693, 0.0374, 0.03863, 0.03946, 0.04274, 0.04475, 0.04546, 0.04267, 0.04197, 0.0372, 0.03238, 0.03175, 0.03351, 0.03555, 0.03798, 0.03729, 0.03245, 0.02895, 0.02975, 0.02903, 0.02545 .

Day 7 - 0.03062, 0.03127, 0.02925, 0.02938, 0.03038, 0.03053, 0.03171, 0.03256, 0.03753, 0.03921, 0.04062, 0.03721, 0.03893, 0.03903, 0.0395, 0.04009, 0.04123, 0.045, 0.0427, 0.04232, 0.03898, 0.03526, 0.03468, 0.03313 .

Charging constraints for the EVs ensure they can't charge above 75% or below 25%. When the battery can charge, the price must be higher than the average value of 0.042264083333333333€. This value was obtained through averaging several workdays(Monday-Friday) of energy prices, to ensure the EV charges when the prices are sufficiently high enough. Discharging is only done when the price is lower than 0.0399323€, which is 5.51724% lower than the buying price. The 5.51724% are from the conclusion of the first part of this paper, representing the safety amount to aid in breaking even.

That same week has the solar statistics as well, which are used to spread the RES production across the day in the correct way. The variables, 24 for each hour of the day and in kWh, are:

Day 1 - 0, 0, 0, 0, 0, 0, 0, 0, 0.08, 1.456, 4.015, 6.367, 8.008, 8.683, 7.584, 5.086, 1.863, 0.113, // 43.255 0, 0, 0, 0, 0, 0 .

Day 2 - 0, 0, 0, 0, 0, 0, 0, 0, 0.088, 1.489, 3.927, 6.443, 8.02, 7.695, 6.155, 4.472, 2.095, 0.225, 0, 0, 0, 0, 0, 0 .

Day 3 - 0, 0, 0, 0, 0, 0, 0, 0, 0.064, 1.32, 3.378, 5.348, 6.525, 6.618, 5.38, 3.465, 1.459, 0.114, 0, 0, 0, 0, 0, 0 .

Day 4 - 0, 0, 0, 0, 0, 0, 0, 0, 0.179, 3.357, 8.084, 12.291, 15.057, 15.069, 12.914, 8.327, 3.032, 0.175, 0, 0, 0, 0, 0, 0 .

Day 5 - 0, 0, 0, 0, 0, 0, 0, 0, 0.091, 1.371, 3.222, 4.76, 5.299, 4.55, 3.976, 3.155, 1.306, 0.089, 0, 0, 0, 0, 0, 0 .

Day 6 - 0, 0, 0, 0, 0, 0, 0, 0, 0.052, 1.219, 3.311, 4.996, 6.116, 7.109, 6.613, 4.666, 2.077, 0.161, 0, 0, 0, 0, 0, 0 .

Day 7 - 0, 0, 0, 0, 0, 0, 0, 0, 0.032, 0.707, 2.404, 3.928, 4.482, 4.221, 3.749, 2.448, 0.689, 0.029, 0, 0, 0, 0, 0, 0.

Of the load profiles used, the first two were random houses from the list of housing load profiles of the German city Hessen [25]. The third, to contrast the lower load requirements of the first two, was an example from a house that uses more electricity [26]. The variables, 24 for each hour of the day and in kWh for the 3 House Agents that will be used in all simulations, are:

Load 1 - 0.319, 0.226, 0.199, 0.193, 0.193, 0.214, 0.379, 0.615, 0.671, 0.628, 0.583, 0.582, 0.634, 0.658, 0.59, 0.532, 0.514, 0.6, 0.782, 0.922, 0.876, 0.73, 0.615, 0.469 .

Load 2 - 0.321, 0.226, 0.199, 0.193, 0.193, 0.214, 0.38, 0.616, 0.671, 0.629, 0.583, 0.583, 0.636, 0.659, 0.593, 0.533, 0.516, 0.601, 0.783, 0.924, 0.876, 0.732, 0.616, 0.469 .

Load 3 - 1.3, 1, 0.8, 0.8, 0.89, 1.22, 1.6, 2.25, 2.32, 2.1, 1.82, 1.54, 1.4, 1.33, 1.18, 1.17, 1.26, 1.5, 2.53, 2.85, 2.7, 2.47, 2.2, 1.7 .

Next the simulation starting parameters and results:

1. Simulation 1 (S1) - 1 Day; 1 DSO Agent; 0 EV Agents; 1 RES Agent; 3 House Agents. Results:
 - 51.4kWh supplied by the DSO.
2. Simulation 2 (S2) - 1 Day; 1 DSO Agent; 2 EV Agents - 30kWh starting battery, 40kWh battery capacity, 3kWh charging parameter; 1 RES Agent; 3 House Agents. Results:
 - 17.4kWh supplied by the DSO.
 - Each EV Agent charged 1 time, discharged 7 times, was idle 16 times.
 - Each EV battery at the end of the simulation was at 13kWh.
 - Each EV Agent earned 0.84143€.
3. Simulation 3 (S3) - 1 Day; 1 DSO Agent; 2 EV Agents - 10kWh starting battery, 40kWh battery capacity, 3kWh charging parameter; 1 RES Agent; 3 House Agents. Results:
 - 57.4kWh supplied by the DSO.
 - Each EV Agent charged 7 times, discharged 6 times, was idle 11 times.
 - Each EV battery at the end of the simulation was at 13kWh.
 - Each EV Agent earned 0.19068€.
4. Simulation 4 (S4) - 1 Day; 1 DSO Agent; 2 EV Agents - 30kWh starting battery, 40kWh battery capacity, 7kWh charging parameter; 1 RES Agent; 3 House Agents. Results:
 - 25.4kWh supplied by the DSO.
 - Each EV Agent charged 1 time, discharged 3 times, was idle 20 times.

- Each EV battery at the end of the simulation was at 17kWh.
 - Each EV Agent earned 0.64561€.
5. Simulation 5 (S5) - 1 Day; 1 DSO Agent; 2 EV Agents - 67.5kWh starting battery, 90kWh battery capacity, 7kWh charging parameter; 1 RES Agent; 3 House Agents. Results:
- No kWh supplied by the DSO, offset by the amount total provided by the EVs(24.6kWh).
 - Each EV Agent charged 1 time, discharged 7 times, was idle 16 times.
 - Each EV battery at the end of the simulation was at 29.5kWh.
 - Each EV Agent earned 1.88217€.
6. Simulation 6 (S6) - 1 Week; 1 DSO Agent; 2 EV Agents - 30kWh starting battery, 40kWh battery capacity, 3kWh charging parameter; 1 RES Agent; 3 House Agents. Results:
- * Day 1 statistics
 - 17.4 kWh supplied by the DSO.
 - Each EV Agent charged 1 time, discharged 7 times, was idle 16 times.
 - Each EV battery at the end of the day was at 13.0kWh.
 - Each EV Agent earned 0.84143€.
 - * Day 2 statistics
 - 70.25 kWh supplied by the DSO.
 - Each EV Agent charged 11 times, discharged 8 times, was idle 5 times.
 - Each EV battery at the end of the day was at 22.0kWh.
 - Each EV Agent lost -0.00804€.
 - * Day 3 statistics
 - 48.5 kWh supplied by the DSO.
 - Each EV Agent charged 6 times, discharged 7 times, was idle 11 times.
 - Each EV battery at the end of the day was at 19.0kWh.
 - Each EV Agent earned 0.44227€.
 - * Day 4 statistics
 - 46 kWh supplied by the DSO.
 - Each EV Agent charged 8 times, discharged 7 times, was idle 9 times.
 - Each EV battery at the end of the day was at 22.0kWh.
 - Each EV Agent earned 0.11123€.
 - * Day 5 statistics
 - 32.4 kWh supplied by the DSO.
 - Each EV Agent charged 3 times, discharged 7 times, was idle 14 times.

- Each EV battery at the end of the day was at 10.0kWh.
- Each EV Agent earned 0.8315€.
- * Day 6 statistics
- 93.6 kWh supplied by the DSO.
- Each EV Agent charged 11 times, discharged 4 times, was idle 9 times.
- Each EV battery at the end of the day was at 30.0kWh.
- Each EV Agent lost -0.63416€.
- * Day 7 statistics
- 58 kWh supplied by the DSO.
- Each EV Agent charged 3 times, discharged 3 times, was idle 18 times.
- Each EV battery at the end of the day was at 30.0kWh.
- Each EV Agent earned 0.0633€.
- * Full statistics for the whole week.
- 366.2 kWh supplied by the DSO.
- Each EV Agent charged 43 times, discharged 43 times, was idle 82 times.
- Each EV battery at the end of the simulation was at 30.0kWh.
- Each EV Agent earned 1.64753€ total.

7. Simulation 7 (S7) - 1 Week; 1 DSO Agent; 2 EV Agents - 67.5kWh starting battery, 90kWh battery capacity, 7kWh charging parameter; 1 RES Agent; 3 House Agents. Results:

- * Day 1 statistics
- No kWh supplied by the DSO, offset by the amount total provided by the EVs(24.6kWh).
- Each EV Agent charged 1 time, discharged 7 times, was idle 16 times.
- Each EV battery at the end of the day was at 29.5kWh.
- Each EV Agent earned 1.88217€.
- * Day 2 statistics
- 94.25 kWh supplied by the DSO.
- Each EV Agent charged 11 times, discharged 8 times, was idle 5 times.
- Each EV battery at the end of the day was at 50.5kWh.
- Each EV Agent lost -0.04076€.
- * Day 3 statistics
- 40.5 kWh supplied by the DSO.
- Each EV Agent charged 6 times, discharged 7 times, was idle 11 times.
- Each EV battery at the end of the day was at 43.5kWh.
- Each EV Agent earned 1.00553€.

- * Day 4 statistics
 - 54 kWh supplied by the DSO.
 - Each EV Agent charged 8 times, discharged 7 times, was idle 9 times.
 - Each EV battery at the end of the day was at 50.5kWh.
 - Each EV Agent earned 0.23927€.
- * Day 5 statistics
 - 39.6 kWh supplied by the DSO.
 - Each EV Agent charged 3 times, discharged 7 times, was idle 14 times.
 - Each EV battery at the end of the day was at 22.5kWh.
 - Each EV Agent earned 1.8854€.
- * Day 6 statistics
 - 143.64 kWh supplied by the DSO.
 - Each EV Agent charged 11 times, discharged 4 times, was idle 9 times.
 - Each EV battery at the end of the day was at 67.5kWh.
 - Each EV Agent lost -1.41394€.
- * Day 7 statistics
 - 58 kWh supplied by the DSO.
 - Each EV Agent charged 3 times, discharged 3 times, was idle 18 times.
 - Each EV battery at the end of the day was at 67.5kWh.
 - Each EV Agent earned 0.1477€.
- * Full statistics for the whole week.
 - 366.2 kWh supplied by the DSO.
 - Each EV Agent charged 43 times, discharged 43 times, was idle 82 times.
 - Each EV battery at the end of the simulation was at 67.5kWh.
 - Each EV Agent earned 3.70537€ total.

8. Simulation 8 (S8) - 1 Week; 1 DSO Agent; 2 EV Agents - 67.5kWh starting battery, 90kWh battery capacity, 3kWh charging parameter; 1 RES Agent; 3 House Agents. Results:

- * Day 1 statistics
 - No kWh supplied by the DSO, offset by the amount total provided by the EVs(32.6 overflow).
 - Each EV Agent charged 1 time, discharged 15 times, was idle 8 times.
 - Each EV battery at the end of the day was at 25.5kWh.
 - Each EV Agent earned 2.05407€.
- * Day 2 statistics
 - 70.25 kWh supplied by the DSO.

- Each EV Agent charged 11 times, discharged 8 times, was idle 5 times.
- Each EV battery at the end of the day was at 34.5kWh.
- Each EV Agent earned 0.00516€.
- * Day 3 statistics
 - 48.5 kWh supplied by the DSO.
 - Each EV Agent charged 9 times, discharged 10 times, was idle 5 times.
 - Each EV battery at the end of the day was at 31.5kWh.
 - Each EV Agent earned 0.61014€.
- * Day 4 statistics
 - 46 kWh supplied by the DSO.
 - Each EV Agent charged 10 times, discharged 9 times, was idle 5 times.
 - Each EV battery at the end of the day was at 34.5kWh.
 - Each EV Agent earned 0.19713€.
- * Day 5 statistics
 - 50.4 kWh supplied by the DSO.
 - Each EV Agent charged 11 times, discharged 12 times, was idle 1 time.
 - Each EV battery at the end of the day was at 31.5kWh.
 - Each EV Agent earned 0.8315€.
- * Day 6 statistics
 - 125.6 kWh supplied by the DSO.
 - Each EV Agent charged 16 times, discharged 4 times, was idle 4 times.
 - Each EV battery at the end of the day was at 67.5kWh.
 - Each EV Agent lost -1.19028€.
- * Day 7 statistics
 - 58 kWh supplied by the DSO.
 - Each EV Agent charged 3 times, discharged 3 times, was idle 18 times.
 - Each EV battery at the end of the day was at 67.5kWh.
 - Each EV Agent earned 0.0633€.
- * Full statistics for the whole week.
 - 366.2 kWh supplied by the DSO.
 - Each EV Agent charged 61 times, discharged 61 times, was idle 46 times.
 - Each EV battery at the end of the simulation was at 67.5kWh.
 - Each EV Agent earned 2.62206€ total.

3.3.4 Simulation Discussion

The S1 was a simple simulation of the system without EVs. The 3 House Agents need 65.4kWh in total for the day, the RES Agent produced 14kWh bringing down the total daily electricity need the DSO had to provide down to 51.4kWh.

The S2 had 2 EVs but otherwise identical settings to S1 allowing for comparing the impact of the EVs directly. First point to note is that the DSO Agent had to only supply 17.4 kWh of electricity in total during the day, the rest came from the 14k RES and the EVs - 20kWh was discharged per EV, 3kWh was charged per EV. In total the difference in DSO-energy need was of 40kWh, 11kWh per EV. This means the inclusion of the EVs has helped the DSO during peak usage times more than it was a burden due to the charging. The reason for that is that the Day starts with 00:00, where electricity price is already low and getting lower, which gives the time window for the EV to charge and store electricity so it can be discharged later during the day when the price is higher and the electricity need is bigger. Second point to note is the EV participation - a total participation of 33.3%, a third of the day. One reason for that is that the first several hours the EVs are idle due to starting the day fully charged from the start and not discharging due to low prices. Another is that when prices are high the EVs discharge until they are at the minimum threshold (25%) but the price can still be high enough to not charge it yet, so they are idle waiting for good times to charge which they do later in the night before the day ends. Third point is the money, with the day ending on a positive 0.84143€ increase per EV. However the battery ending at nearly minimum with 13kWh makes it so this simulation needs to be done across more than a day length to have an average value to calculate for yearly income, as the next day would start with many hours of charging. Finally, the fourth point of interest is the battery usage. In this day simulation the EV discharged 6 times 3kWh and 1 time 2kWh until it was at the minimum 10kWh, waiting until the prices drop to recharge. This means that a full cycle wasn't even reached in the first day, with only the discharge happening. However the battery of the day ends at 13kWh, so with more days of testing the cycle usage per week and per day can be established.

S3 is the same simulation as S2, with the difference of starting with minimum battery of 10kWh instead of the maximum 30kWh. So the results will be compared to simulation 2 with the aim of understanding the differences. The DSO had to supply 57.4kWh in total that day, more than in S1 without any EVs. Reason for this is that each EV charged 7 times, which is 21kWh charge per EV, while discharging 6 times, or 18kWh per EV. In total 3kWh more was needed from the DSO in total due to EV charging. The higher participation of 54.16% is mainly due to the charging times at the beginning after 00:00 until the prices rise more, after which all that could be charged is discharged, akin to S2. Less discharges than S2 are due to the EVs being unable to fully charge before the prices start rising and charging not being profitable anymore. The most interesting point is that the battery at the end of the day is 13kWh, exactly like in S2. This means that both S2 and S3 would continue the week the exact same way, only impacting the money gained on the first day. And while S3 would still have less in total than S2 even with years of running, with time their difference would become very negligible. Hence the starting battery amount can be left at full for the next simulations.

S4 has charging amount is increased to Level 2 charging of 7kWh. This is a substantial increase that would allow the EVs to charge and discharge more per hour, potentially making more or less use out of certain highly cheap or highly expensive hours. DSO had to supply 25.4kWh, as expected from the previous two simulations, helping out the grid on the first day when starting charged. The participation % decreased drastically with only 4 participated hours, or 16.6% of the day. The larger charging amount makes discharging all the stored-up energy finished faster so the EV would be waiting at minimum battery

longer until the prices drop again to refill. Same for the charging, where the battery would charge up faster but then be idle for longer until prices rise. The income is positive at 0.64561€ but compared to S2 it is lower. Reason for that is that the EV automated process discharges all energy as soon as the prices are favorable accordingly to the constraints, possibly missing out on a sudden big price spike in the high or low end. Another reason is the battery amount ending with 17kWh, 4kWh more than in S2. The simulation was intended to observe the EV owner's reaction to real time prices that change every hour, so the spikes in price can still be missed. A way to prevent this is having a large enough EV battery to ensure both charging and discharging is always possible to react to sudden spikes. Another way would be to rely on the Day Ahead Auction which is done a day before, and trying to read out from there when a spike will happen. However the spikes are rare and largely random and unpredictable, so that method would have very unlikely success. Another option is designing the EV smart meter automation as an artificial intelligence that makes choices like waiting until close before the prices start dropping, though the success of an artificial prediction can also be unreliable.

S5 has the maximum battery increased from 40kWh to 90kWh, which puts the 75% - 25% amount to 67.5kWh - 22.5kWh, a total of 45kWh from the starting 90kWh are available which is 25kWh more than what the 40kWh battery simulations had available at 20kWh. The DSO overall didn't need to supply any electricity, in contrary the production was an overflow of 24.6kWh. This however is unlikely to happen in real world examples due to the number of houses with energy demands outnumbering the EVs by more than the 3 to 2 example shown here. It would require many EV owners participating in a V2G system for this to happen, at which point the DSO would have to react accordingly, either by storing the energy, which was the assumption for these simulations in order to gauge the total weekly amount in longer simulations, or by refusing further intake/reducing the prices for their discharge proportionally to the overflow, making them stop. It all relies heavily on how the V2G system is implemented, if it happens. If it is on a personal level with the EV owner, which this paper works on the basis of, then at first their supply would be very unpredictable since any EV owner can choose when and how to charge or discharge. In a V2G system where the EV owner only has to ensure the connection to the grid but otherwise all EVs are operated by the DSO, then the predicted income for the EV owners would most likely be even lower than in these simulations, as the price spikes and energy shortages will be handled in big EV numbers reducing individual income because only enough kWh will be discharged across all EVs to meet the demand. Meaning instead of individual EV owners discharging 7kWh at good times, the DSO would discharge 3kWh or less from each of many connected EVs, possibly even less, depending on RES production and energy demands. A more interesting study case is of the individual EV owner trading energy on his own like other market participants. The EVs charged 1 time and discharged 7, being idle 16 times with a 33.3% participation. This is remarkably the same amounts as in S2, proving similarity in action performance regardless of kWh size. Unlike in S4, the bigger battery here can afford to have higher charging power without being too affected by the lack of energy caused by it.

S6 is similar to S2, but over the course of 1 week. This should average out values such as the income, providing a better insight into the profitability. The DSO was helped a total of 4 Days out of 7, in which a smaller amount was needed than in S1 without EV presence. Meanwhile 3 out of 7 days there was more needed because of the EVs recharging. In terms of participation, overall during the week the EVs had a 51.19% participation. Day 1 went the same way as in S2. On Day 2 the EVs had to charge up the battery a lot more than in Day 1, with 11 chargings, causing a monetary loss instead of gain, which is to be expected during charge-heavy days. Across the rest of the workdays the EVs performed similarly, charging and discharging daily. Most notable are Day 5, which as a Friday generally tends to have higher electricity use and therefore higher prices, as well as the weekends Day 6 and 7, which are known to be

cheaper with prices, making them the ideal recharging days where very little was discharged and earned. However the weekend being used for charging prepares the battery for the upcoming new week with a full battery, the same amount it started with, proving it is a better expected value to start the week with full battery than not. With a battery of 40kWh and 3kWh charging parameters, 6-7 charges and discharges can be done in one cycle. With the final number of charging and discharging being 43 each at the end of the week, the number of cycles per week can be calculated at 6.45. With 52.1429 weeks in a year and 7,100 cycles possible before changing the battery, this equals to 336.3 cycles per year, for a total of 21.11 years of usage. A lot more than expected. The total income at the end of the week was 1.64753€. With the same calculations, this results in 85.9€ per year and 1,813.35€ in the lifetime. However with the earlier established costs of 172€ replacement costs per kWh, replacing this 40kWh battery at the end of those 21.11 years would cost 6,880€, 3.794 times more than the gain. This concludes S6 with V2G not being profitable even with perfect battery use and market participation. However that is only for the current EV battery replacement costs. With the future costs of 94\$/kWh for 2024, the price is 3,760\$/kWh and with the 62\$/kWh costs of 2030, the price is 2,480\$/kWh. With the exchange rate between \$ and € constantly changing these values may be less accurate at the future, but for now that is 3,415€ for 2024 and 2,252€ for 2030. Those come closer to a break-even point, but are still in an overall loss. The difference between charging and discharging price would need to be set up in a way to only charge and discharge when the values are even more apart, which would severely reduce the number of times that an EV can charge/discharge and thus reducing the weekly charges, resulting in it requiring even more than the 22.11 years here to lead to a break-even point.

S7 is similar to S5, but over the course of 1 week. The total daily energy need from the DSO was reduced on 3 out of 7 days. Total EV participation at the end of the week averages out into a bit over half of the time with 51.19%. Interestingly this is the same amount as for S6, the 40kWh battery simulation over a week. This allows for a good comparison in performance between the bigger and smaller EV battery. When on the maximum of 67.5kWh only 7 times can be discharged with 7kWh charging power until the battery is at the 22.5kWh minimum. The same is true the other way around when charging, meaning if there are more than 7 favorably high prices in a row or more than 7 favorably low prices in a row then the EV cannot continue, which causes many of the idle hours alongside the price changes. The battery level was between middle and fully charged at the end of most days, with only one day ending with minimum battery. That day was a Friday with a sudden spike of prices around 12:00 which kept rising until 17:00 and only dropping off slowly, with the electricity still being expensive until 01:00 of the next day. Day 6 and 7 are weekend days which usually have low prices and no big price changes, making those less profitable days for V2G use. Days like these will be used by the EV for charging for the most part, making them the least profitable days for the V2G use, but ensuring that a week will most likely end with full battery ready for the next week start. With the final income of 3.70537€, the same calculation about lifetime can be made as for S6. 336.3 cycles per year remain unchanged as does the 21.11 years of lifetime performance. This means a yearly income of 193.2€ and 4,078.63€ overall lifetime income. Repair costs for the present time are 15,480€, 7,686€ in 2024 and 5,069.7€ in 2030. Like in S6, the system is still not profitable. Worth noting still is the 90kWh battery and the 40kWh both cover 80% of their 2030 replacement costs, proving that the battery size truly doesn't impact the performance, as long as the correct charging parameter for the battery size is set.

S8 is similar to S7, but with a charging power of 3kWh. The goal here is to find out whether reducing idle time with less charging power gives positive changes. Just like in S7, the EVs helped the grid 3 out of 7 days while the other 4 days causing more energy need due to charging. However the total income per week is less than before with 2.48082€. The main reason for that is being less able to make use of high

or low-price peaks with only 3kWh charging power per hour, so the higher peak discharge and charge are averaged out with having to discharge and charge at less favorable times. The conclusion of these results is that the charging power of the EV should be proportional to the EV size, as EV owners with bigger batteries profit more out of larger charging power values while EV owners with smaller batteries profit more from smaller charging parameters as seen in S2 and S4 comparison. While the lower charging power allows for the EV participating more often more it averages out the income to a lower amount. Checks need to be done to ensure charge and discharge is done at a bigger price discrepancy, at which point a higher charging power performs better due to fewer charging and discharging times.

3.4 Conclusion

The first part of this paper focused on researching various EV statistics needed to calculate the feasibility of an EV-owner's participation in the V2G system in Germany. The first part worked with fixed prices of buying electricity from the main electricity provider of Stuttgart enBW and determined what a theoretical selling price would need to be under those prices for a break-even point to be reached between the gains of discharging and the losses of charging and eventual battery replacement. The conclusion was that with fixed prices the selling price of electricity must at least be 16.2068% higher in the present time, 8.2758% higher in 2024 and 5.51724% higher in 2030 than the buying price for a break even point to be reached. To test it differently the second part focused on EV-owner participation in the EPEX Spot Market with varying prices each hour. The 5.51724% value concluded at the end of the first part was used for the second part's calculations in determining the best times to charge and discharge. After the V2G system was modeled and implemented several different simulations were run. The results all concluded that the V2G system is not profitable for EV owners to participate in. The battery replacement costs are simply too large, even with the established replacement time being in 21.11 years after start. Not enough money can be generated to cover the battery replacement. This however was mainly seen from the perspective of an individual EV owner participating in the market. If the V2G system is implemented in different ways like the DSO controlling all the EVs connected into the V2G and determining their charge and discharge then the situation could be different if extra reimbursements are given to the EV owners to deal with the degrading battery, which could degrade faster under mass-DSO use of EV fleets. Other than that the income can't be further increased by much. Constraints could be set even more harshly to only charge with very cheap prices and discharge with very high prices, but that would severely reduce the participation in the grid and remove potential benefits which were the original purpose behind the V2G in the first place, as well as the income slowing down a lot due to rarer participation. Other interesting results included that the battery size is irrelevant for V2G performance, and while the income is higher with a larger battery so is the replacement cost, which ends up into the same % amount of income. Furthermore the EV is very idle during weekends, providing the possibility of EV owners driving more on those days with cheaper energy and still charge fully for the next week's start. Situations that rarely happened like negative EPEX SPOT market prices were not considered, which would mean earning money while charging, which happens when power plants produce too much but stopping production and restarting it later would cost them more than the price penalty at that specific hour. However those are very rare case that wouldn't impact the lifetime results significantly. 21.11 years from now battery replacement could be even lower than assumed, or other future possibilities like recycling degraded batteries would make the V2G profitable, but those are only guesses at the time being. V2G system could also be worth it if after this many years the battery isn't replaced and only the money kept, though either way it will have sped up the need to buy a new EV with a new battery. Perfect use may not even be achievable by most EV owners, which

would reduce the lifetime before replacement further. The simulations also didn't account for the battery depleting from personal driving and being off of the grid for some times, and those factors included would just make the V2G system even more unprofitable than it already is. Whether more options in the future will make V2G an economically feasible option that becomes widespread remains to be seen, however at the present the V2G system is not feasible for the EV owner.

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