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Bachelorarbeit

Financial benefit of electric vehicles within a microsystem

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Course of Study:	Softwaretechnik
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Commenced:	April 20, 2022
Completed:	October 20, 2022
CR-Classification:	1.6

Abstract

Germany has some of the highest electricity prices in the world. In the past few years, prices for energy have already been rising, but due to war on the european continent, this has dramatically accelerated. New components such as photovoltaic panels, heat pumps, home storages batteries and electric vehicles bring new possibilities and challenges for the home energy management away from fossil fuels towards a larger electricity usage. Setting up the system and managing it is a crucial but non-trivial task.

This thesis investigates the financial optimization of a single family home which uses electricity as it main source of energy for heating and mobility. It is equipped with a photovoltaic system (PV) for electricity production, a heatpump for heating and warm water production and relying on one electric vehicle for mobility. For the financial optimization, the following solutions are investigated: introduction of a smart energy management system, sizing the PV, sizing a potential home storage battery and finally introducing vehicle to home capabilities.

To answer these questions, a single family home in Germany is simulated over one year. An algorithm developed within the project mimics a smart energy management system, which uses forecasts for of the next 24 hours of all components. This algorithm can decide when to charge or discharge the electric vehicle and the home storage, but can not influence the other actors.

The results indicate, that electric vehicles are not ideal as an energy storage from a financial point of view. Home storage batteries are currently a better choice.

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Acronyms

EV electric vehicle. 20

HP heatpump. 19

HS home storage. 25

PV photovoltaic. 19

SFH single family home. 25

V2H vehicle to home. 20

1 Introduction

Energy production, energy mix of fossil and renewable energies, energy usage, storage and the share of electricity in the total energy usage are some of the key issues in our decade and for the decades to come. This will influence the evolution of our climate as well as the performance of the industrial economies. The ideal solution would be clean, climate neutral, constantly available and affordable energy.

The current German government, which was formed in 2021, intends to increase the production of renewable energies in the near future to reduce emissions and mitigate the effects of climate change. Especially regarding photovoltaic systems, the coalition agreement of 2021 [Koalitionsvertrag22] states that all suitable roofs should be used to produce solar power. In some parts of Germany, such as Baden-Württemberg, this is already mandatory for all new buildings. An increasing number of homeowners who own a photovoltaic system already have a home storage battery as well or have at least thought about aquiring one. These batteries store the electricity produced by the photovoltaic system that can not be used directly and make it available for a later use. This makes the house more self sufficient by reducing the reliance on electricity from the power grid.

The current geopolitical situation with armed conflicts in Europe, involving Russia, previously one of Germanys biggest energy suppliers, has further accelerated the rise in energy prices. The higher these prices, the more it can be worth it to look into ways of optimizing houses and their energy management. Fears of energy shortages have further strengthened the call to get more independant from other nations regarding energy. This further accelerates the shift from fossil energy sources to renewable sources, since Germany does not have much natural gas or oil of its own.

Especially natural gas prices have seen a big increase and have almost doubled for consumers from 2021 to 2022 [BDEWgas22]. The reason for this is mainly that utility providers have to pay three times more for gas themselves, as a result of the current geopolitical situation. As a consequence, heating with natural gas is very expensive and less popular than ever. An alternative that is endorsed by the government consists in installing heatpumps. However since heatpumps use electricity, the overall electricity consumption of a house increases significantly. If possible the house should be equipped with a photovoltaic system and possibly a home storage battery in order to reduce operating costs and minimize the use of fossil fuels.

Electric vehicles are another technology that will find more and more widespread adoption in the near future. The German government aims to have at least 15 million electric vehicles in the country by the year of 2030. In addition, only new vehicles that are carbon neutral will be allowed to be registered from 2035 onwards. These two goals are written in the governments coalition agreement. Since many households will have an electric vehicle sooner or later and vehicle to home technology (enabling discharging the car battery to use the electricity anywhere in the house) is built into an increasing number of those cars, it is worth asking whether this functionality can be used to benefit homeowners financially. With an extra investment into a wallbox that allows for bi-directional charging, the electric vehicle can be used in the same way as a home storage battery and maybe make a dedicated storage obsolete.

Improving the financial performance of existing single family homes by the use of additional energy management software could lessen the burden of high energy prices for many Germans. In addition, if this piece of software makes the investment into the different components such as solar panels becomes more lucrative, more people will buy them. This would have the positive effect of increasing the production of renewable energies and benefit the environment.

In the scope of this bachelor thesis, we investigate whether a smart energy management system can financially benefit homeowners. Furthermore we explore if an electric vehicle with vehicle to home capabilities can benefit a homeowner financially if used instead of or in addition to a home storage battery. We also examine which factors influence the financial performance most, in order to determine what a good house setup would look like.

To answer these questions, different house configurations are simulated over the period of one year with a newly developed simulation software. An algorithm that represents a smart energy management system has access to forecasts of the next 24 hours for all components, such as the photovoltaic system or the heatpump. It then make decisions based on the forecasts, with the objective to benefit the homeowner financially. It controls when to charge and discharge the storage battery and the electric vehicle, as well as when to buy and sell electricity.

This thesis is structured as follows: in Chapter 2 we make a short presentation of the components used in the investigated home system. Chapter 3 is devoted to a comparison of the methodology, configurations, date and software used in this thesis with related work that was previously done by others. Chapter 4 presents the software tool developed for the investigations. The various investigations are then carried out in chapter 5. Finally we conclude and propose some ideas for further work.

Please note, that my colleague Lorenz Keefer developed an algorithm to maximize autarky in the same simulation framework for his bachelor thesis [Autarky22]. The difference between his work and the present one is the target of the optimization: Minimizing the dependance from the grid versus optimizing cost by opimizing the interaction with the grid.

2 Background

Let us have a short look at the components of the system and the financial framework of the electricity market.

2.1 Photovoltaic system

A photovoltaic (PV) system consists of several solar panels and an inverter. The solar panels can be positioned on a roof or on the ground and produce direct current. The inverter then converts it to alternating current which can be used by anything that consumes electricity in the house or it can be fed into the power grid for profit. Photovoltaic systems are a renewable energy source that enables everyone to generate their own electricity and profit financially as well.

2.2 Heatpump

A heatpump (HP) is an electrical heating system. Instead of only heating water using electricity, a heatpump uses the principles of thermodynamics to transfer heat from the air outside or water underground into the house system. By doing so, water can be heated with less electricity. Because they do not use fossil energy sources and have a higher efficiency than conventional electric heating systems, they are considered as better for the environment. Since they increase the overall electricity consumption of a house significantly, they are often paired with PV systems, which is done in this work as well.

2.3 Dynamic prices for consumers

Usually homeowner have a contract with their utility provider to buy all the electricity they need at a fixed/static price per kWh, no matter when they need it. Same goes for the price per kWh paid to the homeowner when he feeds energy into the power grid.

Bigger players such as a company or person with a PV installation with a maximum capacity above 100 kWp (kiloWatt peak), can buy and sell electricity directly on the market. In that case the price for electricity is dynamic and fluctuates according to the current supply and demand.
To allow homeowners to get these prices as well, many houses with small PV systems can be connected together to form a virtual power plant. This is already possible, but is only rarely used to enable homeowners to buy at market prices.

2.4 Home storage

Home storage (HS) batteries are a common way to store electricity produced by photovoltaic systems. The most commonly used battery technology is lithium-ion. All home storage batteries in this thesis are therefore lithium-ion batteries.

2.5 Vehicle to home

The vehicle to home (V2H) technology makes it possible to discharge the electricity stored inside the battery of an electric vehicle (EV) and use it in the house it is connected to. That way the car is not just a car anymore, but can be used the same way as a home storage system. In order to do so, the system requires specific hardware that allows for bi-directional charging. Nowadays there are only a few car models available that already have this capability built in. In addition to this, a special wallbox is also required, which costs significantly more than a regular wallbox. However since more and more car manufacturers have announced to produce cars with bi-directional charging capabilities, this technology is going to become more relevant in the near future.
Using an EV as a storage also comes with disadvantages, such as high energy losses. The battery life is reduced as well, since all batteries available today only last a certain amount of loading cycles before their capacity decreases to a point where it is not suited for an EV anymore. When using an EV as a storage in addition to driving it, the battery degradation is therefore accelerated.

3 Related work

A fairly large amount of research has already been done in the field related to this thesis. We will have a look at some of these studies and at what this thesis can contribute to the research field. The results of these studies are compared with ours in Section 5.7.

3.1 Smart home energy management optimization method considering energy storage and electric vehicle

The objective of the study published by Yuan Hu et al. in 2019 [Rw119] was to use a smart home energy management system to reduce costs and to avoid and flatten peaks in consumption. The cost reduction part is similar the one in this thesis, whereas the second issue will not be treated.

The actors used in the house under investigation are close to those used in this thesis: PV, HS, heating system and EV. The differences are that some of their appliances, such as a dishwasher, can be scheduled and controlled by the energy management system. They did not use a heatpump but instead had an electric water heater, which we in return do not have. They used real time prices, which is partly done in this thesis as well. The prices they used were from "The Australian Energy Market Operator" (AEMO) and their PV production data was from the "European Network of Transmission System Operators" (ENTSOE). In the present thesis all prices, PV production data and consumption data all come from the same region in Germany.
Both simulations use the same granularity (15 min) and the same calculated horizon (24 h). The study used forecasts for different components, similar to what is done in this thesis, but the electric vehicle was always away from home from 7:30 am to 6:30 pm.

The study used heterogeneous datasets, mixing australian prices with european PV production data. Without a more in depth investigation, it is not sure whether this reflects a european house. The simulated timespan in the study was one day and therefore did not include different seasons and different weekdays such as weekends when the car might not be away from home as much. This is where the present thesis can contribute to the research field, by using only consistent datasets from Germany and simulating the house over an entire year. The results are therefore more realistic for german.

3.2 Potential of demand and production shifting in residential buildings by using home energy management systems

This study published by Patrick Wimmer et al. in 2015 [Rw215] aimed to reduce the costs for electricity by reducing the amount that is bought from the power grid. This was the same goal this thesis intends to achieve. The study also looked into autarky, which is not done in this thesis and will not be discussed.

The components of the house are quite similar to those used in this thesis. The main differences are that in the study some devices, such as a dishwasher, could be scheduled by the energy management system and an additional thermal storage was used. In one of the simulated cases, their management system was allowed to control the heatpump as well. Another difference is that the study did not investigate the use of a bi-directional wallbox and an electric vehicle with V2H capabilities. The simulation software they used is SimulationX and was not newly developed by them, contrary to the simulation software in this thesis. Their simulation took into account only forecasts for the PV production, whereas we have access to forecasts for all actors and especially to the need for heating and driving the EV. The house in the study was simulated over one year.

Since the study was carried out in 2015 when electric vehicles with bi-directional charging were not on the market, the study did not include this feature unlike this thesis. The present thesis also includes a sensitivity analysis in order to find out which components influence the results most, whereas the study only presented the results of three specific simulations. Our sensitivity analysis included prices for the different components used in the simulation, which is not done in the study. In the seven years separating the study and the present thesis, electricity prices have increased a lot and certain component prices have dropped drastically. This thesis can therefore contribute to the research field by including new components and their costs in the simulation, using current prices and investigating a multitude of different scenarios.

3.3 Predictive home energy management system with photovoltaic array, heat pump, and plug-in electric vehicle

The study published by Mojtaba Yousefi from the Aalborg university in Denmark in 2021 [Rw321] aimed to minimize electricity costs and to reduce the battery degradation cost of the electric vehicle. The first objective is the same as the one of the present thesis whereas the latter is not part of it.

The house setups are quite similar, a house with non schedulable appliances, a PV and an electric vehicle with vehicle to home capabilities. The main differences are that the heatpump in the study was controlled by the energy management system which is not the case in the present thesis and that the study did not use additional home storage batteries. The simulation in the study had a 24 hours control horizon and a granularity of 1 hour. The prices used were dynamic prices which is in part implemented in this thesis as well. The study also focused on getting more accurate forecasts which is not in the scope of this thesis.

The present thesis can add to the research field is by comparing the results achieved with home storage batteries alone and with the combination of HS and EV with vehicle to home technology, including their respective costs. The timespan simulated in the study was one week with varying scenarios. By simulating the house over an entire year in this thesis, different seasons are included which influences the results and makes them more realistic.

4 Methodology

In order to investigate whether having a home storage battery, a smart energy management system and an electric vehicle with bi-directional charging capabilities benefits the homeowner financially, we developed a simulation software.
The software simulates a single family home in Germany over the timespan of a year. In this case the single family home (SFH) consists of a PV system, a HP, an EV and an optional home storage (HS) and is connected to the power grid. The simulated time is always the entire year 2020. This year was chosen because of the good availability of data for all our components. The timespan of one year was chosen to include all seasons and is divided into 15 minute timesteps. For each timestep we take into account forecasts for the next 24 hours. The forecasts include wheather, electricity production, electricity consumption, market prices for electricity and EV usage. Longer timespans than one year are not simulated entirely because we do not have complete datasets for more than one year. The simulation of the year 2020 is taken as a basis and the following years are extrapolated from this simulation. However in our eyes the most important part of the simulation software is the algorithm which decides which actions to perform at each timestep.

4.1 Simulation software

4.1.1 Software architecture

The backend of the simulation, as shown in Figure 4.1, was entirely newly developped. It is written in python 3.8 and is not dockerized. For an easier deployment on different operating systems, the frontend and the database are dockerized [Docker22]. We used a MySQL database [MySQL22] to store all the data needed to run the simulation such as PV production data or EV driving profiles, as well as all the results generated during the different runs of the software.

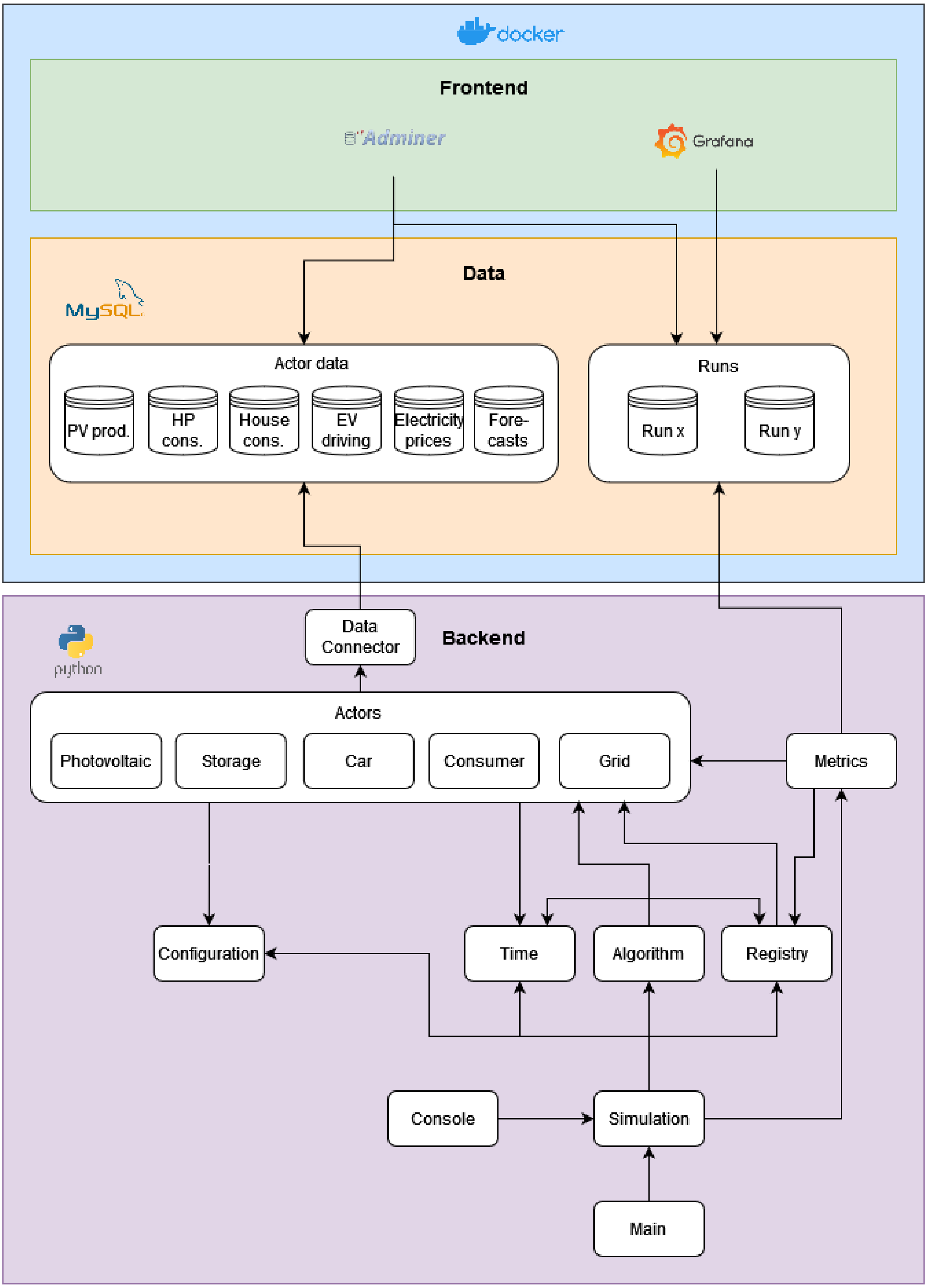

Figure 4.1: Software architecture

4.1.2 Actors

As mentioned before the single family home in the simulation consists of many different actors. There is no limit for the number of actors of each type that can be added, however not all algorithms support an unlimited number for every type of actor. At runtime, all actors are entered in the registry, which the algorithm and the metrics use to access all actors.

actor	consumer	supplier	storage
house	✓	×	×
heatpump	✓	×	×
grid	×	×	×
electric vehicle	(✓)	×	(✓)
home storage	×	×	✓
photovoltaic system	×	✓	×

Table 4.1: All actors used in simulations categorized as consumer, supplier and storage

House and Heatpump

The actor house includes the consumption of all consumers within the SFH except for the heatpump, which has its separate consumption profile. The two consumers house and heatpump do not need to be separated. The simulation would work the same way if both were added together into one consumption profile. Taking the heatpump alone would be useful if it were to be controlled by the software. The consumption of the house could also be broken down into different consumers, such as light, fridge, dishwasher and many more, but this would not have an impact on the results.

Both datasets for the home consumption and the heatpump come from the same study at the Institute for Solar Energy Research in Hamelin [SFHandHP22], where the consumption of several single family homes and their heatpumps have been measured. All houses are located in northern Germany in a small town close to Hannover. They were all built in the late 90s and early 2000s and are equipped with water-water-heatpumps. Their consumption was measured from 2018 to 2020. For the simulation, only the year 2020 was used in order to have consistent data. Having the measurements of the heatpump and the house consumption from the same house ensures that the simulation is as close to reality as possible.

Grid

The grid represents the power grid and does not fall into any of the categories of actors, as can be seen in Table 4.1. Whenever the SFH needs more electricity, it can be bought from the grid and if the SFH has a surplus of electricity it can be sold to the grid. We make the assumption that our grid is an ideal power grid, which means that we can buy or sell as much electricity as we want at any time.

The grid supports both static prices and dynamic prices.
For static prices, a purchase price of 37 ct/kWh is used. This was the average consumer price for electricity in Germany in the first half of 2022, according to the Bundesverband der Energie- und Wasserwirtschaft [BDEW22].
When selling electricity produced by the PV of a house in Germany, the homeowner receives a fixed price per kWh. The price depends on the month the PV was put into operation and is then guaranteed for 20 years. For new PVs in 2022, the price is around 6.5 ct/kWh but decreases by 0.1 ct/kWh every month [SellPrice22]. In the simulation, the price when selling electricity is therefore set to 6 ct/kWh.

For dynamic prices, the day-ahead price data from the ENTSO-E [ENTSO-E22] is used. It provides the market price for electricity at any time. When selling electricity, the exact market price is used. Additionally the buyer needs to pay fees to the grid provider and taxes on top of the market price. In Germany in 2022, this amounts to 16.55 ct/kWh, which is added to the market price automatically. This means that the homeowner can sell at the exact market price but when buying he needs to pay 16.55 ct/kWh more.

Electric vehicle

Similar to the grid, the electric vehicle does not fall into a specific category of actor. It is a consumer but unlike the HP, it needs to be charged in advance and can also serve as a storage, if bi-directional charging is supported.
In order to run the simulation, we need to know when the EV is at home and thereby available for charging and discharging, as well as how much electricity is consumed when it is driven. We created these driving profiles using the python tool emobpy [EV-datatool22]. The tool was developed by the German Institute for Economic Research (DIW Berlin). It takes into account how frequently and how far the EV is driven, what car model is used and even the weather data. Using this tool, we create three different driving profiles. The first represents a person who drives to work every day, the second represents a person who works part time and therefore drives to work less often and the third represents a person who works entirely from home and only drives

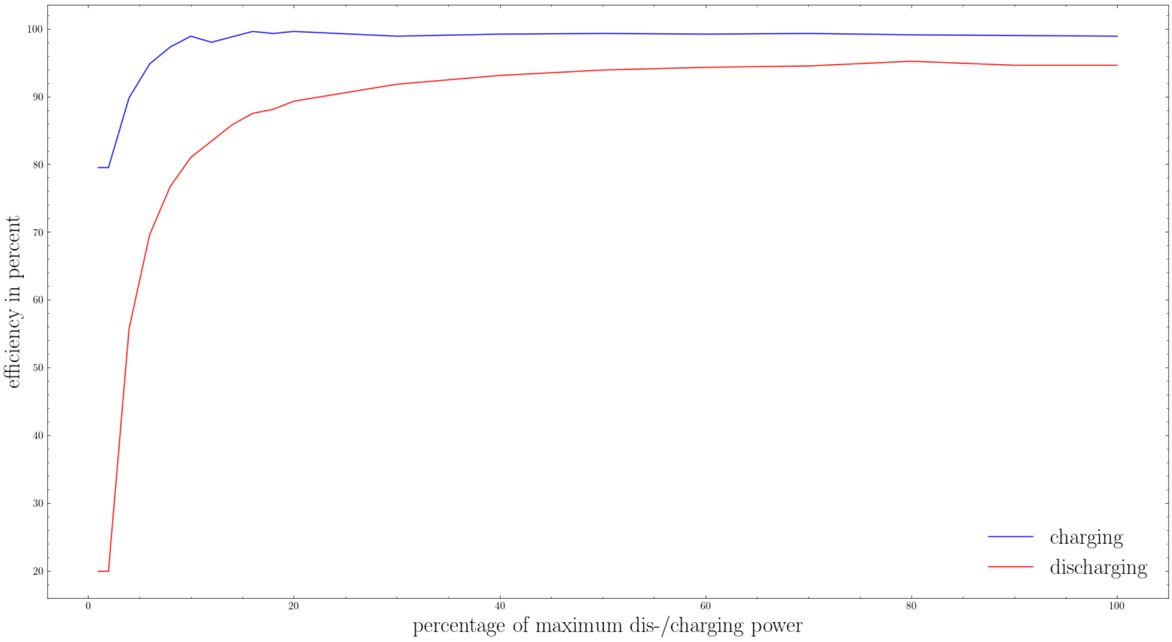

Figure 4.2: EV battery charging and discharging efficiencies

occasionally.

The simulation takes into account two types of energy losses when charging and discharging the car. First, whenever the car is charged or discharged, the electronics of the car are turned on and consume some electricity. In the simulation this consumpion is set to 200 W.
In addition, there are losses when charging or discharging an EV with a wallbox as shown in Figure 4.2. The simulation uses measurements performed by Peter Rotenberger for his bachelor thesis named "Effizienzmessung bidirektionaler Netzanbindungen teilmobiler Speichersysteme im Zusammenhang mit dem zukünftigen Energieversorgungsnetz" at the University of Duisburg-Essen [Losses21].

Home storage

The HS is an optional actor and can be left out if wanted. It can be used to store and release electricity and needs no dataset apart from the battery specifications. We use some presets for storages regarding capacities and charging speeds from the German company e3dc [e3dc22] in order to have realistic values. The price for these storages is around 900 € per kWh of capacity.
The charging and discharging losses are based on measurements carried out by Peter Rotenberger within the framework of the same bachelor thesis as the losses for the EV.

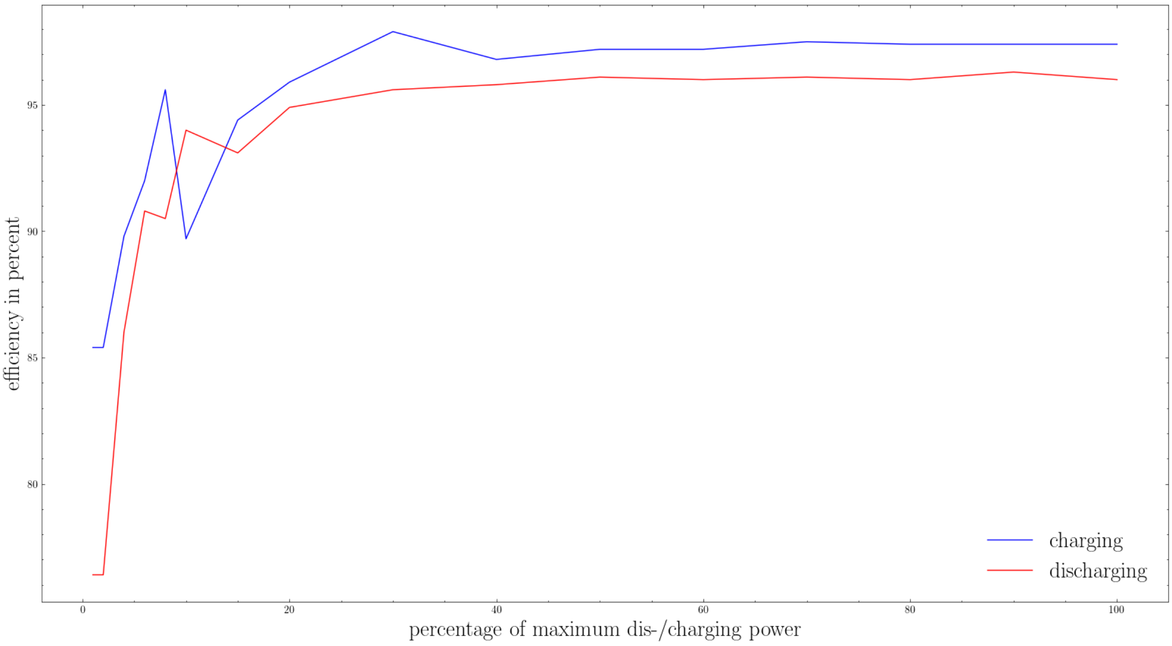

Figure 4.3: Home storage charging and discharging efficiencies

The losses are not the same and can be seen in Figure 4.3. They have been measured for lithium-ion batteries, such as those from the company e3dc. Lithium-ion home storages currently have a lifetime of 10 to 15 years. In this simulation it is set to 12 years.

Photovoltaic system

The photovoltaic system produces electricity whenever the sun is shining. The electricity production data of the PV was generated using PV*SOL premium which is a professional software for planning and simulating photovoltaic systems [PV*SOL22]. The PV used to generate the data consists of 20 "Trina solar Vertex S TSM-DE09.08" 405W modules with a combined maximal power of 8.1 kWp and a "SMA Sunny Boy" inverter. The wheater data is from the year 2020 and nothing throws shade onto the PV. It is located in Hannover, which is close to the houses that were measured to obtain the consumption data.

4.1.3 Configuration

The configuration contains every variable needed to run the simulation as well as some presets for different car and home storage models. In general, every parameter of the simulation can be changed. Parameters concerning the simulation software itself, such as the amount of timesteps that will be simulated or the information how to connect to the database, can only be changed directly in the configuration. Other parameters for example those concerning the electricity prices can be changed both in the configuration or at runtime.

4.1.4 Console

The console can be used to run any python function in the backend code. It allows the user to add and modify actors, change some settings and start simulations without having to change the code.

4.1.5 Metrics

Every data from every actor or any other value calculated during runtime can easily be saved using the metrics singleton. The data that should be saved just needs to be specified in the metrics and will then automatically be exported and saved into a new database for each run. This can only be done directly in the source code.
In order to increase performance, the data is only saved into the database every 1000 timesteps. This reduces the number of requests sent to the database. Between two database requests the collected data is kept locally.

4.1.6 Frontend

Two existing tools were added as the frontend to the software. The first one is Adminer [Adminer22] which can be used to see what is stored in the MySQL database and run SQL commands. The second one is Grafana [Grafana22] which visualizes any data in the database in the form of graphs and can therefore be used to quickly evaluate the results of a simulation. It supports live data and can display the graphs while the simulation is running.

4.1.7 Forecasts

In order for the smart financial algorithm to work, forecasts for the next 24 hours of all actors are required. Forecasts are a prediction of what is supposed to happen. It matches what really happens with a certain probability. This forecast data can be applied to each actor in addition to its actual data.
If it is not possible to get 24 hours forecast data, the simulation software can also

generate these forecasts synthetically. It does so by taking the actual data for all timesteps in the next 24 hours and randomly adding or subtracting a random amount. This is done in order to make the data inaccurate and resembles real forecasts. The maximum amount that could be added or subtracted increases linearly the further away the timestep is, in order to mimic that forecasts get less accurate the further someone looks into the future.
The maximum amount that can be added or subtracted has been set to 5% of the real value at the last timestep of the 24 hours timeframe.

4.1.8 Longterm financial calculation

The simulation only simulates one year of operation. It would be possible to simulate a longer period, but it is hard to find data for longer timespans such as a decade or more. To know how an algorithm or a certain SFH setup performs over a longer period of time, the first year is simulated and the values for the following years are calculated based on the results of the first year. To this end, we assume that the first year is an average year and that the SFH will always consume and produce the same amount of electricity. As for the prices of electricity, it is assumed that they will continue to rise by 4.575% per year, which is the average historic price increase in Germany since the year 2000, according to the data of the BDEW [BDEW22]. In order to account for inflation as well, the Net Present Value (NPV) is calculated as shown in the Equation (4.1). The initial cashflow is the cost of the system and the cashflow is what is later earned by selling electricity or spent for buying electricity. The inflation is set to the inflation rate targeted by the European Central Bank, which is 2%. The timeperiod for the calculations is 12 years, which is the lifetime of the component with the shortest lifetime, the home storage.

$$NPV = -initialcashflow + \sum_{t=0}^{lifetime} \frac{cashflow}{1 + inflation} \tag{4.1}$$

4.2 Naive algorithm

The naive algorithm is used to simulate a regular house without a smart energy management system and without vehicle to home funtionality. It can be used as a reference for assessing the results achieved by the financial algorithm with the same setup. The naive algorithm has no limit for the amount of actors of each type it can simulate and does not need forecasts.

It works the following way:

At every timestep, the total consumption of all consumers is calculated. With the setup used in this work this is the consumption of the SFH plus the consumption of the HP. Whenever the car is at home, we assume that it is connected to the wallbox and starts charging immediatly until it is fully loaded.
The power needed to charge the car is added to the total consumption.

Now two possible cases can occur:

1. If the production of the PV is higher than the total consumption, the entire consumption is covered by the production.
   If there is a buffer storage available, as much electricity as possible is charged into it and the rest is sold to the power grid.
   If there is no buffer storage, all the remaining electricity is sold.
2. If the production is lower than the consumption, as much of the consumption as possible is covered with the electricity produced by the PV.
   If there is a buffer storage available, as much electricity as needed and possible is discharged in order to cover the consumption.
   If there is still consumption that cannot be covered locally or if there is no buffer storage, the missing electricity is bought from the grid.

4.3 Financial algorithm

The financial algorithm simulates a smart energy management system with the goal to perform as good as possible financially, i.e. minimize cost and if possible achieve maximal gains. It requires forecasts to run and supports V2H. The financial algorithm works with as many suppliers and consumers as desired, but only allows exactly one EV and zero or one buffer storage.

The owner of the SFH should not be inconvenienced by the decisions taken by the algorithm. Therefore it can not influence the consumers such as the heatpump. It can however control when to charge or discharge the car or the buffer storage. In addition, it can decide when and how much electricity is bought or sold. To ensure that the car does not run out of electricity if the forecasts were not accurate enough, a safety threshold is set to a state of charge of 30% of the EV's maximum capacity. The car battery cannot be discharged below the threshold and based on the forecasted driving, the algorithm ensures that whenever the car returns from a drive, the state of charge is still above the threshold.
The financial algorithm is more complex than the naive algorithm and has therefore been divided into four phases that are performed sequentially.

Phase 1

The first phase is used to calculate some values that will be used to make decisions in later phases.

First the forecasts for all actors are collected for the next 24 hours.
For every 15 min timestep, the delta between production and consumption is calculated. This is the total production minus the total consumption during these 15 min.
Based on the car's driving forecasts, the next 24 hours are divided into sections, depending on whether the car is home or away, as shown exemplarily in Table 4.2.
In every section where the car is away, the total consumption is calculated.
In every section where the car is at home, the energy that needs to be charged into the car in this timeframe is calculated based on the car's current state of charge and the future consumption.
This also takes the fact into account that the car should always be charged above the safety threshold of 30%.

section	car's state	consumption	needed charge	number of timesteps
1	home	0	11	27
2	away	13	0	28
3	home	0	2.7	41
4	away	2.7	0	5

Table 4.2: Example of a 24h forecasts divided into different sections

Phase 2

In this phase, it is made sure, that the car is charged sufficiently.

If there is a need to charge the EV in any part of the next 24 hours, the goal is to charge it with as much solar energy as possible and to buy as little as possible from the grid.
The car is therefore charged whenever there is an overproduction of solar power. If dynamic prices are used, this is first done at times where the electricity is cheapest and therefore selling it at this moment would lead to the least profit.
If there is not enough production from the PV in order to charge the car sufficienty, the remaining electricity is bought when it is cheapest. The amount of electricity will then be added to the consumption of the specific timesteps.

Phase 3

In this phase the algorithm deals with the remaining delta between production and consumption at each timestep.

Timesteps with positive delta
For timesteps where the delta is positive, the goal is to store as much solar power as possible for later use. If the storage capacity is full at some point, another goal is to store the produced electricity when selling prices are low and sell when they are higher.
First, as much of the remaining energy as possible is stored into the HS.
If there is still energy left, it is used to charge the EV.
In the case of dynamic prices, this is first done for the timesteps where electricity prices are low and selling then would lead to the least profit.
If for either the HS or EV the charging/discharging losses would be too high, the energy is not stored.
The energy that cannot be stored because there is no more storage capacity available or the losses would not be worth it, is sold.

Timesteps with negative delta
For timesteps where the delta is negative, the goal is to cover as much of the consumption as possible, using the HS and the EV if V2H is available. If there is not enough stored energy to cover the consumption throughout the entire day, the consumption will be covered when the prices are high and additional electricity will be bought when they are low.
First the HS is discharged to cover the consumption. If this is not sufficient and the EV is available and has enough electricity stored in the battery, some of it is discharged. Because of the high losses when discharging the EV, this is only done to cover high consumption peaks. In addition, whenever the EV is discharged and the HS is empty, some load is shifted from the EV to the HS. That way, the relative losses when discharging the EV are lower and the HS is now able to cover more of the consumption in further steps, possibly when the EV is away.
For dynamic prices, the goal is to first cover the timesteps where electricity prices are high, in order to save as much as possible and only cover the consumption in other timesteps if possible.
In general if for either the HS or EV, the predicted discharging losses were too high, the needed electricity would not be discharged but bought from the grid.
For every step where the consumption can not be fully covered, the needed electricity is bought.

Phase 4

In the last phase all buying, selling, charging and discharging actions are performed. By performing those actions, the metrics are updated as well.

5 Simulation runs and analyses

Numerous simulations are carried out with different configurations and strategies, in order to answer the questions the homeowner or his energy adviser ask themselves when configuring the home energy management: is there a benefit in applying smart energy management? Do I need a home storage system? If yes, which capacity? Is a vehicle to home electricity transfer capability beneficial? The simulation software is flexible and can perform many ”what if?” simulations. The scenarios investigated can be evolved and be refined once the first results are available, when new questions come to the mind of the user.

In the somehow basic investigations like the first two meant to explore some potentials, the prices of the components are not taken into account. For simulations designed to orient the decision on upgrading a system or choosing the components dimension, cost is brought into play.
The variables which are modified in the runs are: the PV size, the HS size, the EV battery size, the V2H capability, the pricing model and the management strategy, naive or financially optimized.
The variables describing the financial and technical framework of the investigations are kept constant in all runs and are therefore not mentioned in the description of the runs.

These are:

- The driving profile is the one of the part-time worker as described in Section 4.1.2.
- The wallbox has a maximum charging speed of 11 kW, which is standard in Germany.
- If it is a bi-directional wallbox, the discharging speed is 11 kW as well.
- In this case a cost of 2000 € is added to the total cost of the system.
- When using fixed prices, the purchase price is set to 37 ct/kWh and the sell price to 6 ct/kWh.
- For longterm calculations, the price increase for electricity is set to 4.575% per year and the inflation rate is set to 2% per year.

- The lifetime of the storage is set to 12 years.
- The price for the home storages is set to 900 € per kWh of capacity.
- The EV used is a Tesla Model 3 with the configuration shown in Listing 5.1.
- The charging speeds for the different sizes of home storages can be seen in Table 5.1.

The variables which are modified in the runs are: the PV size, the HS size, the EV battery size , the V2H capability, the pricing model and the management strategy, naive or financially optimized.

Listing 5.1 Tesla model 3 preset

```
tesla_3 = {
   "max_capacity": 60,     #in kWh
   "charging_speed": 11,   #in kW
   "discharging_speed": 11, #in kW
   "required_min_charge_in_percent": 30, #the lowest battery percentage the car should
       have when returning home
   "initial_charge": 30,   #in kWh
   "consumption": 14,      #in kWh per 100km
   "base_consumption": 0.2 #in kW, consumption of the car when it is on but not
       driving, for example when charging or discharging
}
car_presets["tesla_3"] = tesla_3
```

HS size in kWh	charging and discharging speed in kW
2.9	1.5
5.8	1.5
10.8	4.5
17	7.5
27	9

Table 5.1: Home storage sizes and their corresponding charging speeds

Let us have a look at an example of configuration and simulation result. Table 5.2 presents the investigated configuration.

PV size	HS size in kWh	EV battery size in kWh	V2H / bidi	price model
8.1 kWp	0	60	no	static

Table 5.2: Configuration example run

Figure 5.1 shows an example for the financial results of a simulation. The "spent" line is the cumulated amount of money spent to buy electricity. The "earned" line is the cumulated amount of money earned by selling electricity. The "delta" line is the cumulated amount earned minus the cumulated amount spent. Thus, negative "delta"-values mean costs, positive values mean benefits for the homeowner.
In the comparisons of different simulation runs that follow, only the delta line will be shown.

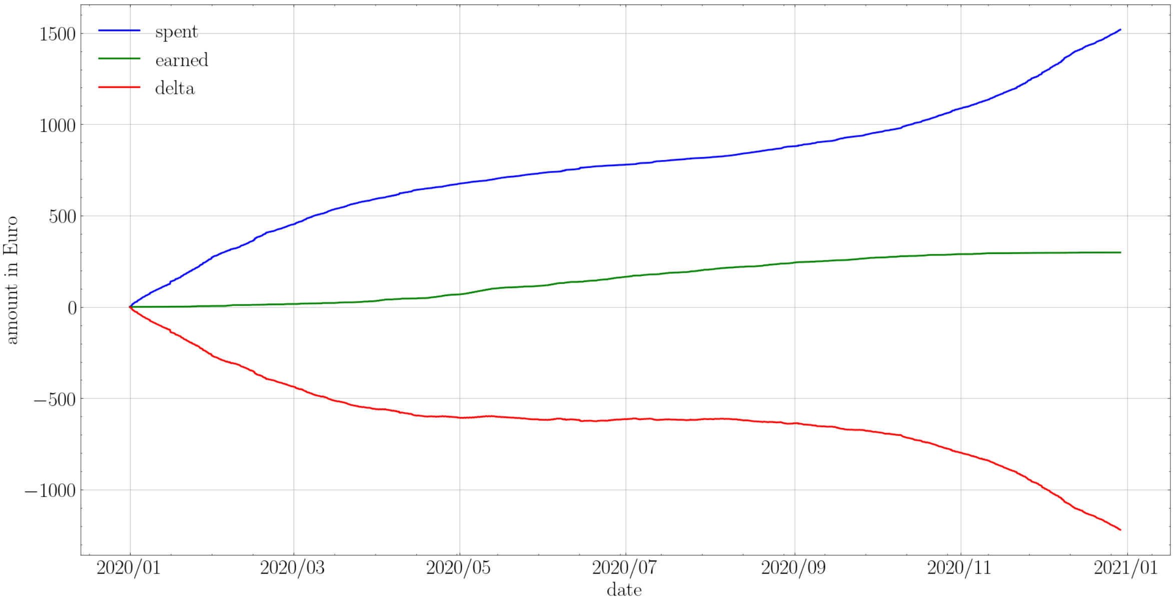

Figure 5.1: Example for spent, earned and delta metrics

5.1 Effect of a smart energy management system

Investigation and observations

First, the effect of a smart energy management system is evaluated for a simple case. The naive algorithm and the financial algorithm are compared with different sizes of storage for static prices. This corresponds to a regular house (naive algorithm) and a house with a smart energy management system (financial algorithm). The system configuration is summarized in Table 5.3.

The simulation results over one year and over the longterm are presented respectively in Figure 5.2 and Figure 5.3. In all cases, the financial algorithm performs better than the naive algorithm. For the HS sizes 0 kWh, 2.9 kWh and 10.8 kWh, the home owner would have 22 to 29% less costs for electricity over one year when using a smart energy management system. However for the largest HS with a 27 kWh capacity, the improvement was only 2%. In the case of no storage (0 kWh) the performance is obtained only thru the charging strategy of the EV.

PV size	HS size in kWh	EV battery size in kWh	V2H / bidi	price model
8.1 kWp	0, 2.9, 10.8, 27	60	no	static

Table 5.3: Configuration financial vs naive algorithm static prices

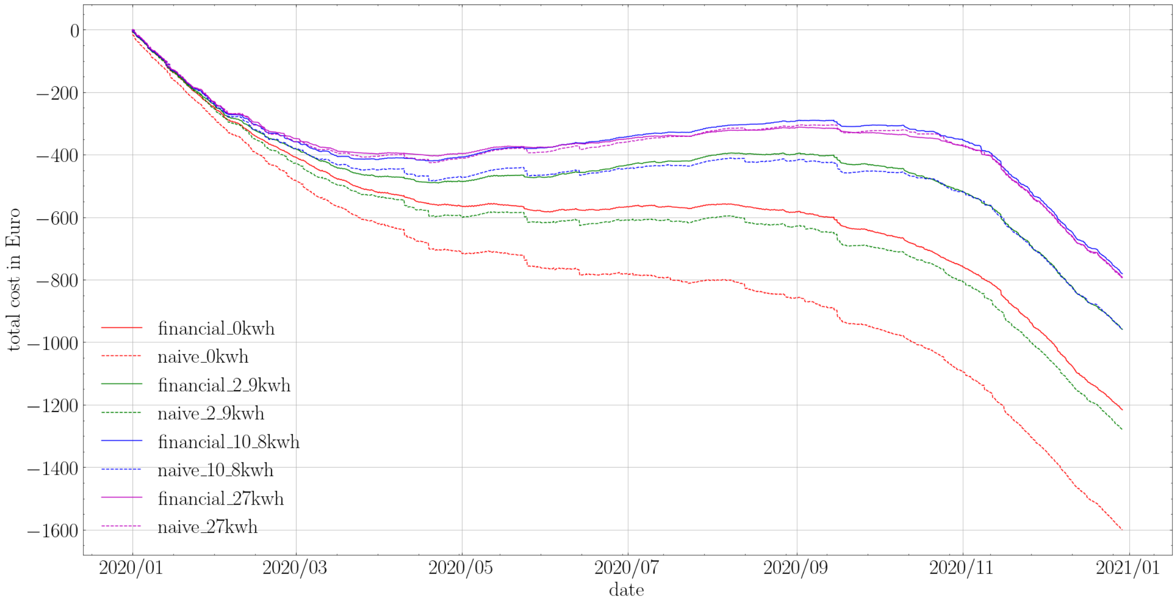

Figure 5.2: Financial algorithm vs naive algorithm over one year in the case of static prices

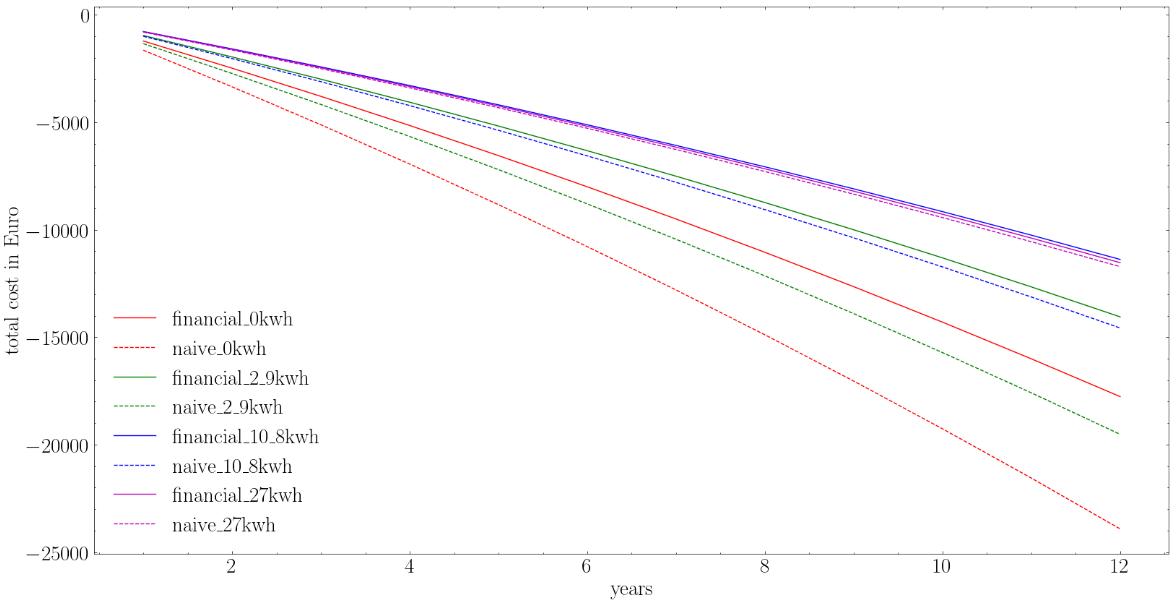

Figure 5.3: Financial algorithm vs naive algorithm over longterm in the case of static prices

In a second step, the influence of dynamic prices is examined. The same simulation runs with dynamic prices leads to a similar result with the financial algorithm beating the naive one in every scenario, as can be seen in Figure 5.4 over a one year period and in Figure 5.5 over 12 years. The financial algorithm leads to a cost reduction of 18% for the biggest HS and 26 to 30% percent for the sizes 0-10.8 kWh.

The relative performance increase is better with dynamic prices than with static prices, especially with the largest HS system. However, in absolute values, the improvement with the static price model is more significant.

PV size	HS size in kWh	EV battery size in kWh	V2H / bidi	price model
8.1 kWp	0, 2.9, 10.8, 27	60	no	dynamic

Table 5.4: Configuration financial vs naive algorithm dynamic prices

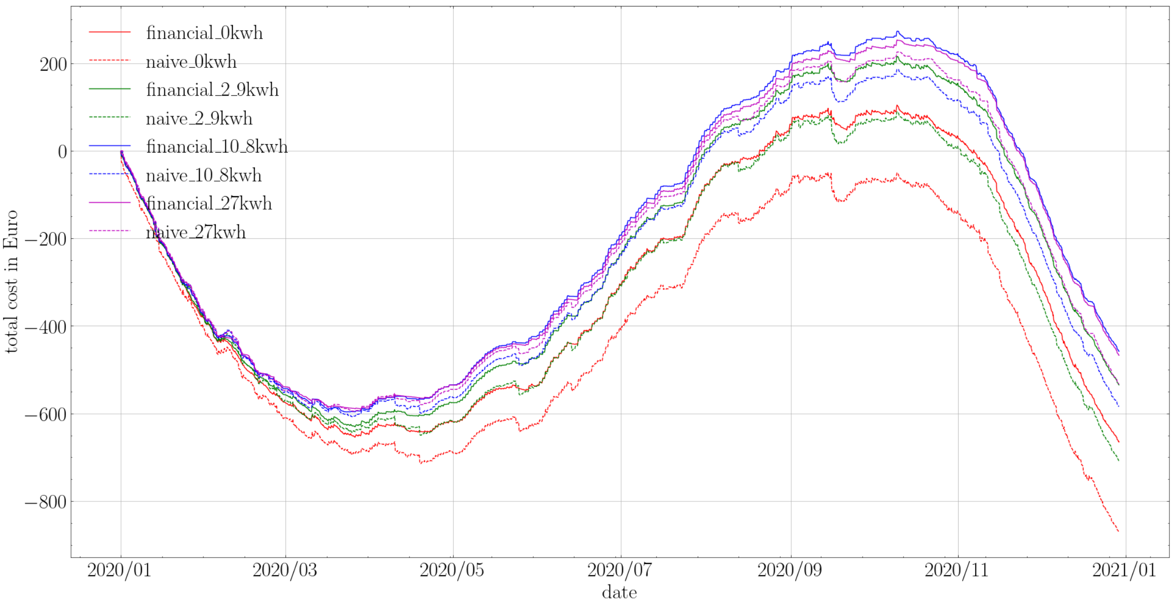

Figure 5.4: Financial algorithm vs naive algorithm over one year in the case of dynamic prices

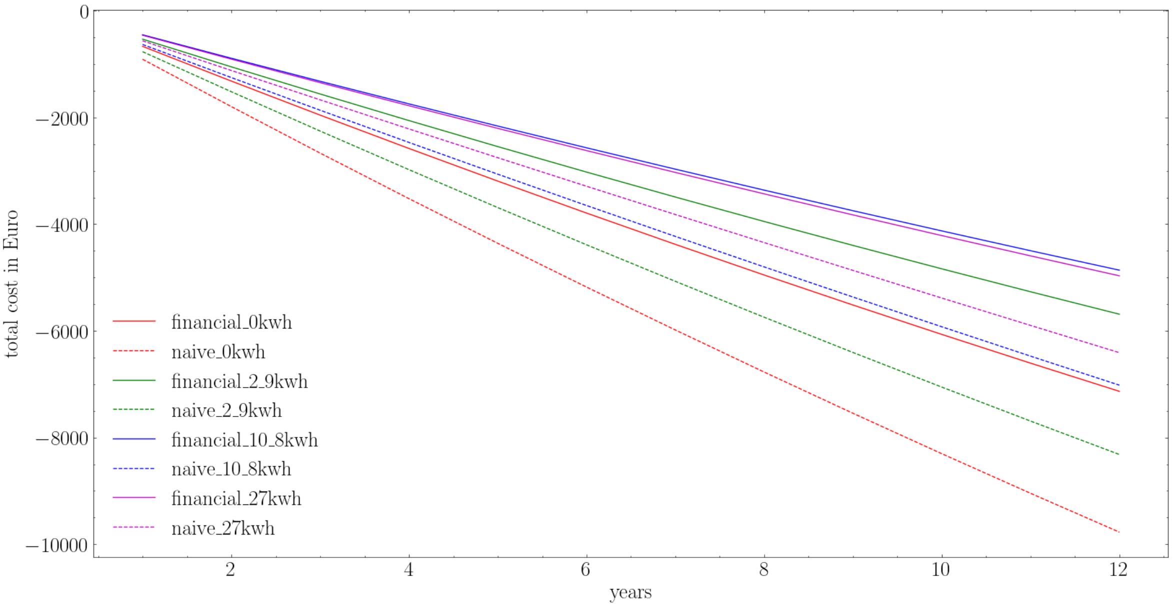

Figure 5.5: Financial algorithm vs naive algorithm over longterm in the case of dynamic prices

Analysis and explanations

One reason for the small performance increase with the financial algorithm in the case of the biggest HS, is that the bigger the storage, the less managing is needed. The 27 kWh HS rarely comes to its limit and the electricity produced by the PV can almost always be stored and is more available when needed. With smaller home storages this is not the case and a smart energy management system can help maximize the benefits of the storage. In the case of 0 storage, the timing of the vehicle charging makes all the difference, which is more than 20%.

Another factor is that because of the higher maximal charging and discharging speeds which the biggest HS has, it is less efficient for lower powers than a smaller HS. This is due to the fact that the efficiency when charging or discharging is best when using the maximum power as can be seen in Figure 4.3. With the PV production and house and heatpump consumptions used in this simulation, the power that could be charged into or discharged from the HS is mainly between 0 kW and 6 kW. This means that the biggest HS is rarely working at a high efficiency and if the efficiency is too low it will not be used at all.
With dynamic prices, this degradation of the financial benefit was not as noticable when only comparing it to the naive run with the same HS, since it still reduced spending by 18%. However it still performed worse than the HS with a 10.8 kWh capacity by about 1%.

For one given house setup the benefit of the financial algorithm is higher when dynamic prices are used. This is due to the higher earnings when selling directly at market rates.

Using a smart energy management system leads to more financial benefits when added to a system with no HS or one with a small to medium capacity.
In absolute values it is also more beneficial to a system with static prices.

5.2 Effect of adding vehicle to home technology

Investigation and observations

In this scenario defined in Table 5.5 the single family home using the financial algorithm as a smart energy management system is compared to the same system where the car is capable of bi-directional charging (bidi) and V2H.

With static prices Figure 5.6 and Figure 5.7, the V2H capabilities reduces the cost at the end of one year by 5% when no storage is used and by 4% when paired with the 2.9 kWh HS. For the two larger storages, there is no significant benefit.

PV size	HS size in kWh	EV battery size in kWh	V2H / bidi	price model
8.1 kWp	0, 2.9, 10.8, 27	60	yes/no	static

Table 5.5: Configuration financial with and without V2H in the case of static prices

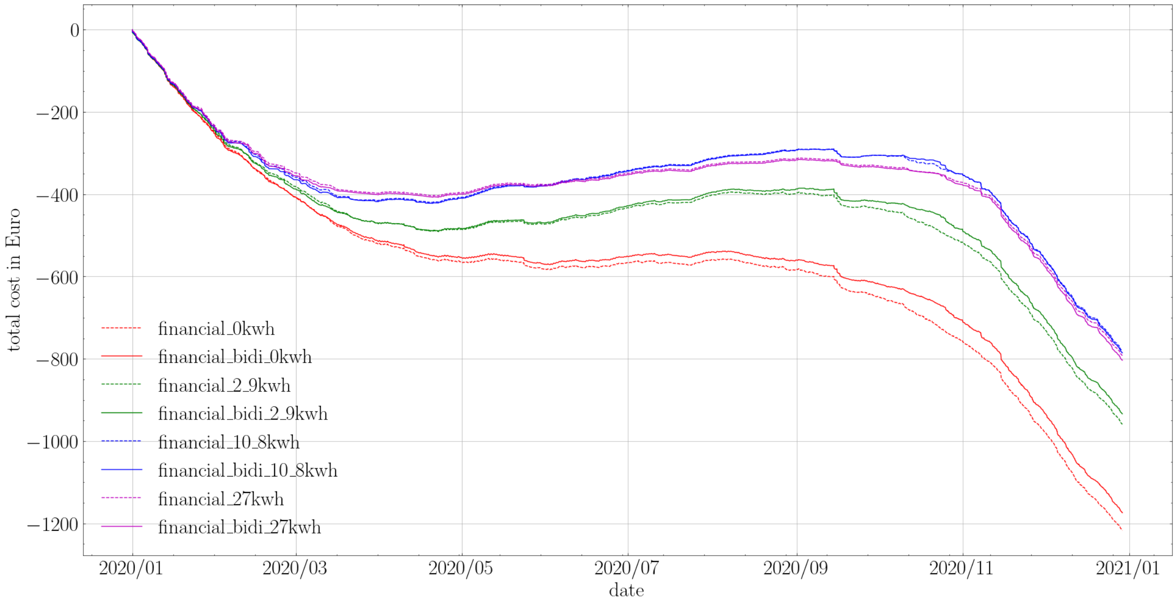

Figure 5.6: Financial algorithm over one year with and without V2H in the case of static prices

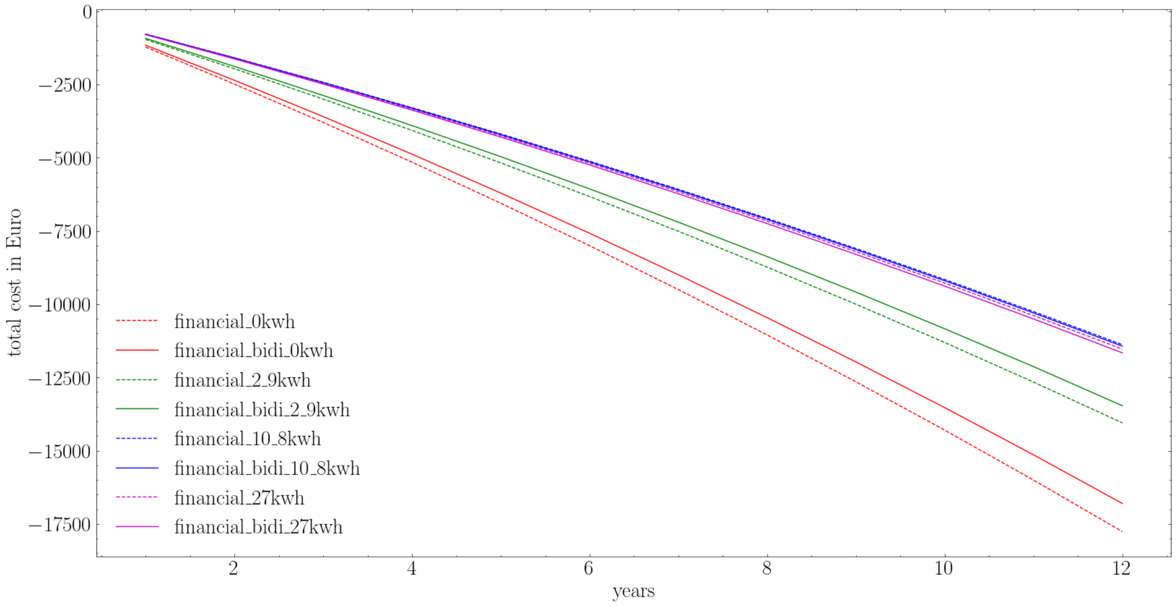

Figure 5.7: Financial algorithm over longterm (12 years) with and without V2H in the case of static prices

With dynamic prices, the addition of the V2H capabilities has no significant impact on the end result of the simulation over one year in Figure 5.8 or over the longterm in Figure 5.9.

PV size	HS size in kWh	EV battery size in kWh	V2H / bidi	price model
8.1 kWp	0, 2.9, 10.8, 27	60	yes/no	dynamic

Table 5.6: Configuration financial with and without V2H in the case of dynamic prices

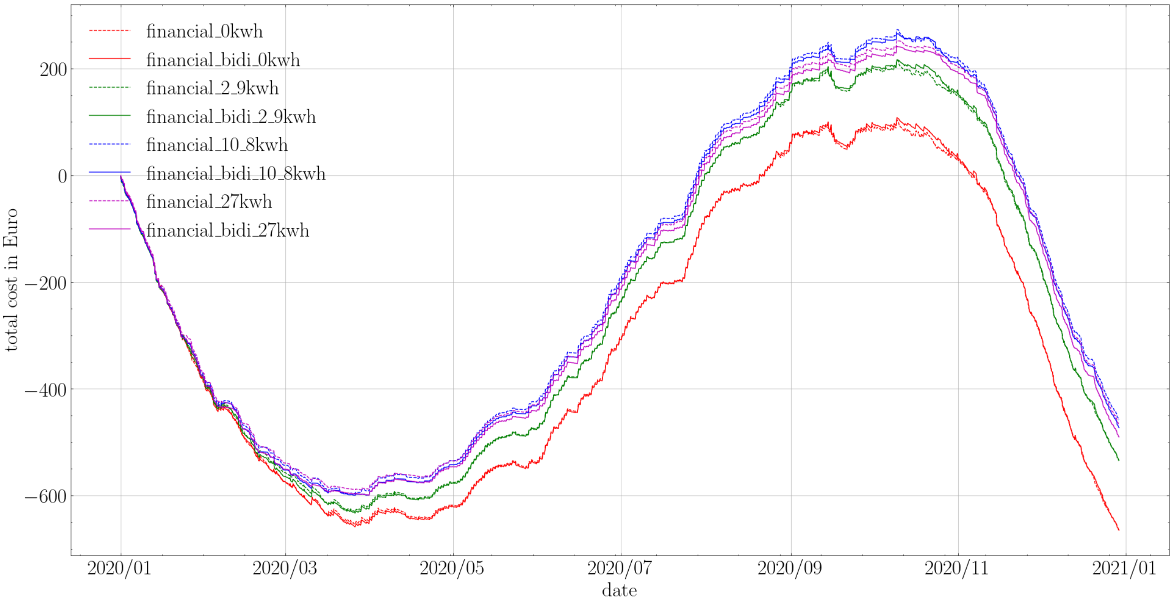

Figure 5.8: Financial algorithm with and without V2H in the case of dynamic prices, one year

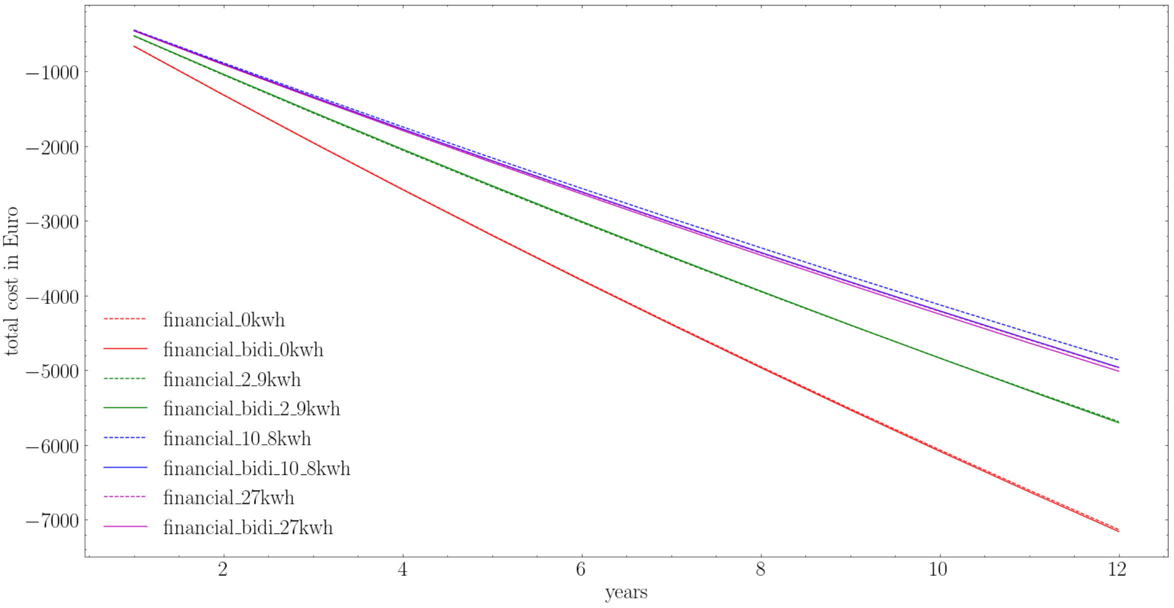

Figure 5.9: Financial algorithm over longterm with and without V2H in the case of dynamic prices

Analysis and explanations

The EV has the same problem with bad efficiency (Figure 4.2) as the biggest HS in Section 5.1. Since it has a maximum charging and discharging speed of 11 kW and especially the discharging efficiencies are worse than those of a HS, a lot of electricity is lost. On top of this comes the consumption of the car's electronics whenever it is charged or discharged, which causes further losses.
Both types of loss result in oftentimes not using the EV as a storage, which limits its potential benefits.

Another factor that makes an EV less useful as a storage is the fact, that it is not available all the time. If there is already a HS, the need for an additional, less reliable storage, is greatly reduced. This is especially the case with medium to big home storages.

Adding V2H capabilites can therefore only slightly improve the overall financial performance of the system and only in cases where there is no HS or only a small one.

5.3 Is an upgrade worth it?

In the previous two sections, we have first seen the benefits of using smart management via the financial algorithm developped in this thesis for different home storage sizes and then investigated the potential connected to current bidirectional charging systems. Now we want to apply the simulations to answering the question faced by a homeowner with a basic setup: a PV system, a heat pump and an EV running on the naive algorithm. Is it financially worth it to add a home storage system and if yes which size? The same question applies to the bidirectional charging capability.

Investigation and observations

The house without a HS and using the naive algorithm is compared to the same house with added home storage and an added bi-directional wallboxe which enables V2H. The additional costs for these components is divided by the amount of years the components last in order to have the additional costs over one year. This amount is substracted at the beginning. Table 5.7 presents the investigated configuration parameters.

As can be seen in Figure 5.10 in all simulations with a HS smaller than 10.8 kWh, the amount spent over one year is less than in the base configuration. With the 10.8 kWh HS, the perfomance is the same as the base configuration and with an additional bi-directional wallbox, the perfomance is worse than the base configuration due to the additional costs.
The simulation with the best result is the one where only a 2.9 kWh HS is added.

PV size	HS size in kWh	EV battery size in kWh	V2H / bidi	price model
8.1 kWp	0, 2.9, 5.8, 10.8	60	yes/no	static

Table 5.7: Configuration upgrade case

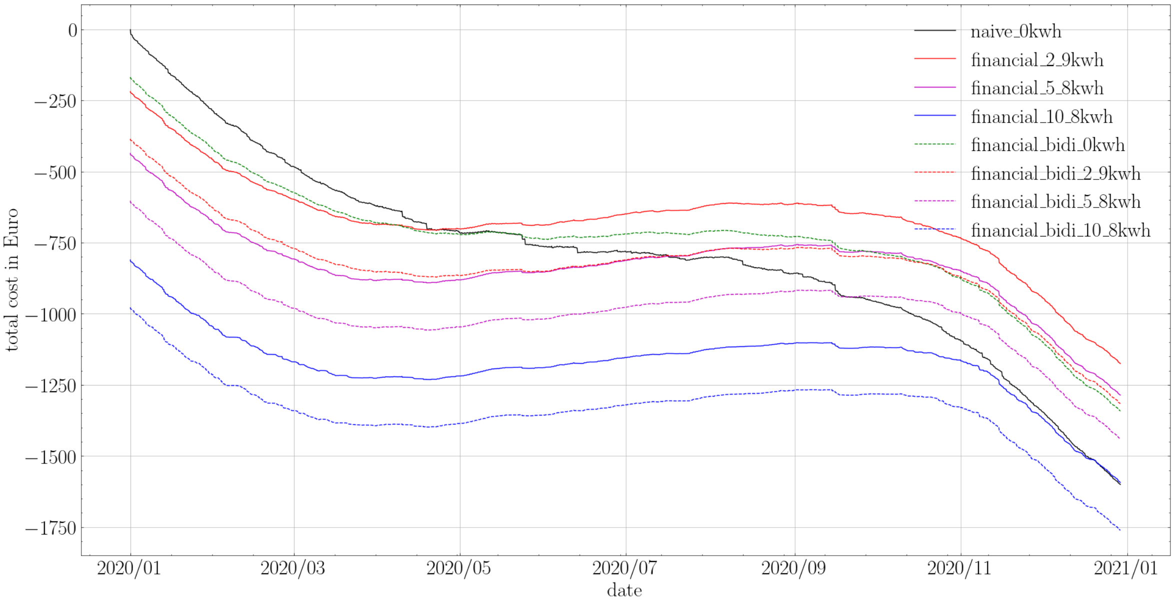

Figure 5.10: Comparison of naive base system and different configurations including differerent HS sizes with and without bidi capability including component cost with static prices

Analysis and explanations

Due to the high costs for bi-directional wallboxes and for large home storages (Chapter 5), upgrading the hardware is not always worth it financially. The best result is achieved by adding the smallest HS with a 2.9 kWh capacity.
Adding only the bi-directional wallbox to enable V2H performs worse than the 2.9 kWh HS, despite costing less. This is due to the fact, that the EV is not as good as a storage, because of the limited availability and restricted use due to high losses.

5.4 Comparison of different EV battery sizes

After seeing that the benefit of bidirectional charging is small with the original setup, one is tempted to check if a different battery capacity would help changing this observation.

Investigation and observations

In these simulations V2H is available and different sizes of car batteries are tested from 60 kWh up to 120 kWh.

As can be seen in Figure 5.11, a larger EV battery size only leads to a slightly better performance. Even doubling the size of the EV battery has very little impact.

PV size	HS size in kWh	EV battery size in kWh	V2H / bidi	price model
8.1 kWp	0	60, 70, 80, 90, 100, 110, 120	yes	static

Table 5.8: Configuration EV battery size comparison

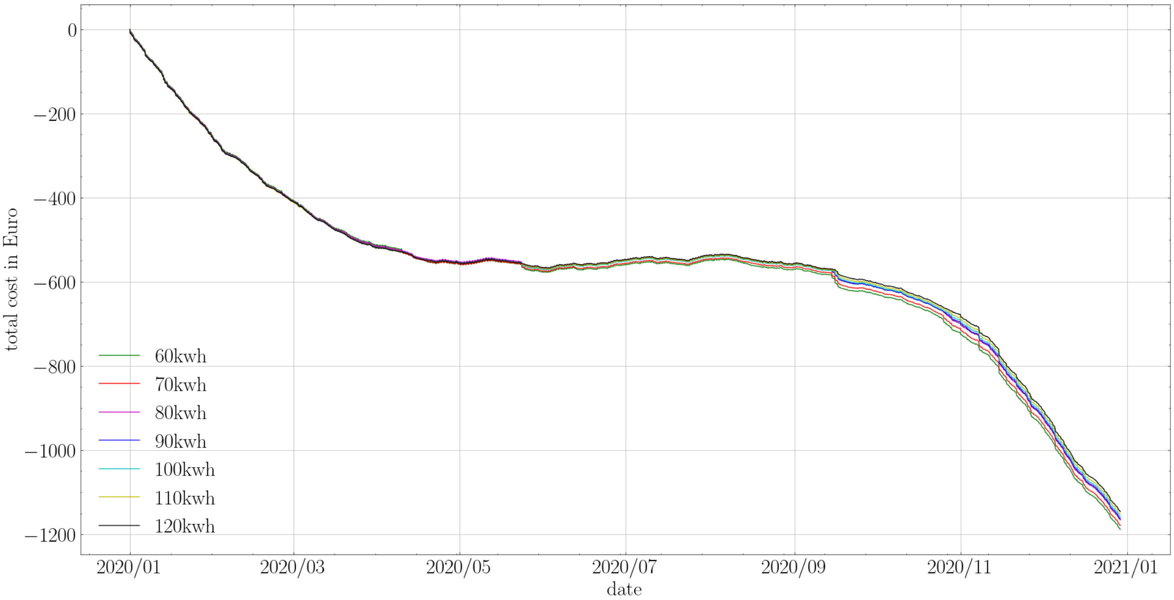

Figure 5.11: Comparison EV battery sizes with financial algorithm and static prices

Analysis and explanations

Increasing the size of the EV battery only has a limited effect on the financial performance, because it is not the main limiting factor of the EV. The small 60 kWh EV battery is already 2 times larger than the largest HS in this study.
The more important problem is that the EV is not available all the time. Even when it is at home, the high losses limit the cases where it brings a financial benefit when it is used for storage.

Reducing the losses or increasing availability would improve the performance more than increasing the battery size.

This confirms that for this home configuration and for the components under investigation, bidirectional charging is not leveraging much energy and financial efficiency.

5.5 Effect of different PV and HS sizes

When planning a photovoltaic and home storage installation, the first question that arises is the sizing of both components and the adequation of these sizes relative to each other. This is the subject of the following investigation, first without taking the cost of the system into account and then including it in the simulation for answers applicable to real life.

Investigation and observations

First, different sizes of PV systems are simulated in combination with different sizes of home storages. The sizes for the PV vary from 0 kWp to 13 kWp with increments of 1 and the sizes of the HS vary from 0 kWh to 13 kWh with increments of 1 as well, as shown in Table 5.9. The results can be seen in Figure 5.12.

Increasing the size of the PV while keeping the same HS always leads to a better performance. The improvement when increasing the PV production capacity by 1 kWp is more significant when the PV is smaller. For PV system with a producion capacity of 6 kWp or above, the effect is less significant.

Increasing the size of the HS does not always lead to a visible improvement. For a small PV system in particular, a bigger HS changes almost nothing because of insufficient charging capability. For bigger PV systems, the performance increase is more noticable, but only for a HS up to a size of about 5 kWh. From then on, further increasing the size of the HS has no significant impact.

PV size	HS size in kWh	EV battery size in kWh	V2H / bidi	price model
0 - 13 kWp	0 - 13	60	no	static

Table 5.9: Configuration PV and HS sizes

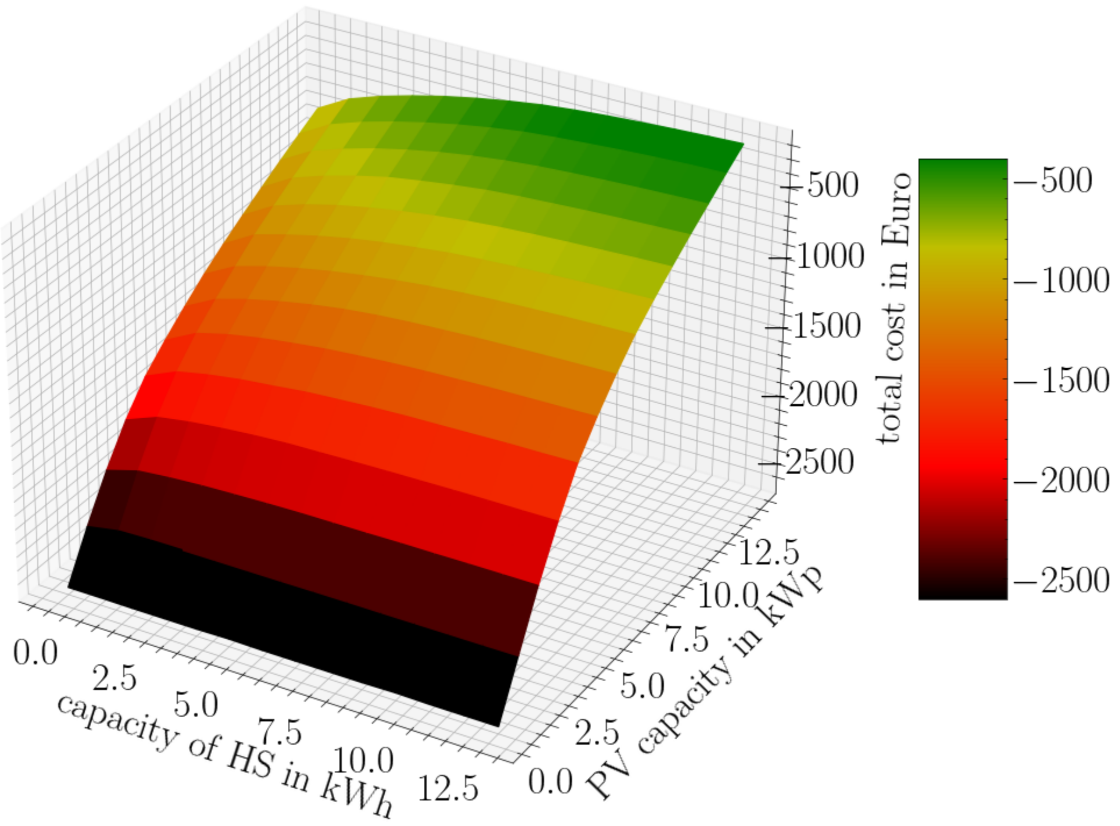

Figure 5.12: Cost over one year for different PV sizes and home storage sizes

Analysis and explanations

Increasing the size of the PV system increases the amount of produced electricity. This electricity can then either be used for the own consumption or sold to the grid. Using the electricity for the own consumption saves 37 ct/kWh because it does not have to be bought from the utility provider. By selling it, the homeowner only earns 6 ct/kWh. Using as much as possible of the electricity produced by the PV to cover the own consumption is therefore the most beneficial financially.

With smaller PV systems, most of the produced electricity is used directly to cover the own consumption and only very little is sold. After a certain PV size, the own consumption is already covered as much as can be and a further size increase means that all the extra electricity is sold. This is why after a certain size, the financial benefit of increasing the PV size by another kWp is less significant than for smaller PV systems.

The HS can lead to a financial benefit because it can be used to store electricity when there is more production than consumption. This electricity can then be released when there is not enough production to cover the own consumption, such as during the night.

For smaller PV systems where there is rarely more production than consumption, a HS does not improve the peformance much, because there is rarely any electricity that could be stored. For medium to bigger PV systems, it can improve the performance, but only up to a certain HS size. At a certain point the HS is already capable of covering the consumption in most cases where there is not enough production. Further increasing the HS size therefore does not lead to a significant improvement.

From a financial point of view, there is a sweet spot for the size of both the PV and the HS. In this example this seems to be a medium sized PV (5-7 kWp) system and a small HS (3-4 kWh). The exact sizes depend mainly on the consumption and it can therefore not be generalized. For homeowners with a small PV system, adding a HS does not lead to significant improvements. In general, the bigger the size of the PV, the greater the benefit from adding a HS.

As of now, home storages are still expensive and the best result relative to its cost can be achieved with a small system. Above a certain size, the financial benefit of storing and using more of your own solar power is less than the cost.

Investigation and observations including costs for PV and HP

Unlike the previous simulations which do not include any component costs, the second serie of simulations does so, see Figure 5.13. The price for the HS is set to 900 € per kWh. The prices per kWp for the PV have been taken from [PVprice22] and can be seen in Table 5.10. All prices which are needed, but are not included in the table have been linearly approximated.

PV size in kWp	price per kWp	price PV	HS size in kWh	HS price
4	1600 €	6400 €	4	3600 €
7	1450 €	10150 €	7	6300 €
10	1300 €	13000 €	10	9000 €

Table 5.10: Prices for different PV and HS systems

The best results are achieved with a large PV system and a small HS. Large home storages above 6 kWh coupled with small PV systems with less than 5 kWp do not perform well.

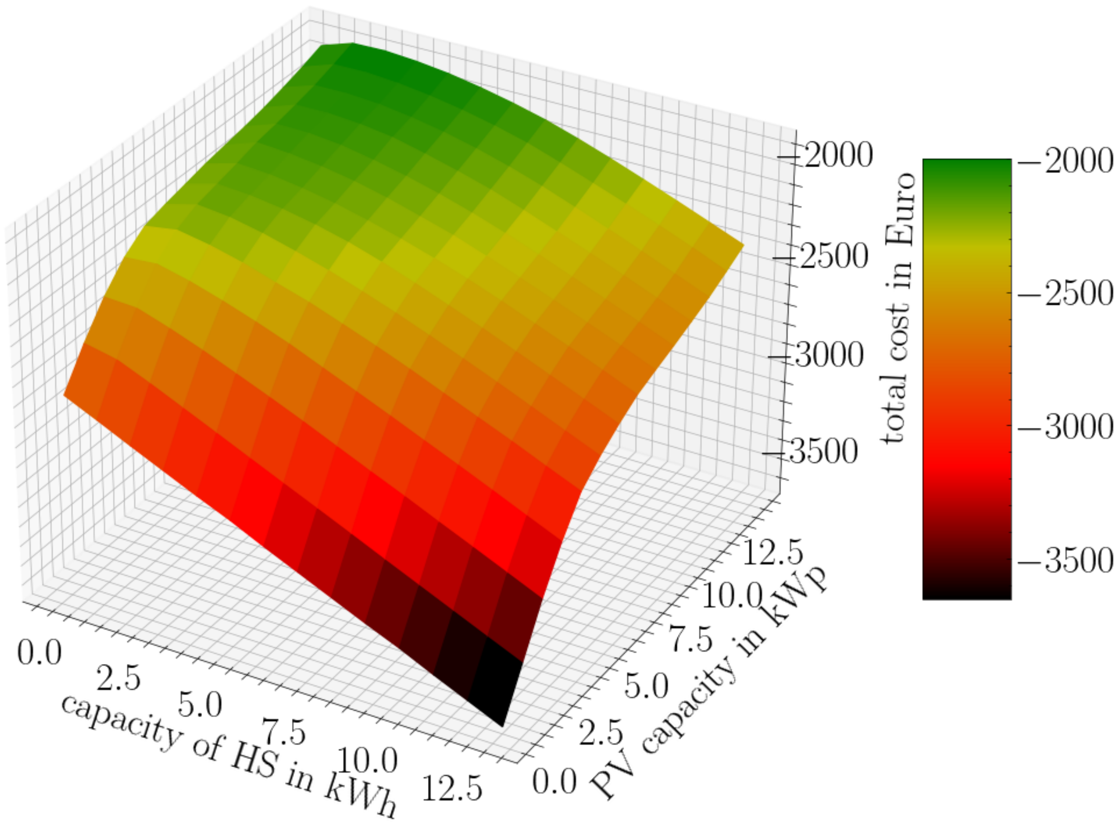

Figure 5.13: Cost over one year for different PV sizes and home storage sizes including component cost

Analysis and explanations

For now, home storages are still expensive and the best performance relative to costs can be achieved with a small one. Above a certain size, the financial benefit of storing and consuming more of your own solar power is lower than the purchase cost and therefore financially not interesting.

5.6 Effect of increasing prices on algorithm performance

For all previous simulations, we have considered a given price pair (37 ct/kWh for buying, 6 ct/kWh for selling). Now we investigate the performance of the financial algorithm for the case of higher energy prices, which is likely to occur in the lifetime of our system.

Investigation and observations

The graph in Figure 5.14 shows how much the financial algorithm outperforms the naive algorithm over one year. The investigated configuration can be seen in Table 5.11 and the different lines show what happens when the price the homeowner has to pay for electricity rises from 34 cents up to 46 ct/kWh. The price for selling electricity remains the same at 6 cents, since homeowners get a fixed rate for 20 years.

As can be seen, the higher the price, the more the financial algorithm outperforms the naive one.

PV size	HS size in kWh	EV battery size in kWh	V2H / bidi	price model
8.1 kWp	10.8	60	no	static

Table 5.11: Configuration PV and HS sizes

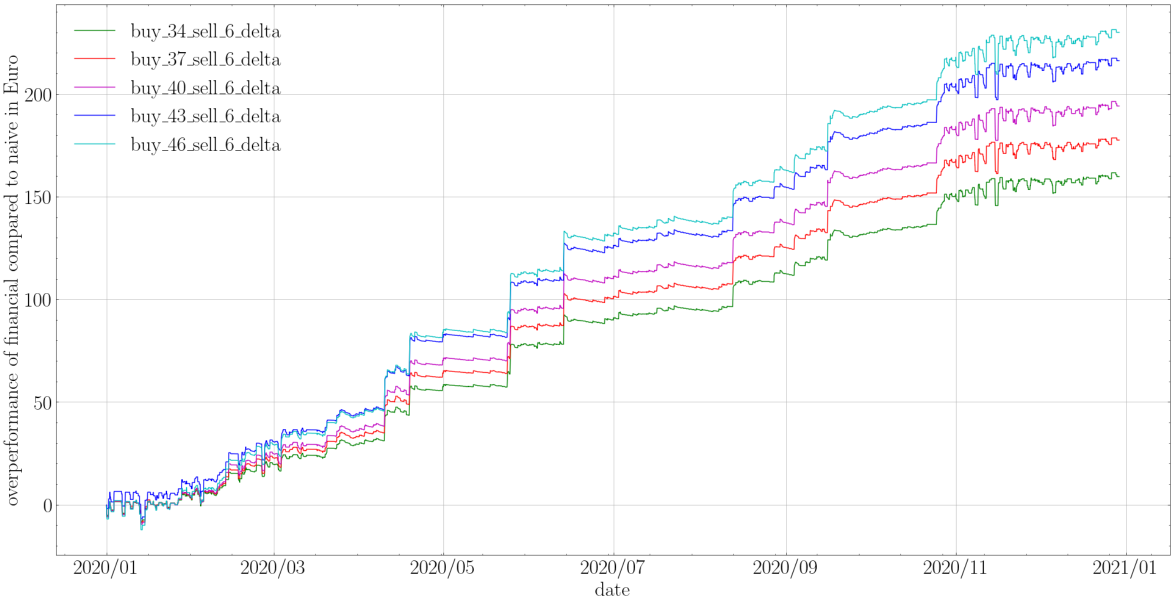

Figure 5.14: Effect of increasing electricity prices on algorithm performance

Analysis and explanations

The reason for the better performance with higher prices is that the difference between what can be gained by selling excess electricity directly and storing it to cover the own consumption later, is bigger as well. Selling only gains 6 ct/kWh, but using it to cover the own consumption at prices of 34 to 46 ct/kWh saves way more. The algorithm therefore tries to cover as much of the own consumption as possible with electricity produced by the PV and to sell as little as necessary. The higher the difference between buy and sell prices the more beneficial the algorithm is.

This means, that with increasing electricity prices, the benefits of a smart energy management system increase as well. This therefore makes it more lucrative to switch to such a system and for everyone who has already done this, the effect of price increases will be less noticable. Such a system is a good investment.

5.7 Result comparison with the related work

5.7.1 Smart home energy management optimization method considering energy storage and electric vehicle

Using their management scheme [Rw119], the authors were able to maximize the use of the electricity produced by the PV. Compared to the same system without management, their home energy management system was saving 9% of costs. This is lower than what is achieved with the home energy management system in this thesis, which is due to the fact that in their simulation the car was always away at day-time while the PV was producing electricity. If this was the case in the simulations performed in this thesis, the results would probably be similar.

5.7.2 Potential of demand and production shifting in residential buildings by using home energy management systems

Both the energy management system in the study [Rw215] and the one in this thesis are able to minimize the purchase of electricity from the grid and thereby the costs. In one of the cases evaluated in the study, their energy management system was able to manage the heatpump and the thermal storages as well, which led to significantly higher savings compared to the other cases they evaluated. In all cases which are comparable to simulations performed in this thesis the results are similar. The savings of the energy management system in this thesis are generally higher, which is at least partly due to the fact that the study was done in 2015 when electricity prices were significantly lower than today and therefore a house had less expenses it could possibly save.

5.7.3 Predictive home energy management system with photovoltaic array, heat pump, and plug-in electric vehicle

The home energy management system in the study [Rw321] was able to reduce costs by 34%, whereas our energy management system in this thesis is only able to reduce costs by 26% when using dynamic prices and a comparable house setup. The reason for the better performance of the energy management sytem in the study is their ability to control the heatpump as well. However the temperature in the simulated house of the study dropped by up to 5°C within a few hours in some cases. This could cause inconveniance to the homeowner, which is why in this thesis the heatpump is not controlled by the energy management system in a first step.

The last two studies showed the financial potential present in the management of the heating and warm water systems. The key to the success of such a strategy is in minimizing the impact comfort.

6 Conclusion and outlook

In this report we tried to provide some answers to questions regarding the financial optimization of the electricity configuration and management of a modern single family home (SFH) with a photovoltaic system (PV), a heatpump (HP) and one electric vehicle (EV) as part of the mobility solution. To this end a piece of simulation software was developed with the goal of minimizing the cost of the electricity. Various simulations were carried out. Among others, the PV size, the HS size, the EV battery size and the vehicle to home (V2H) capability were investigated. Many more simulations could be done.

In conclusion, upgrading to a smart energy management system such as the financial algorithm presented in this work, leads to a significant financial benefit in all cases except for those with the largest HS.
In most scenarios it is not worth increasing the size of the home storage. Nevertheless if the SFH does not have a home storage yet, adding a small one makes sense financially.
Investing in a bi-directional wallbox that allows to use V2H for feeding electricity back into the house does not lead to significant financial benefits in most cases. This is mainly due to the high costs of the V2H and the limited availability of the EV. In addition, the high energy losses and the increased battery degradation do not make it an ideal solution.
For these reasons, home storages are still a better option. However if electricity prices continue to increase at the current rate and prices for home storages and bi-directional wallboxes continue to decrease, a reassesment should be done and different configurations might become appropriate.

The energy management system presented in this work could be used to benefit homeowners financially. For now it is only a proof of concept and several aspects would have to be looked into first:
Regarding hardware, the algorithm should be able to run on any microcontroller with an internet connection or it could be run by a smart home system, if available.
The simulation in this work is based on a simplified model and some parameters, such as the cost of such an energy management system have not been included.
Another crucial issue would be to get accurate forecasts for all actors.

The financial algorithm in its current state perfoms well in terms of reducing costs in most scenarios, it is however not optimal and could be further refined. One could also imagine using artificial intelligence and machine learning to further improve performance. Allowing the management system to schedule some consumers like appliances or a water heater, as has been done in other studies, could be one way of improving it. Interaction with the grid and the electricity producers could be expected to play a larger role in the future for increasing the stability of the grid by smoothing peaks in demand and production.

Further pursuing the ideas explored in this work could be more and more financially worthy in the future. Especially in the context of rapidly increasing energy prices and decreasing component prices at the same time. This could create an incentive for more investment in PV systems by homeowners, resulting in a positive impact on the environment.

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Declaration

I hereby declare that the work presented in this thesis is entirely my own and that I did not use any other sources and references than the listed ones. I have marked all direct or indirect statements from other sources contained therein as quotations. Neither this work nor significant parts of it were part of another examination procedure. I have not published this work in whole or in part before. The electronic copy is consistent with all submitted copies.

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