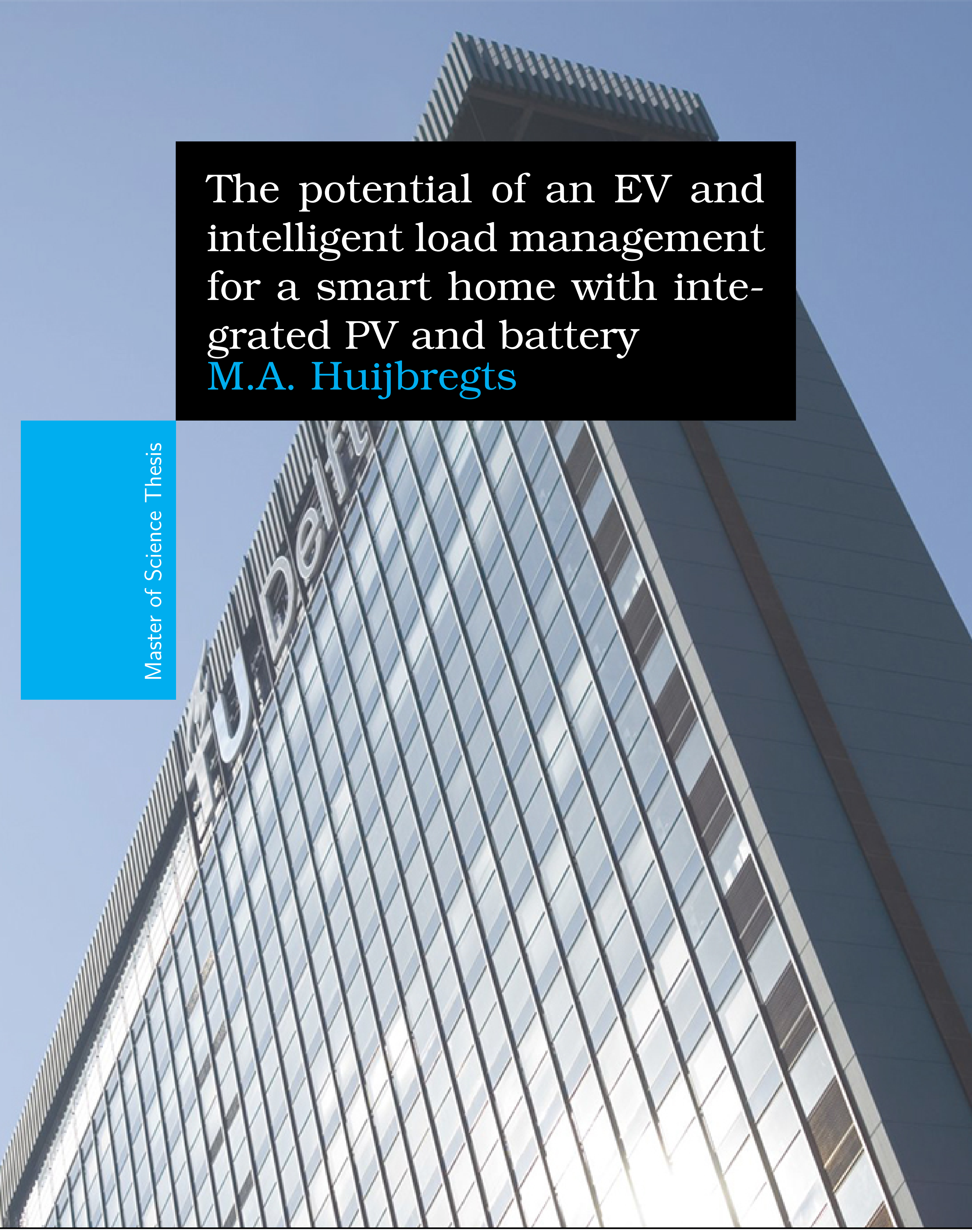

The potential of an EV and intelligent load management for a smart home with integrated PV and battery

M.A. Huijbregts

Master of Science Thesis

Delft University of Technology

DC Systems, Energy Conversion & Storage

The potential of an EV and intelligent load management for a smart home with integrated PV and battery

Master of Science Thesis

For the degree of Master of Science in Electrical Power Engineering (Electrical Sustainable Energy) at Delft University of Technology

M.A. Huijbregts

April 7, 2019

Faculty of Electrical Engineering, Mathematics and Computer Science (EEMCS) · Delft University of Technology

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The potential of an EV and intelligent load management for a smart home with integrated PV and battery

by

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in partial fulfillment of the requirements for the degree of

Master of Science of Electrical Power Engineering
(Electrical Sustainable Energy)

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Abstract

With the increase in home energy consumption due to the electrification of house heating and charging of electric vehicles (EVs), the self-sufficiency and reduced impact on the utility grid from a house has become a more exciting topic. In combination with the price decrease for lithium-ion batteries the potential for storing PV generated energy in batteries has become more beneficial. However, the price for batteries is still a large part of the total investment of a PV system with home battery. Correct sizing of the home battery and PV installation is essential to reduce investment costs and as a result a decrease in payback time. Besides the correct sizing of the home battery and PV installation, these two parameters are also influenced when using an EV in the energy management system of the house. EVs have large batteries (thirty to hundred kWh) to give the EVs an extented driving range. The average EV owner does not use the full capacity of the battery on a regular day. The unused capacity of an EV battery has the potential to reduce the home battery capacity when used as a storage facility.

To reduce the impact of the upcoming changes in house consumption, this thesis investigates load shifting in combination with a charged EV as addition to the house with integrated PV and battery. The results show that a charged EV can have a positive contribution to a house on grid energy autonomy, peak shaving capability and electricity cost. In combination with load shifting the benefits are further increased.

Acknowledgements

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Delft, University of Technology M.A. Huijbregts
April 7, 2019

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Chapter 1

Introduction

This chapter focuses first on the motivation of the research (section 1.1). Second, the thesis objective and research questions are given in section 1.2, followed by the scope of the thesis and thesis goals (section 1.3). Last the thesis outline and layout of the thesis (section 1.4) are given.

1.1 Motivation

The energy consumption of houses will increase in the coming years. The electrification of heating and charging the EV will have a significant impact on the load pattern of the house. The increased consumption will lead to congestion on the utility grid. Initially, the utility grid is designed for centralised electricity generation with end-users as energy consumers. Distributed generation can potentially lead to high power peaks on the utility grid when the (surplus of) solar power is directly fed into the grid. This also applies to charging an EV with power from the utility grid, this leads also to power peaks on the utility grid. To reduce this impact on the utility grid, the locally produced PV energy has to meet the local energy demand as much as possible. The electricity grid of the future smart home is a microgrid. Microgrids have a distributed energy source (like PV) and a battery to store the surplus of PV energy when needed. A battery is needed to store the PV energy for using it when there is reduced generation and increased demand like in the evenings. This is the result of the temporal mismatch between the PV generation profile and load profile. Storing energy in batteries results in a higher self-consumption of the PV energy. However, the investment in a battery is still a large part of the total investment for a house with integrated PV and battery. The price of a home battery is €1,000/kWh [6]. To reduce the capacity of the home battery, the batteries of EVs can potentially help the house.

EVs have large battery capacities from thirty to hundred kWh and power ratings up to tens of kW. When EVs are used intelligently, EVs have the potential to store the entire PV energy of a house for a day. They can also deliver the power to meet the (peak) demand of a Dutch household with an average annual consumption of 3,000 kWh [7]. The high penetration of renewable energy sources (RES) in the current electricity grid leads to opportunities for emission-free electricity consumption. These two phenomena combined has a promising potential to generate, store and use energy from RES only.

At home the EV can be used in several ways:

1. The EV is charged at home
2. The EV has no interaction with the home grid
3. The EV is used as a bidirectional load

When the EV is charged at home (case 1), the total consumption of the house is profoundly affected. The average annual house consumption in The Netherlands is 3,000 kWh [7]. When an EV is used five times a week for commuting traffic of one hundred kilometres, the EV energy demand is around 5,000 kWh (section 4.4). The EV consumption is, in fact, higher when the non-commuting traffic of the EV is added. Charging at home is challenging to do it with PV energy only.

In case 2 the EV has no interaction with the home grid. The EV is not charged or discharged at home. When the EV is not charged at home, the EV has to be charged at fuel stations with fast chargers. The PV installation and home battery are then only sized for the house consumption without EV.

Another way of tackling the massive impact of an EV is to use it as a bidirectional load (case 3). The battery of the EV is then used as a storage facility. An ideal situation is that the EV directly charges its battery from PV energy. This is challenging to do this at home. The solar generation has a temporal mismatch with the presence of the EV at home, as can be seen in figure 1.1.

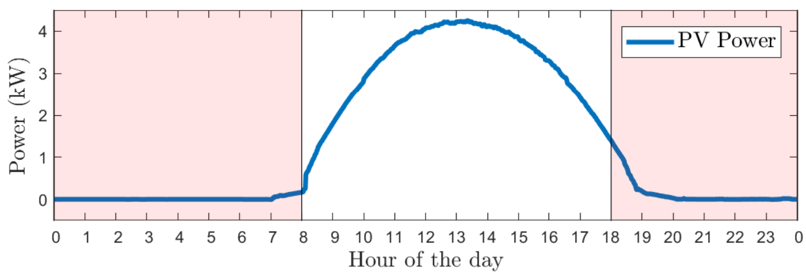


Figure 1.1: Mismatch between PV generation in The Netherlands [1] (blue line) and EV presence at home [2] (red area)

To charge the EV directly with PV energy, the PV installation and EV has to be at the same place at the same time when the PV installation generates energy. Most EVs are parked at work when the PV energy is generated at home. When the EV can be charged at work, the EV can be directly charged with PV energy. Charging the EV at work with locally produced PV energy is investigated in [8]. In this study, they have concluded that EVs parked at work can be charged with locally produced PV energy.

To be able to store the extra energy needed for the house, the unused capacity of the EV battery has to be quantified. The average consumption of an EV is 18.6 kWh/hundred kilometres (section 4.4). When the commuting traffic is set to one hundred kilometres per day, the consumption for commuting traffic is 18.6 kWh. With battery capacities ranging from 32-95 kWh, the battery is not fully used for commuting traffic on a regular day. The difference between the total energy of the battery and the energy used for commuting traffic can potentially be used for storing the household needs. As stated before, the average household in The Netherlands has an annual energy consumption of 3,000 kWh, which is about 9.7 kWh per day. The unused capacity of the battery of the most common EVs varies from 13.4-76.4 kWh. This means that the EV has the potential to power the house partially. If the EV is charged by locally generated PV energy for the extra energy needed for the house demand, then the energy consumption of the house is more/fully sustainable.

The EV can be used as a storage facility and as a power source. This affects the capacity of the home battery and the size of the PV installation at home. The EV has the potential to make the house more sustainable, grid independent and cost-effective.

Work done

Since solar panels have become affordable for home-owners, the research on integrating a PV installation and home battery into a house have become interesting. Several studies [9], [10] investigated the optimal sizing of PV-battery systems by maximising the economic value created by using a home battery and PV system. These studies have focused on improving self-consumption, energy autonomy and cost advantages.

With the worldwide increase in the amount of EVs, research to implement an EV as vehicle-to-home (V2H) has taken a flee. The EV has the potential to assist distributed grids (like house microgrids) and the utility grid. The EV can smooth the domestic electricity demand in a V2H operation [11]. This research has focused on using the EV battery to smooth the electricity, they have concluded that V2H improved the peak grid demand and load factor in comparison to a system without V2H. V2H is also used as backup power in case of a grid outage [12], the EV is only used as backup and is not used as a regular daily power source.

The temporal mismatch between PV energy and energy demand can be reduced with intelligent load management. [13], [14] have focused on demand-side management to schedule the load to reduce the cost of electricity and energy consumption of the utility grid.

This thesis aims to investigate if the energy management system of a house can beneficially integrate the EV as a storage facility and power source. Intelligent load management can use the potential of the EV to power the household load by the EV instead of only shifting it to times when solar energy is generated at home. Also, load shifting to remove/reduce demand peaks with the help of EV can be done. The price of Li-ion home batteries will drop over time [15] [16] and using a battery will become more beneficial in the future. However, the home battery will always be a massive part of the investment cost of a PV installation at home. Researching the gap from previous work regarding the combination of intelligent load management with a charged EV is the primary objective of this thesis.

1.2 Thesis objective

As stated in the motivation section, this thesis investigates the benefits for a house with a PV installation and a home battery to integrate an EV into the EMS. The capacity of EV batteries has been increased since a couple of years to enlarge the range of the EV. In combination with the low average distance for commuting traffic, the total capacity of the EV's battery will not be fully used on a regular day. The unused capacity of an EV's battery has the opportunity to fill (partly) the gap of storing energy. This is done in combination with load shifting to reduce the temporal mismatch between the house consumption and PV power and to obtain improvement on the grid energy autonomy, peak shaving capability and electricity cost.

The main objective of this thesis is:
What are the economic benefits of using the EV battery as a V2H coupled with intelligent load management for future smart houses with integrated PV and battery?

The main research question is divided into three sub-questions:

- Which of the home appliances are suitable to be part of intelligent load management?
- What is the impact of intelligent load management in terms of grid energy autonomy, peak shaving capability and electricity cost?
- What is the effect of incorporating the EV in the house power management strategy with load shifting on the optimal sizing of the PV with home battery in terms of grid energy autonomy, peak shaving capability and electricity cost?

1.3 Scope of the thesis and thesis goals

In part 1.1 is the motivation of the research explained and in this section, the scope of the thesis is discussed, and thesis goals are given.

The scope of the thesis is limited on a few aspects to determine the feasibility of the energy management system (EMS):

1. The house model used in this thesis is fully working on direct current (DC). Nowadays houses are connected to an AC grid, and many AC/DC transformers are used inside the house to make use of DC equipment. This thesis assumes that a DC residential grid is the future microgrid of a house.
2. The solar generation of the smart house is assumed to be known. The altitude and azimuth are fixed on 28 and 185 degrees respectively.
3. For this research, the load data comes from dataport from the Pecan Street Project in the US [17]. The available datasets from this source are very detailed and all household appliances have their load pattern. The consumption of home appliances is checked and scaled to common Dutch standards.
4. Energy trading (buying cheap energy and selling more expensive energy) is outside the scope of this thesis. Buying and selling for consumption reasons is allowed, the house is always grid-connected.

Certain aspects influence an EMS design. These aspects are, for this case, the number of solar panels at home, the size of the home battery, shifting of household appliances and partly the capacity of the EV battery. Fast(er) chargers can also influence the amount of energy that the battery of the EV can be charged at work, but that is in the hand of the employer/charging station owner. For simplicity and limiting reasons, the maximum amount that the EV can be charged at work is based on [8]. To judge the EMS design, the system is optimised for specific targets. Grid energy autonomy, peak shaving capability and electricity cost are the primary targets for this thesis.

The goals of the thesis are divided into four parts:

- Analyse the different (non-)shiftable loads in a household.
- Develop an EMS which schedules the shiftable load appliances in combination with an EV that can deliver energy to the house (V2H).
- Evaluate the results of the EMS on grid energy autonomy, peak shaving capability and electricity cost.
- Compare a smart house with integrated PV and home battery, with an EV as a new energy source/storage facility included, to a smart house that stores the surplus of energy into the grid or home battery.

1.4 Thesis outline and layout of the thesis

This section is about the thesis outline followed by the layout of the thesis. The thesis outline is given in figure 1.2.

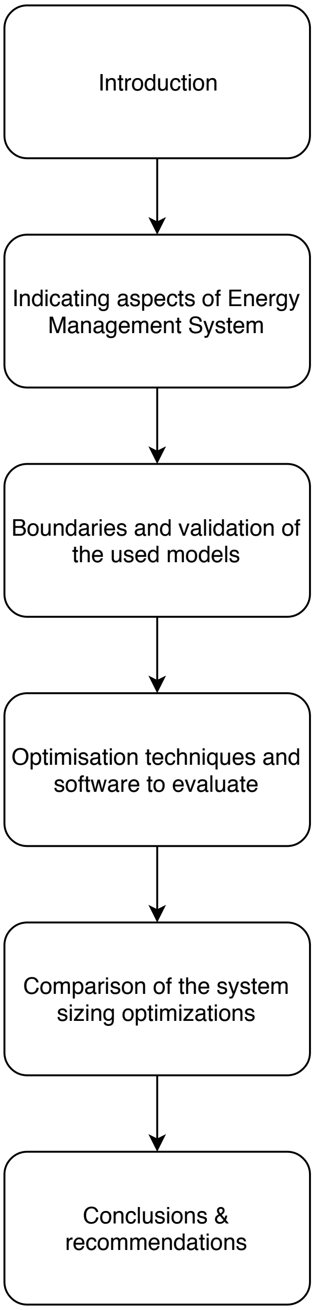


Figure 1.2: Outline of the thesis

The thesis is divided into chapters. In this section the chapters are listed with briefly their contents.

- **Chapter 2: Energy Management System Theory** - The thesis starts by indicating several parts of an EMS. Generation, load, electrical energy storage, battery wear/lifetime, pricing and existed EMS technologies are treated in this chapter.
- **Chapter 3: Demand Side Management** - The chapter starts with an overview of the several techniques to change/reduce a load pattern. The focus is then on one of these techniques (load shifting), which is used in this thesis. The load shifting algorithms based on price tariffs, solar generation and solar generation including EV availability are explained. The chapter ends with the introduction of the system sizing optimisation program that is used to evaluate the (shifted) load patterns on grid energy autonomy, peak shaving capability and electricity cost.
- **Chapter 4: Techno-economic model of a smart DC house** - In this chapter the model aspects which are taken into account for this thesis are described. The chapter starts with the solar generation, followed by the extensive mapping of various loads in a household. After that, the chapter focuses on the home battery and the analysis of an EV's battery to estimate the unused part of the battery. The chapter ends with the used pricing environment in the model.
- **Chapter 5: System Sizing Optimisation** - In this chapter the results of the load shifting and system sizing optimisation are displayed. Comparisons on grid energy autonomy, peak shaving capability and cost analysis are examined.
- **Chapter 6: Conclusions and recommendations for future work** - In the final chapter, conclusions are drawn from including load shifting with an EV in an EMS. Furthermore, this chapter gives a summary of the thesis and highlighting the main contributions of the work. It concludes with recommendations for future work on the thesis' subject.

1.5 Contributions

The main contributions of this thesis are:

1. Analyse the home appliances that are suitable to be part of intelligent load management.
2. Investigate the effect of incorporating an EV in the house EMS in terms of grid energy autonomy, peak shaving capability and electricity cost.

3. Investigate the effect of intelligent load management on the grid energy autonomy, peak shaving capability and electricity cost with equal consumption.

4. Study the effect of reducing the cost benefit of net metering on the electricity cost by comparing a case with and without an EV integrated into the EMS.

Chapter 2

Energy management system theory

In this chapter an overview of the parts of an Energy Management System (EMS) is given. An EMS includes:

- Generation (section 2.1)
- Load (section 2.2)
- Electrical Energy Storage (section 2.3)
- Battery wear/lifetime (section 2.4)
- Pricing (section 2.5)
- EMS technologies (section 2.6)

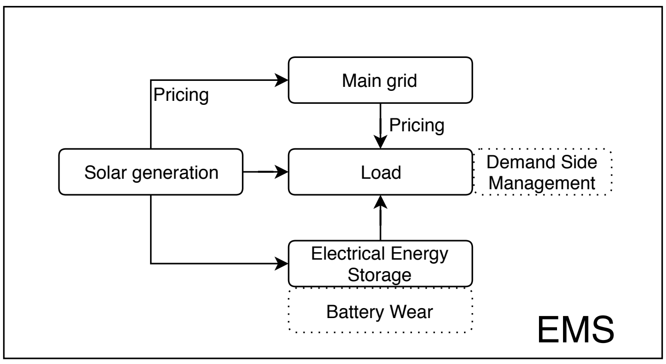


Figure 2.1: Overview of an EMS

2.1 Renewable generation

The first part of an EMS is the generation. An EMS cannot function without generation. Generation can be distributed or centralised. The trend from centralised to decentralised is the path that has been taken in today's world.

2.1.1 Transition to RES

The shift from fossil fuels to RES is a vast topic in today's society. Fossil fuels have been used for more than 150 years with a rapidly increasing consumption due to higher welfare and upcoming economies in the last decades. Due to this increasing demand, the price of energy will also be higher. This, in combination with the emission of greenhouse gasses and the dependency on possible unstable countries with the largest oil reserves, justifies the change to RES. The change to RES requires a different main electricity grid to maintain its reliability. The old way from a power plant to consumers has to become bidirectional. One of the causes are the prosumers [18], prosumers are consumers that have installed small distributed generation [19] on their premises, like solar panels on roofs.

RES are the new electricity sources, the penetration of RES will be very high in the future. In The Netherlands will mainly be focused on wind and solar energy. Wind energy can be relatively easily implemented at sea, which is a must for The Netherlands with the land scarcity. Another convenient side effect of placing wind turbines at sea is that landscape pollution is minimised. Also Not In My Back Yard (NIMBY) problems are avoided. Solar energy is very suitable for (small) businesses and private individuals, but energy suppliers also open solar parks. Space is rare in The Netherlands and therefore solar parks at sea are also investigated [20]. The combination of wind and solar energy is an excellent one, because they are more or less complement to each other. Higher yield from wind energy in autumn/winter and during the night, higher yield from solar resources in spring/summer and during the daytime.

2.1.2 PV sizing

In an EMS for a household it is essential to scale all of its sides as efficient as possible, a well-scaled EMS demands the right amount of energy to work with. On the generation side this can be done by scaling the solar panel installation on the dwelling's roof. Solar energy is the most used RES in households. It is affordable, easy to install and environment-friendly. The price of a PV system reduces year after year, which leads to a reduction in the economic payback time. A household in The Netherlands needs on average ten panels (rated 300 Wp per panel) to fulfil in its electricity demand [7]. Properly sizing can only be done when solar radiation forecast is used. These models are widely available and thus the generation is good to predict. [21] and [22] use these solar radiation fluctuations to size the PV system for their purposes. [23] designed a system to determine the optimal wind energy turbine capacity and the capacity for storing the energy.

In The Netherlands almost all houses are heated with natural gas, which is still cheaper than electrical heating. However, the Dutch government wants to decrease the heating with natural gas, to reduce the CO_2 emission and greenhouse gasses. The last couple of years many (relatively heavy) earthquakes appeared in Groningen due to the gas extraction and thence the transition to electrical heating and other kinds of heating is accelerated. The government increased the taxes on natural gas in 2018 and continues this in the coming period, the price increase per m^3 gas is visible in figure 2.2. Every house is striving to become self-sufficient. Electrical heating and charging of an EV increases the electricity demand, the PV system should be extended firmly to meet this new demand. This can be done by placing extra panels (if space is available), realising a significant increase in efficiency of PV panels (out of consumers' hands) or alternatively buying the extra electricity demand from the utility grid.

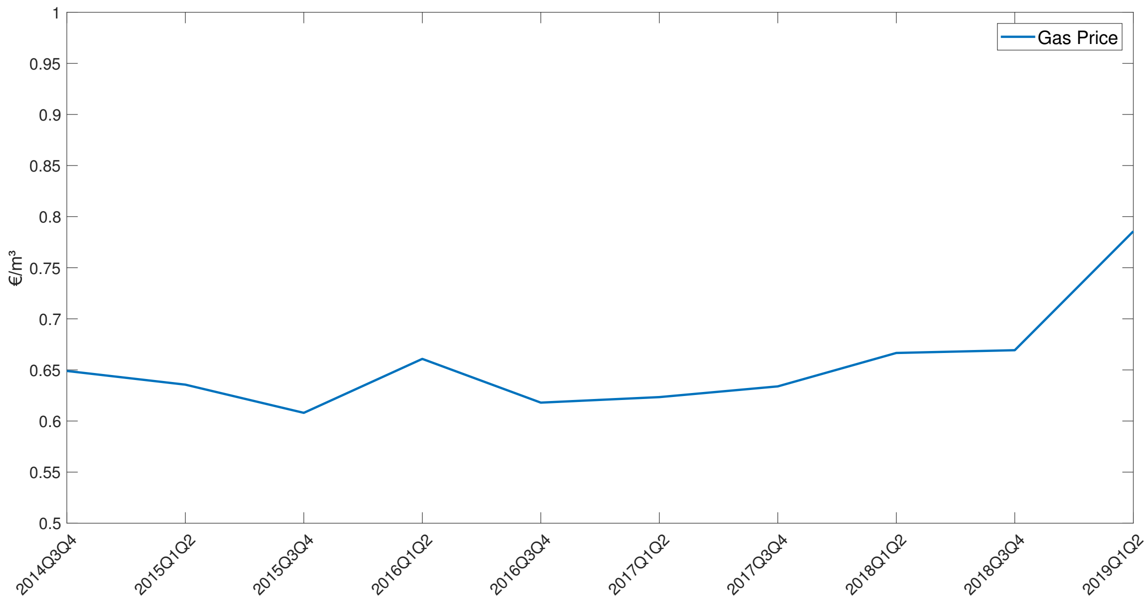


Figure 2.2: Gas price development in The Netherlands 2014-2019, source: Energy Circle

2.2 Load identification

The load is also an attribute of an EMS that can be controlled in certain ways. A downside of the load side is that not all load can be controlled. The average household in The Netherlands consumes 3,000 kWh per year [7]. When looking to data from the Pecan Street Project [17] it can be seen that the average annual consumption for a household is over 13,000 kWh. This usage is a multiple of the Dutch average annual consumption, but is also depending on the quality of the house insulation. The charging of an EV, the electrical heating and cooling have a significant impact on the consumption, when compared to a Dutch load pattern without those energy users. To reduce the load of a household in general, several aspects can be influenced.

Changing load patterns can be divided into the following three topics:

- Changing human behaviour
  Changing human behaviour is the hardest part to reduce the load. A yearly invoice is not stimulating enough to change someone's behaviour. Human behaviour is best affected when the reward is on a small timescale. Energy monitoring devices, like "Toon" from energy producer and supplier Eneco, can have a positive influence on human behaviour and therefore on the energy bill.
- Increase the efficiency of devices
  The increase in devices' efficiency can, in contradiction to human behaviour, be more influenced. To increase the efficiency of the devices, one can merely buy newer equipment. The downside is that the payback time will be several years and you cannot buy new equipment just for an increase in efficiency for a small period. The overall consumption decreases when buying new equipment, but in terms of cost it would be an investment that can only be done for a larger time frame.
- Changing the time of use of devices
  Changing the time of use (TOU) means that devices can shift their usage to a lower tariff time slot or lower peak to reduce the cost and influence on the grid. If implemented correctly, changing TOU will have almost no effect on human behaviour. Dishwashers, for example, are perfect for shifting their consumption. The dishwasher in most households is fully loaded after dinner or breakfast. People switch on the dishwasher after those meals. When buying energy from the grid, the dishwasher can wait for a lower tariff. For example during the day when solar power is widely available the price will be lower in a TOU pricing environment. It is more cost efficient to run the dishwasher at those times than at the switch on time of the machine. The consumer has to set the time that the dishwasher must be finished. Changing the TOU depending on the load peaks is also a possibility, this is especially cost reducing when high load peaks are charged extra by the energy supplier or distribution system operator.

2.2.1 Base load

Base load or non-shiftable load are all electrical appliances that cannot be interrupted in principal. In an EMS this is called the base load, load that is always present on specific times and is constant for most of the time.

- Refrigerator and freezer
  The refrigerator and freezer are similar energy users. A freezer and refrigerator try to maintain the same temperature for the whole day. The highest consumption occurs when the freezer or refrigerator door is opened, this phenomenon can happen at any time. When the door is closed, during the night for example, the consumption is at its lowest. The shiftable options are minimal for these devices. The only possible shiftable function is that the freezer can cool down a bit further and back to its set temperature after. Then a kind of energy storage is created.

- Equipment that always needs a reasonable amount of energy
  Pumps for aquariums, pools and water ponds are examples of equipment that are always switched on for at least most of the time. All those pumps are needed to maintain certain water quality. Pool pumps can be switched off during winter time, but are present for a particular time of the year. In this section also heating equipment for aquariums, terrariums or unique plants can be thought of.

- Appliances with standby functions
  Many appliances have a standby mode, but do not use that much energy while on standby. The standby mode can be switched off, but in practice this is rarely done. Examples are burglary alarm and TVs. The router is a household appliance that cannot be switched off, especially in a smart home is an internet connection always necessary.

2.2.2 Stochastic load

The hardest load to control is the stochastic load, that load is fairly unpredictable on a daily basis. Some stochastic load is better to predict (electrical kitchen equipment, hair dryer) than others (computer, television). This all depends on the routine of the residents.

- Lighting
  Lighting is not shiftable, because it is needed at the same moment as when it is switched on. It cannot be stored or used at a later time. Light Emitting Diodes (LEDs) have decreased the demand from lighting significantly.

- Microwave, hot plate, kettle and other cooking equipment
  All cooking equipment is used when switched on. It mostly depends on the way of cooking or recipe. Slow cooking leads to lower load peaks, but creates a load that is more extended present. The shiftable potential of a stochastic load is hard to qualify and outside the scope of this thesis.

2.2.3 Shiftable load

Shiftable load are the primary source for smart appliances. They are instrumental in a demand response game [24]. The most common shiftable loads in a house with significant impact on the load pattern are:

- Dishwasher
  A dishwasher only has to be finished at a certain, by the user preset, time. A dishwasher is fully shiftable.

- Washing machine
  The usage of a washing machine is different than for a dishwasher. The washing machine will has days with high utilisation ratios and days without it being used. Where a dishwasher is switched on for five/six days a week on average, a washing machine runs on two or three days a week.

- Dryer
  Similar to a washing machine, but less frequent use. Not present in some households.

- Charging an EV
  An EV often generates a load peak right after work. The duration of charging the battery is dependent on the home-work distance and maximum charging power. The charging power can be lowered to reduce the high load peaks. It will charge for a longer time with a lower charging power to achieve the same energy transfer. The charging can also be shifted to lower tariffs times, to reduce the overall charging costs. Already back in 1981 Gellings [25] mentioned the challenges with EVs. He said that it would have a significant impact when everyone connects their EV to the grid at the same time. This gives, according to Gellings, a "kind of demand that could conceivably create night peaks that exceed today's day peaks". The EV is indeed a big load as can be seen in figure 2.3. The enormous impact on the load pattern can also be deducted from figure 2.3 (data from Pecan Street [17]), the higher peaks in the total usage are caused by charging the EV.

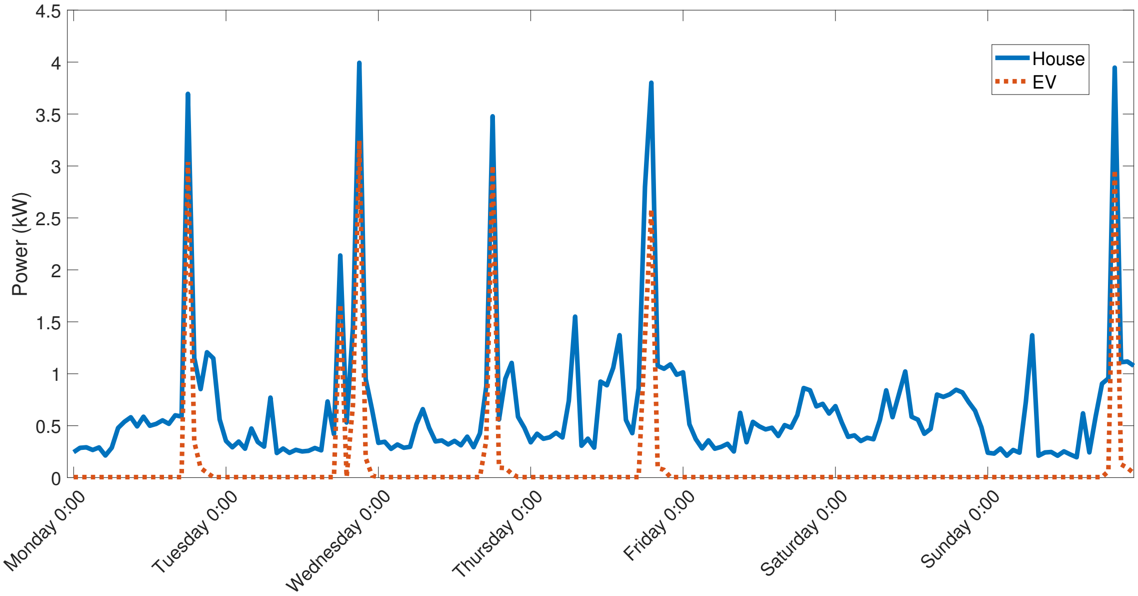


Figure 2.3: Week load pattern: EV usage vs total house usage

2.3 Electrical energy storage

The storage of energy becomes more and more important in the smart home of the future. Net metering will be less beneficial in the future and with electrical energy storage can a household use more energy from its PV installation. Energy storage can be done centralised or distributed. Several energy storage systems can be used like hydrogen, pumped hydroelectric storage, home batteries and the EV's battery. The EV's battery is also used for ancillary services and other purposes.

2.3.1 Net metering

Consumers who generate their electricity is becoming more common. In 2017 in The Netherlands 49% of the total installed solar power was generated by private individuals (see figure 2.4). Solar panels are relatively easy to install on roofs. With an economic payback time of about seven to ten years is it a good solution for reducing the overall electricity costs. Unfortunately, the generation of solar energy and the load demand are not in line, during the day solar energy generation is often higher than the demand. Due to this misalignment an electrical storage facility is needed. Currently, the utility grid serves as an electrical storage facility, a household can do net metering (in Dutch: salderen). Net metering is the phenomenon when the generation is equal or less than the usage, the price of a kWh is equal for putting it into the grid and for withdrawing it. In that case, the utility grid provides free storage for private individuals. Using the utility grid as a free electrical storage facility is not a situation that will continue forever. The Dutch Government included in their coalition agreement [3], [26] that they start searching for an alternative for net metering in 2020. When the advantages of net metering are reduced, the price for buying a kWh will be higher than for selling a kWh.

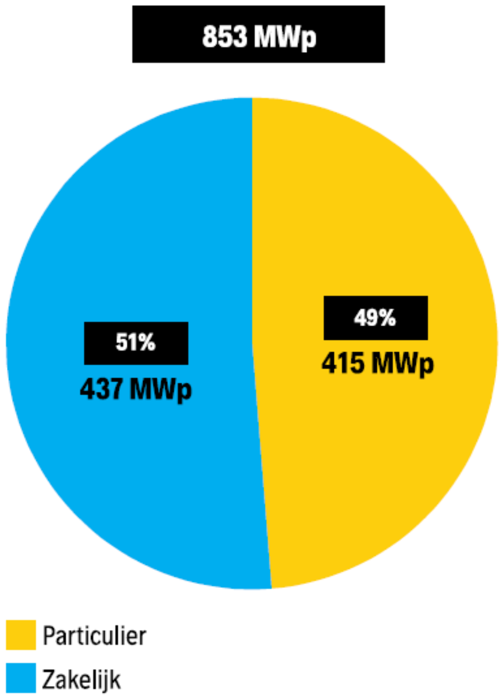


Figure 2.4: Comparison total installed solar power by private individuals (right, yellow) and businesses (left, blue) in The Netherlands in 2017 [3]

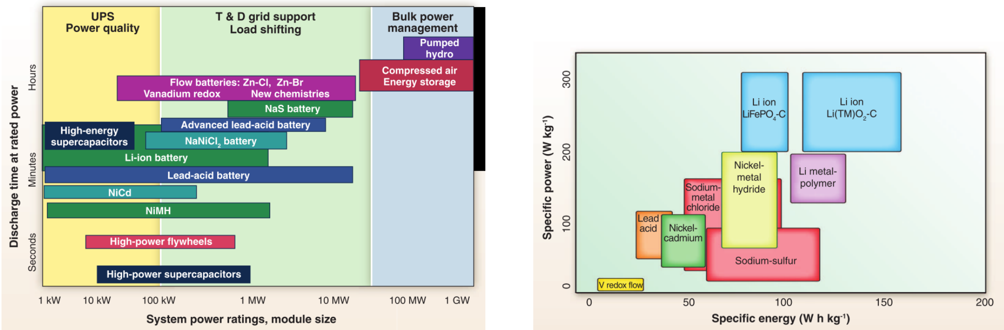
2.3.2 Centralised and distributed storage

Storage can be done centralised or distributed depending on the specifications and the goal of storing energy. centralised storing can be done to minimise the fluctuations from RES, which are very present when making use of RES. Pumped hydro-storage is also a centralised way of storing energy, especially in countries/areas with significant height differences. In The Netherlands the IJsselmeer is often named as a possibility from pumped hydro-storage but is not profitable yet [27].

Instead of centralised storage, distributed storage can also be beneficial. Providing local electrical storage is an option for household owners to mitigate the opportunity loss of free storage on the utility grid. The last years much research has been done in the field of electrical storage facilities for households and small businesses. This thesis mainly focuses on batteries and hydrogen storage.

As previously mentioned, energy storage is for homeowners an increasingly good option to be able to consume their own generated electricity. The prices of batteries are decreasing every year and will be affordable for more homeowners. With a lower price for batteries, the payback time of those batteries also decreases.

In figure 2.5 the constraints for different types of batteries are shown. When choosing the best battery for a particular case, one has to set the boundaries in what the battery has to operate. When the size (watt-hour per kilogram) and the maximum power output (watt per kilogram) both matter, the best solution is lithium-ion (Li-ion) as can be deducted from figure 2.5a and 2.5b.



(a) Battery technologies: discharge versus module size [28]

(b) Battery technologies: Energy versus energy [28]

Figure 2.5: Energy storage properties for several rechargeable battery techniques

Restrepo [29] investigated if the time was right to invest in domestic batteries in 2015. It was and still is with the downgrading of the financial benefits of grid storage (net metering) [26] in the coming years. An example of a domestic battery is Tesla's Powerwall [30], which already has a second generation. [31] investigated the best suitable batteries for solar systems. Lead-acid, NiMH and Li-ion batteries were investigated, with lead-acid batteries as most cost-efficient technology. This was with the technology back in 2004. [32] focused on lead-acid and Li-ion and concluded that Li-ion was better, but was still too expensive then. Hydrogen storage is also investigated for stand-alone systems with solar and wind energy in [33] and [34], only on solar energy in [35] and combined hydrogen and battery storage in [36].

2.3.3 EV as storage facility

Today the EV is often only seen as a load in a household. Much research has been done to include the possibilities from an EV in an EMS as a battery. They use it for ancillary services [37] and electrical energy storage [38]. Researching the EV as an electrical energy storage facility for a household is the primary target of this thesis. [8] has made a simulation to see what the optimal charge strategy for EVs at the workplace is. In that research the focus was to optimally charge EVs for the ride back to home and back to work on the next day. This is different for the use in this thesis, it is only used to verify if the required energy needed for the house can be charged at work.

2.4 Battery wear/lifetime

Battery wear is the only cost that has to be considered if storing energy in batteries is advantageous. Many studies have been done in the direction of battery wear. In this thesis, battery wearing is included, but only from previous work by others. For this thesis the focus is on Li-ion batteries which are used in EVs and Tesla's Powerwall.

Battery degradation in electric vehicles

Battery degradation of EV batteries is a vast topic with the transition to EV instead of fossil fuel powered cars [39]. Modelling battery degradation of Li-ion batteries in EVs [40] is needed to give a realistic prediction of the cycle life of the battery. Li-ion is the most used battery for energy storage and used as a battery in EVs. When an EV is used as V2G, the cost of using the battery for the grid is an essential factor to justify that technique. The cost-effectiveness of V2G mostly depends on the battery wearing as [41], [42], [38] and [43] concluded. Battery wear also depends on the ambient temperature and depth of discharge according to [40]. Parked cars are a useful source for electricity for the utility grid [44] and can also be used for vehicle-to-business (V2B) [45].

V2H is closer to the objective of this thesis. In [46] the functionalities for a plugin hybrid electric vehicle (PHEV) are investigated. The research was done in 2011, when the full EV was not that popular yet. The focus of that research is on the peak moments in the load pattern and the positive sides to include the PHEV for peak shaving. [12] also investigates V2H with a PHEV, but then in case of a grid outage.

Cost of battery wear

In this thesis the cost of battery degradation of the EV's battery for powering the house, is based on the work of G. Mouli. In his PhD thesis he used 4.2 € cents/kWh for using the EV's battery [47]. Many other studies have been done in the field of the cost of battery wear, like [40], [42] and [48]. For this thesis the cost for using the battery is fixed on 4.2 € cents/kWh.

2.5 Pricing

The pricing environment determines if a system/algorithm is beneficial or is not. This environment comes in many forms and shapes. The simplest one is when the cost per kWh is fixed for every minute of the year. Also two tariffs pricing and up to dynamic pricing like real-time pricing are possibilities. In this section a few major pricing techniques are treated.

One and two tariff(s) pricing

In The Netherlands private individuals can have a single or double energy tariff. A single energy tariff means that consumers pay one tariff for every kWh they use. With two tariffs consumers have a higher day tariff between 7 AM and 9/11 PM (differs per province), but a lower night tariff for the rest of the hours. The price difference between day and night tariff is 2-3 cents per kWh. In figure 2.6 the Dutch average energy tariff for a single and double tariff is displayed.

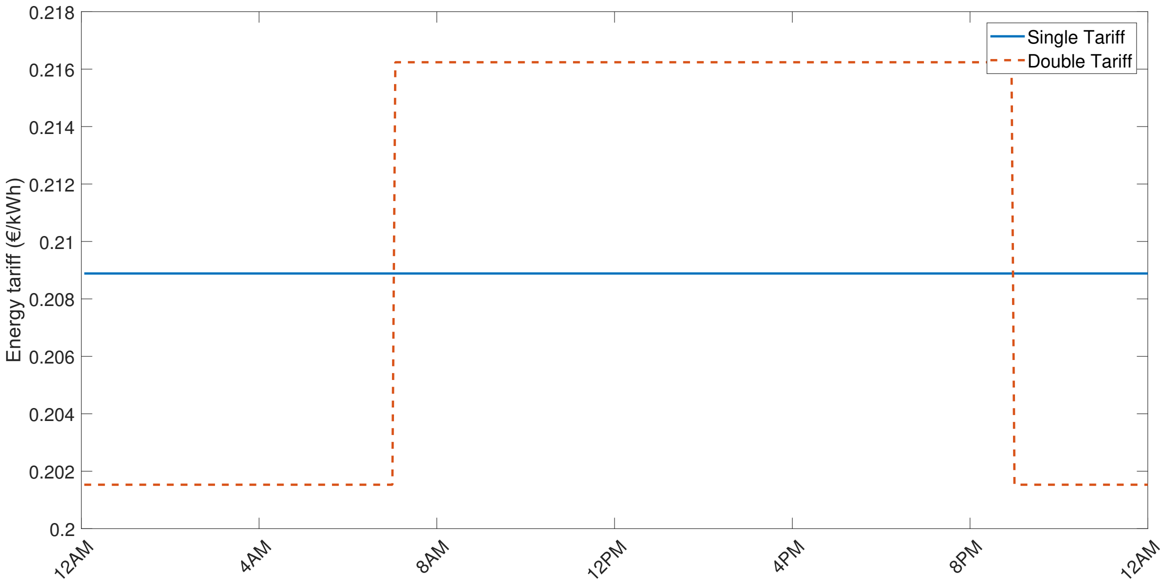


Figure 2.6: Energy tariff during a weekday for single and double tariff system

Dynamic Pricing

The night tariff was the first step towards dynamic pricing and price based demand shifting. The night tariff can be extended with hourly tariffs to divide the demand even further throughout the day. The benefit for the distributed system distributor is the "peak shaving" (lower peaks than usual) and for the consumer who has a lower overall price. Selling own generated energy to the grid is often less beneficial than using your own generated energy. In contradiction to the one and two tariff(s) pricing, the future pricing model will be dynamic pricing. In a dynamic pricing environment, the price can change several times a day (e.g. hourly or three-hourly, depends on the selling party). With this system the price is higher in case of peak demand and lower for off-peak hours [49]. In this thesis fully dynamic pricing is not implemented, two tariffs (day and night) are used.

Implementing dynamic pricing is not the standard when selling electricity to consumers, this is also valid in The Netherlands. The barriers for changing the pricing environment to a dynamic one are investigated by [50]. Dynamic pricing is the future pricing environment and first studies about the reaction from households to dynamic pricing are done [51].

2.6 EMS technologies

EMS became a promising system for households when the energy generation changed from centralised to distributed. This was mainly the result of the price decrease of solar panels and easiness to install such a system on household roofs. For an EMS it is crucial to investigate the demand response of a house to create a smart home [52], [24].

[53] speaks about a SEMS (smart energy management system), it takes power forecasting, an energy storage system and an optimisation module into account. [54] combined the EMS with power scheduling, which leads on one side to a cost reduction for households and on the other side a benefit for the utility companies with a lower peak-to-average ratio. Another aspect of an EMS is the sizing of the PV system with home batteries [55].

2.7 Conclusion

In this chapter the several aspects of an EMS are researched to get an overview of (a part of) the work that is done in this field. In this thesis the focus is on sizing the optimal amount of PV panels in combination with the home battery. To deal with the fact that the EV is not at home during the daytime. In that case the home battery can be much smaller than when the solar generation is providing the total energy consumption of the household. Storage is done with an EV battery and home battery. All parts are taken into account in the cost analysis at the end of this thesis.

Chapter 3

Demand Side Management

For a financial balance it is important that the income and expenses are in balance. In an EMS the generation can be seen as the income and the expenses side corresponds to the energy demand side when that idea is translated to the energy world. For every balance both sides can be tweaked to gain the best equilibrium. This chapter focuses on the demand side of the energy balance and techniques on how to change and improve this side. The chapter starts with the theory behind various load changing techniques, followed by the used power management algorithms to implement load shifting and finishes with the explanation of the system sizing optimisation program.

3.1 Load changing techniques

Electric devices need a specific amount of power to work correctly. All the power requested by the devices combined leads to the load pattern of a household. The used load patterns in this thesis are extensively described in the modelling chapter. The total load of a household is not a fixed number. It can be increased or decreased in value and changed in shape, when specific techniques are used. To get an overview of the several load changing techniques with their effects on the total load pattern, six techniques are described in more detail. The load changing techniques (figure 3.1) treated are:

- Load Shifting
- Conservation
- Valley Filling
- Peak Clipping

- Load Building
- Flexible Load

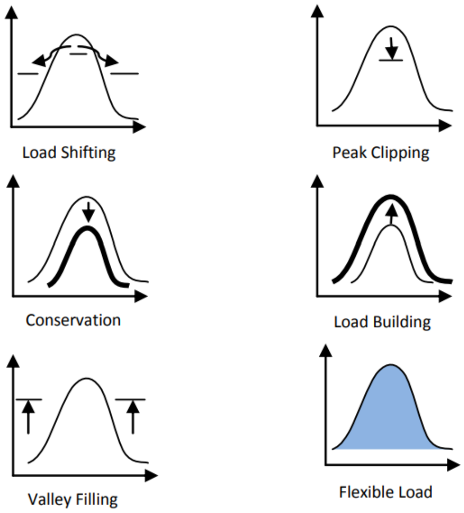


Figure 3.1: Overview of load changing techniques [4]

Load Shifting

When an appliance runs in the peak demand period and is rescheduled to another time, that is the load shifting technique. This can lead to cost benefits and reduced impact on the main grid. The demand is distributed more evenly throughout the day, leading to lower peaks in the load pattern of the house.

Conservation

Conservation is the opposite of load building. It leads to a reduction of the entire consumption of the house. This can be done with more efficient appliances or less frequent use of appliances. The increase in consumption leads to cost benefits and reduces the impact on the main grid.

Valley Filling

In the valley filling technique the "valleys" have increased consumption. This leads to a more constant load pattern and an increase in consumption. The lack of high peaks and low valleys reduces the stress on the main grid.

Peak clipping

The idea of peak clipping is to reduce the load during peak demand periods. The reduced load pattern at a specific time, is not increased at a later time. This results in a reduction of the entire house consumption. Peak clipping is often not a useful technique, because load shedding is undesired.

Load Building

Load building is the phenomenon that the entire load pattern is increased in consumption. Increased consumption can be the result of a change in the number of house occupants. An extra occupant leads to overall higher consumption. Also changes in work habits lead to higher consumption, for instance when the consumer retires and is more frequently at home.

Flexible Load

Consumers' appliances can be controlled without limitations. This often leads to lower tariffs from the energy supplier.

The load shifting technique is the technique that is used in this thesis. Some of the load changing techniques are not suitable for households like peak clipping and conservation. When peak clipping is used, the task that required the power is not scheduled to a later time but is skipped. Load shifting is for households the best technique to implement.

3.2 Power management algorithms

All parts in an EMS are controlled with power management algorithms. An EMS contains many algorithms which are used to reach the desired result. This optimisation can go in many directions, like for example optimising for cost, the lifetime of the home battery or using the own generated solar generation as much as possible. This part focuses mainly on load shifting algorithms.

3.2.1 Load shifting based on price tariffs

Load shifting can be done based on several requirements. In this part the load shifting is based on the tariff for a kWh at a specific time. The objective of the algorithm is to minimise the cost of the electricity bill. This is done by shifting loads to a period with a lower tariff per kWh. Not all load can be shifted so that the load pattern can be only partially improved for the cost of the electricity bill. Of the three types of load (base, stochastic and shiftable) only the shiftable load can make a difference in the cost. The shiftable load is the only load that has to be taken into account, as can be seen in equation 3.1.

$$minimise \quad C = \sum_{t=1}^{T} P_t^{shl1} p_t^{tar1} + \sum_{t=1}^{T} P_t^{shl2} p_t^{tar2} + \sum_{t=1}^{T} P_t^{shln} p_t^{tarn} + ... \tag{3.1}$$

where C is the total cost of the energy bill, P_t^{shln} is the shiftable load in that time frame at time t and p_t^{tarn} is the tariff used in the corresponding time frame.

The equation in 3.1 is for a case with an unspecified number of changes in the tariff. In this thesis only two tariffs are taken into account: the higher day tariff between 7 AM and 9 PM and the lower night tariff outside those hours. The equation of 3.1 changes then into formula 3.2.

$$minimise \quad C = \sum_{t=1}^{T} P_t^{shl1} p_t^{day} + \sum_{t=1}^{T} P_t^{shl2} p_t^{night} \tag{3.2}$$

where C is the total cost of the energy bill, P_t^{shl1} and P_t^{shl2} are the shiftable loads at time t and p_t^{day} and p_t^{night} are the tariffs used in those particular hours (day 7 AM-9 PM, night 9 PM-7 AM).

The constraints for this optimisation are:

$$0 \leq P_t^{shl1}, P_t^{shl2} \qquad \forall \quad t \tag{3.3}$$

$$0 \leq P_t^{shl1}, P_t^{shl2} \qquad \forall \quad t \tag{3.4}$$

$$\sum_{t=1}^{T} P_t^{shl1} + \sum_{t=1}^{T} P_t^{shl2} = \sum_{t=1}^{T} P_t^{shltot} \qquad \forall \quad t \tag{3.5}$$

3.2.2 Standardized Load Shifting Algorithm

The load shifting algorithm that is proposed in this thesis is based on the work of Logenthiran [56]. Formula 3.10 is the equation that was used by Logenthiran.

$$\sum_{t=1}^{T} (P_{Load}(t) - Objective(t))^2 \tag{3.6}$$

The algorithm minimises the difference between P_{Load} and an objective function. The objective function can be any function that is desired by the user. The load vector can be adjusted, when using this algorithm . However, not every load can be shifted to a different time. This is possible for several appliances, but for this thesis only the fully shiftable loads are taken into account.

3.2.3 Load shifting algorithm based on solar generation

For the first optimisation technique the P_{Load} is the shiftable load pattern with the base load and the objective function is the solar generation pattern. The optimisation finds the minimal difference between the load function and the objective function. The load function can be influenced by using the shifting ability of the shiftable appliances. The optimisation formula can be found in equation 3.7. The total load pattern consists of the base load (P_{bl}), stochastic load (P_{stl}) and shiftable load (P_{shl}). For the base load it is assumed that it is known. The base load is different in every house, but has likely a (yearly) recurring load pattern. The stochastic load, on the other hand, is harder to predict when data from previous years are analysed. The stochastic load is left out of the equation for the load shifting algorithm, due to its unpredictability. P_{Load} includes then P_{bl} and P_{shl} (equation 3.8). The base load is not suitable to be part of an energy management game, due to the lack of shifting possibilities. That only leaves the shiftable appliances to match the objective function as best as possible. The shiftable appliances used are the dishwasher (P_{dw}), washing machine (P_{wm}) and dryer (P_{dr}), see equation 3.9. To limit the discomfort for the homeowners, the shiftable appliance has to be scheduled within the day that the original switch on time was set. The objective function is for this load shifting algorithm the solar generation pattern (see figure 3.2).

$$\sum_{t=1}^{T}(P_{Load}(t) - P_{Gen}(t))^2 \tag{3.7}$$

where $P_{Gen(t)}$ is the available solar power at time t.

$$P_{Load}(t) = P_{bl}(t) + P_{shl}(t) \tag{3.8}$$

$$P_{shl}(t) = P_{dw}(t) + P_{wm}(t) + P_{dr}(t) \tag{3.9}$$

To show the working of the optimisation, the load pattern for a house with shiftable appliances is used. This load pattern is explained extensively in chapter 4, in this case the dishwasher is used five, the dryer two and washing machine three times. The distribution of the shiftable appliances before the shifting process is visible in figure 3.3. In figure 3.4 the result of the shifting process is shown. It can be seen that the appliance with the highest peak power is placed at the solar peak power of that day. All appliances are shifted inside the time that the solar panel system is generating energy. In figure 3.4 it is visible that on day five the shiftable appliance peak and solar peak are not aligned. Figure 3.5 answers to that observation, the base load has a peak in its load pattern at the same time as the solar peak. The algorithm also takes the base load into account and calculates that the best place for the appliance's peak is not aligned anymore with the solar peak.

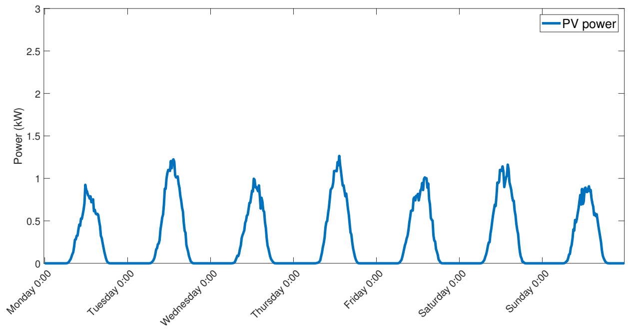


Figure 3.2: Objective function: solar generation pattern

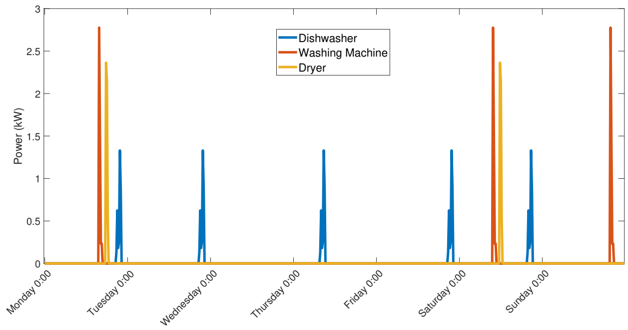


Figure 3.3: Shiftable appliances before shifting

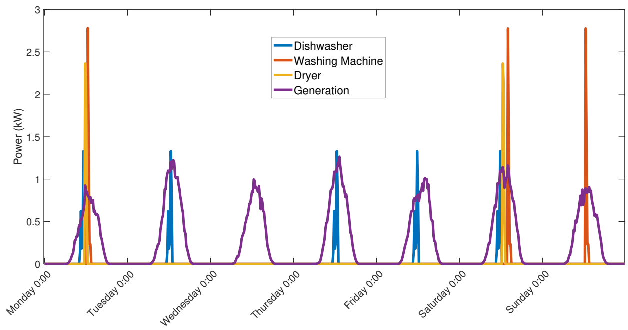


Figure 3.4: Shiftable appliances after shifting, with solar generation included

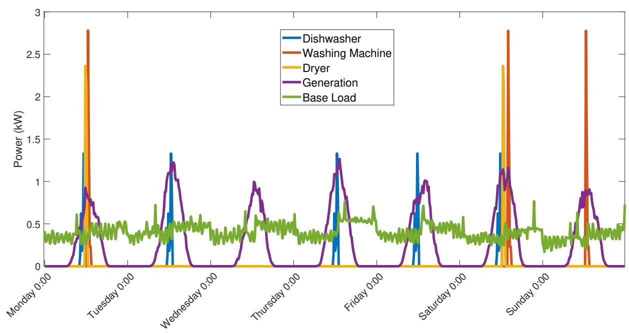


Figure 3.5: Shiftable appliances after shifting, with base load included

3.2.4 Load shifting algorithm based on solar generation and EV availability

This load shifting algorithm is similar to the previous algorithm when only the solar generation was taken as the objective function. In this case the EV is added as a potential energy source. The EV can be used as a power source the home appliances. The objective function is no longer only the solar generation curve, but now also includes the EV power availability. The EV's availability is determined by specific qualifications, the state of charge of the battery and presence at home of the EV. Ultimately the EV provides the energy demand when it is at home and the solar generation is the energy source for outside those hours. The capacity of the home battery is minimised and the costs are reduced in that way.

$$\sum_{t=1}^{T}(P_{Load}(t) - (P_{Gen}(t) + P_{EV,dis}(t)))^2 \tag{3.10}$$

where P_{Load} is the load pattern of the household $P_{Gen(t)}$ is the available solar power at time t and $P_{EV,dis}(t)$ is the power that the EV can provide at time t.

The objective function is displayed in figure 3.6. The distribution of the shiftable appliances before the shifting process is visible in figure 3.7. In figure 3.8 the result of the shifting process is shown. Most of the appliances are shifted to the periods where the solar panel system is generating energy and the EV is still at home. This can be seen in figure 3.4 the objective function and shifted appliance have aligned their peaks.

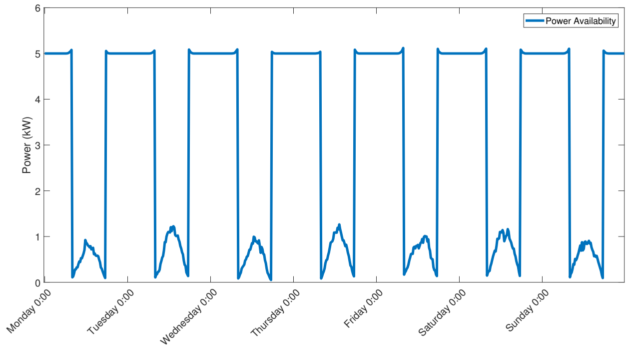


Figure 3.6: Objective function: solar generation with EV availability pattern

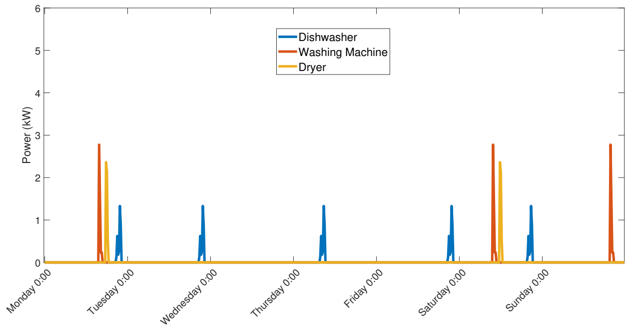


Figure 3.7: Shiftable appliances before shifting

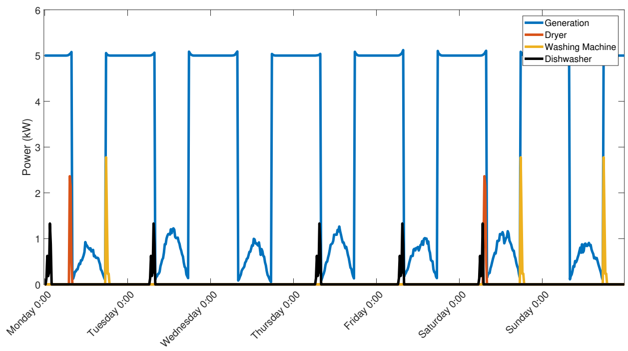


Figure 3.8: Shiftable appliances after shifting, with objective function included

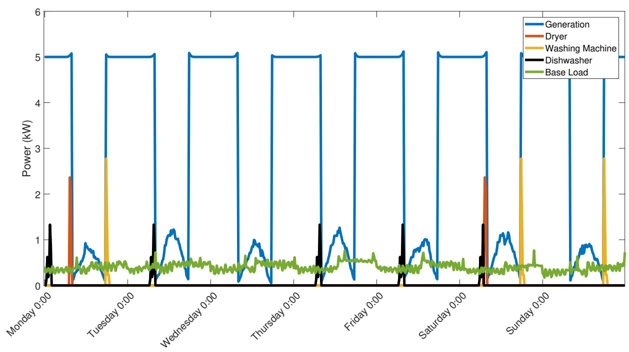


Figure 3.9: Shiftable appliances after shifting, with base load included

3.3 System sizing optimisation program

The results of the shifting program for various cases are put through the system sizing optimisation (SSO) model that is used as a partly black box model. This model is party developed by S. Bandyopadhyay as part of his PhD at the department of DCE&S. The model is adjusted on certain parts to reach the goals of this thesis. In short, the model calculates the outcomes for several configurations when changing the values for the size of the home battery in combination with the size of the solar panel system. To see if the shifted load pattern generates any advantage, the standard load pattern and shifted load pattern are inserted in the SSO model and have as output the capital cost, peak shaving capability, grid energy autonomy and cost analysis.

In chapter 5 the results of the SSO model are displayed, discussed and conclusions are drawn. The following cases are evaluated by the model, both for standard and shifted load patterns.

- House without locally produced PV energy
- House with PV installation and home battery
- House with PV installation, home battery and standard EV
- House with PV installation, home battery and smarter EV
- House with PV installation, home battery and charged EV

The results of the cases are given in chapter 5. In this part the used calculations for this thesis are highlighted and explained.

The calculations that are focused on are:

- Capital costs
- Grid energy autonomy
- Peak shaving capability
- Impact on the home battery
- Impact on the EV's battery
- Market cost

3.3.1 Capital cost

The capital cost of a project is the amount of money that is invested to create the project. In the case of a PV installation with home battery the following parts are considered:

- Cost of solar panels C_{PV}
- Cost of converters C_{conv} (PV panel installation, battery and grid connection)
- Cost of home battery C_{batt}

The total capital cost is calculated with formula 3.11.

$$C_{total} = C_{PV} + C_{conv} + C_{batt} \tag{3.11}$$

where

$$C_{PV} = \#PVpanels * C_{onePVpanel},$$

$$C_{conv} = C_{PVconv} + C_{battconv} + C_{gridconv},$$

$$C_{batt} = E_{batt} * C_{battperkWh}$$

3.3.2 Grid energy autonomy

The grid energy autonomy of a house is determined by the energy bought on the energy market and the loads that are shedded to maintain a stable and reliable energy management system. The grid energy autonomy is the percentage of energy that is provided by the own energy sources (like the PV installation or the charged car). This is not a percentage that can be read as islanded mode percentage. For islanded mode the actual power has to be considered instead of the total energy. The grid energy autonomy definition for this thesis in formula form can be found in equation 3.12.

$$1 - \frac{E_{bought}^{year} + E_{shed}^{year}}{E_{load}^{year}} \tag{3.12}$$

where E_{bought}^{year} *is the total energy bought from the main grid,* E_{shed}^{year} *is the total yearly shedded energy and* E_{load}^{year} *is the total yearly consumption of the house.*

3.3.3 Peak shaving capability

The peak shaving capability is, in contrast to the grid energy autonomy, power based. Significant power peaks in a load pattern are not desirable. Those peaks can come from switching on many appliances at the same time or appliances with high power demand. Also main grid operators do not want large demand peaks and in the future could be paying for the height of peaks a possible pricing environment.

In equation 3.13 the peak shaving capability is written in formula form. The peak shaving capability calculates every day the maximum of the shedded power plus the grid power related to the maximum value of the power load pattern. When the house requires lower peaks from the main grid, then the peak shaving capability increases.

$$1 - \frac{1}{365}\sum_{t=1}^{T}\frac{|max(P_{shed} + P_{grid})|}{|max(P_{load})|} \tag{3.13}$$

where P_{shed} is the shedded power, P_{grid} is the power to/from the main grid and P_{load} is required power by the house.

Impact on the home battery

The impact on the home battery is taken into account in the model, but is treated as a black box. The model calculates the lifetime of the battery and replaces it when needed, the extra cost for replacing the battery is added to the capital cost.

Impact on the EV's battery

The impact on the EV's battery in this thesis is taken into account in a financial matter. As stated in chapter 2, the cost of the degradation of the EV's battery for storing energy is fixed at 4.2 cents per kWh. The financial cost of using the battery is then:

$$C_{EVbatt}^{year} = E_{work}^{year} * p_{evdegbatt} \tag{3.14}$$

where $E_{work}^{y}ear$ is the extra energy charged at work for the V2H operation $p_{evdegbatt}$ is the price per kWh for using the EV battery.

3.3.4 Market cost

This section covers the cost analysis formulas from the SSO program. The simulated cases are compared on market cost. Also the total electricity cost is possible to use, but the cases are compared for even capital cost. This means that the amount of generated electricity is equal and so is the price for generating. The market cost is the total cost that the homeowner has to pay or receive for interaction with the main grid. When the amount of energy sold is higher than the energy bought, the homeowner receives a fee for selling the surplus of energy to the main grid. The yearly market cost is calculated in formulas 3.15 and 3.16.

The case with the charged EV is different than the other cases. In that case the EV is charged with extra energy to power the house. Buying the extra energy for the house at work is added to the market cost from the main market. Seen for the house this is also buying energy from a market.

$$C_{market}^{year} = (E_{bought}^{year} - E_{sell}^{year}) * p_{buy}^{yearcurve} \qquad \forall \quad E_{bought}^{year} - E_{sell}^{year} \geq 0 \quad (3.15)$$

$$C_{market}^{year} = (E_{bought}^{year} - E_{sell}^{year}) * p_{sell}^{yearcurve} \qquad \forall \quad E_{bought}^{year} - E_{sell}^{year} < 0 \quad (3.16)$$

For the case with the charged EV, C_{market}^{year} changes to:

$$C_{market}^{year} = (E_{bought}^{year} - E_{sell}^{year}) * p_{buy}^{yearcurve} + E_{work}^{year} * p_{work} \qquad \forall \quad E_{bought}^{year} - E_{sell}^{year} \geq 0 \quad (3.17)$$

$$C_{market}^{year} = (E_{bought}^{year} - E_{sell}^{year}) * p_{sell}^{yearcurve} + E_{work}^{year} * p_{work} \qquad \forall \quad E_{bought}^{year} - E_{sell}^{year} < 0 \quad (3.18)$$

where p_{work} *is the price per kWh for charging the EV battery at work.*

Chapter 4

Techno-economic model of a smart DC house

This chapter describes the modelling part of the thesis. The system sizing optimisation model needs a annual load pattern as input and gives the grid energy autonomy, peak shaving capability and cost analysis as output. This output is only valuable if the input is accurate and reliable. Every model has assumptions and also the input and conditions face boundaries. The input of the model is described in this chapter.

The smart house contains several components:

- Solar Generation
- Load
- Home Battery
- Electric Vehicle

4.1 Solar Generation

Solar generation is the electricity source of tomorrow's household. Solar generation differs from season to season. The sun stands lower in winter time and reaches its highest point at summer time. The efficiency of a solar panel is dependent on the temperature of the panel. For this thesis the optimal azimuth and altitude in The Netherlands are used. In figure 4.1 the altitude and azimuth are displayed. The used azimuth is 185 degrees with an altitude of 28 degrees as panel orientation. These values are optimal for a solar system situated in The Netherlands.

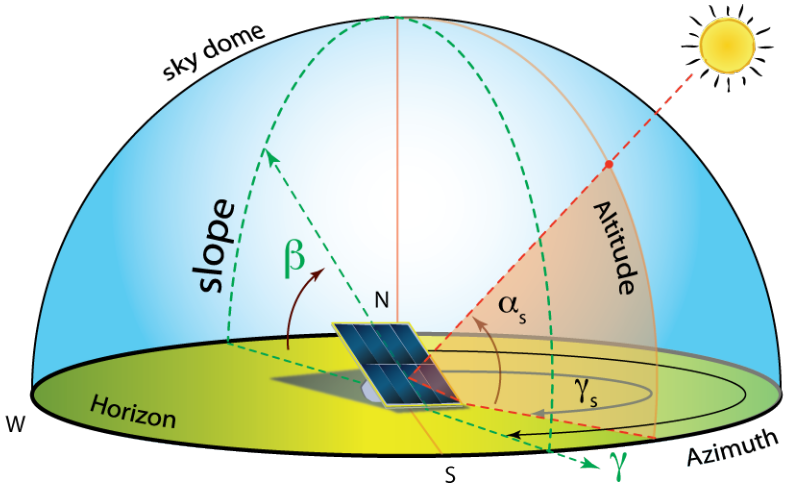


Figure 4.1: PV panel orientation with altitude and azimuth [5]

An azimuth of 185 and an altitude of 28 degrees is the best option for a panel in The Netherlands, but often is a solar panel oriented differently. This has a few reasons:

- Solar panels are often placed on roofs and the panels are placed parallel to the roof to reduce possible wind forces and minimise installation costs. This leads to an altitude of the solar panel that is not optimal.
- Solar panels are often directed differently than 185 degrees, this is because of the orientation of the roof. An orientation towards the south (180 degrees) gives a good result, but not the highest possible outcome. However, a roof directed to the south is considered quite optimal to install solar panels on.

The energy output of a solar system is different in each season. This difference is visible in figure 4.2. This is for a solar panel system that is directed at 185 degrees with an altitude of 28 degrees. Table 4.1 shows the differences between the seasons in percentage. It can be concluded that the generation in winter/autumn time is significantly lower than in the spring/summer.

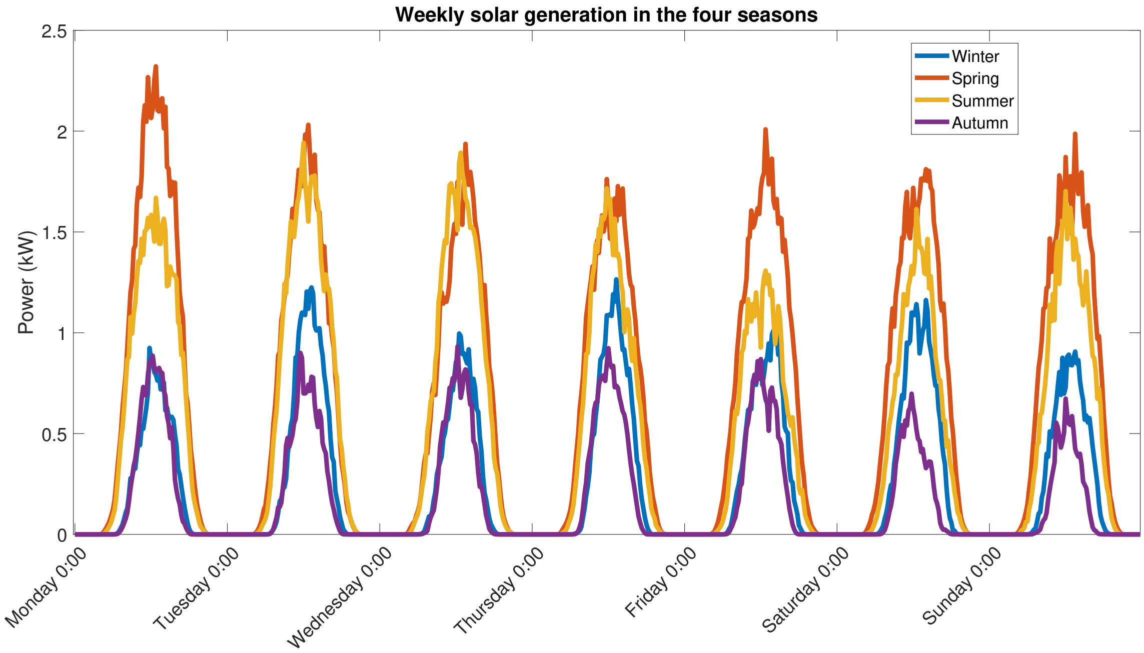


Figure 4.2: Difference in average generation per season for a week for the same solar panel system

Season	Winter	Spring	Summer	Autumn
Weekly generation wrt spring (%)	39.6	100	80.9	27.4

The generation patterns are not an input of the SSO program. Those patterns are used in the load shifting algorithms to shift the shiftable appliances to the best place. The SSO model creates the solar generation pattern according to the sized solar panel installation.

4.2 Load

The load is another important aspect of a microgrid with EMS. This part discusses the load of a household in this thesis. The different types of load are described and analysed. The limitations of the load are given and justified. The load of a household can be divided into three different parts, namely base, stochastic and shiftable load.

4.2.1 Base Load

Loads that qualify as base loads are non-shiftable and are present all day or at a fixed part of the day. Many loads who contributed to the base load would not come up into everyone's mind immediately. They are minimal loads and are often not seen as an important energy user. The loads referring to, are the loads that have a standby mode. Many appliances have a standby mode: televisions, the clock on microwaves, game consoles, stereo installations and printers for example. Standby modes do not use much energy, but are present in a household load pattern. [57] has shown that standby power can be quantified for one household, but it is hard to quantify a standard number for all households.

The base load does not only consists of small energy users. A fridge-freezer and aquarium are loads that can be counted to a significant part of the base load consumption.

Fridge-freezer

The fridge-freezer is one of the most significant base loads in a household. It has to be switched on at all times to maintain a certain preset temperature. In figure 4.3 weekly load patterns for a fridge-freezer in different seasons are shown. Figure 4.3a corresponds to the power demand during a week in the winter and figures 4.3b, 4.3c and 4.3d for a week in spring, summer and autumn respectively. The data for these figures is created as dataid 26 by the Pecan Street Project in Austin, Texas. This data is compared (and scaled) to common Dutch standards for maximum power and annual consumption of a fridge-freezer. It can be seen in figure 4.3a-4.3d that the energy consumption is quite steady with occasional peaks. Those peaks are the result of the defrost mechanism or opening the fridge-freezer.

No seasonal differences are present when comparing the load patterns. In table 4.1 the total weekly energy consumption is noted for the figures in figure 4.3. A fridge-freezer consumes more energy when the space temperature around it is higher. The temperature in a house is controlled and quite steady, so the season does not have a significant influence on the energy consumption. As can be concluded from table 4.1 and figures 4.3a-4.3d.

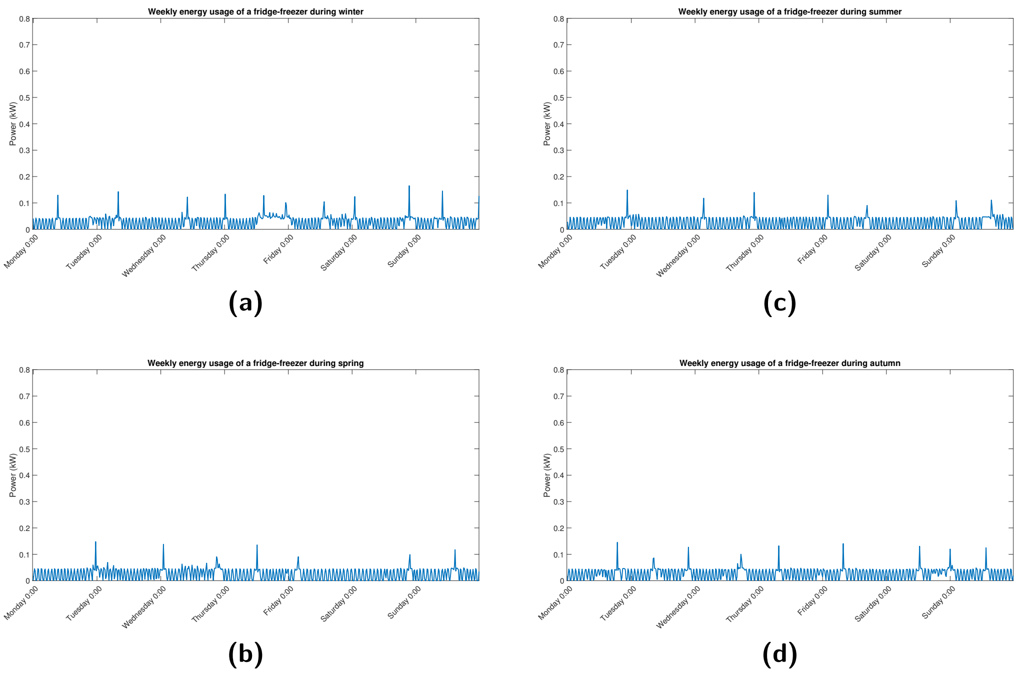


Figure 4.3: Load pattern fridge-freezer for all seasons: (a) Winter (b) Spring (c) Summer (d) Autumn

Table 4.1: Overview fridge-freezer consumption and peak power

	Winter	Spring	Summer	Autumn	Annual
Consumption one week (kWh)	4.79	4.21	4.36	4.58	233.1
Maximum power (W)					170

Aquarium

Next to the fridge-freezer is an aquarium also a big load which can be classified as base load. Most aquariums have heating equipment like a heat lamp (infrared), standard lighting and water heater. In figure 4.4 weekly load patterns for an aquarium in different seasons are shown. Figure 4.4a corresponds to the power demand during a week in the winter and figures 4.4b, 4.4c and 4.4d for a week in spring, summer and autumn respectively. The data for these figures is created as dataid 399 by the Pecan Street Project in Austin, Texas. This data is compared (and scaled) to common Dutch standards for maximum power and annual consumption of an aquarium. It can be seen in figures 4.4b, 4.4c and 4.4d that the energy consumption is quite steady. The minimal required power is 50 Watt, this is most likely the water pump with filter. An aquarium also needs a heat lamp, which switched on each day for about eleven hours. The heat light is switched on with a timer, since it switches on and off every day at the same time. The winter load pattern in figure 4.4a is different than the other three seasons.

This is because of the equipment that heats the water, the consumption is for that week higher than in other seasons. That the heat lamp is still switched on and off at specific times, can still be deducted from figure 4.4a. In table 4.2 an overview is given of the consumption for the different seasons, annual consumption and maximum power of the aquarium. The consumption in winter time is twice as high as in the other seasons.

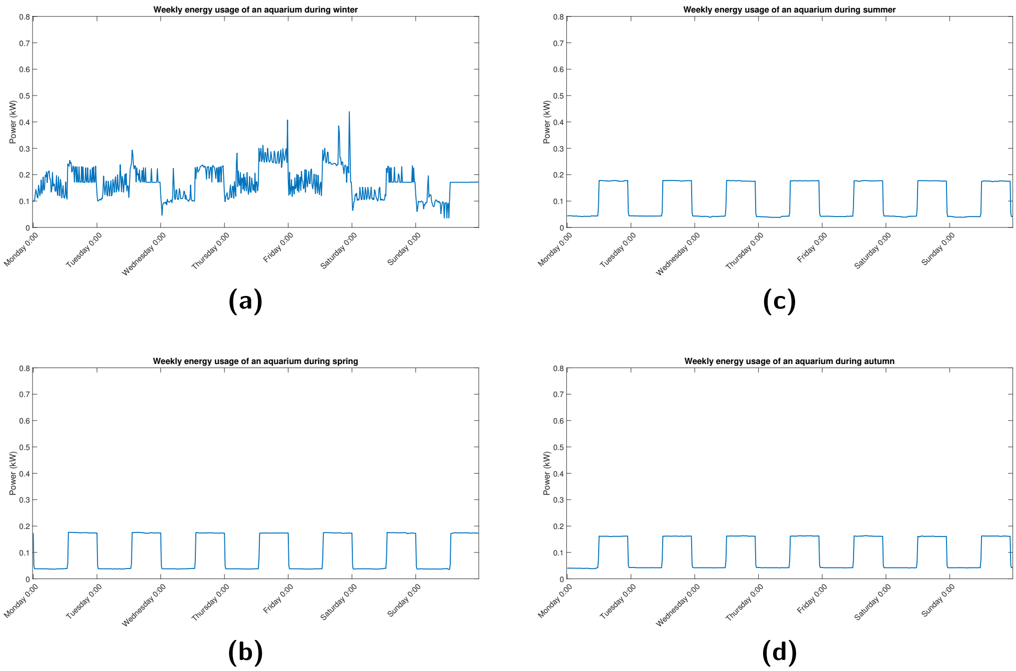


Figure 4.4: Load pattern aquarium for all seasons: (a) Winter (b) Spring (c) Summer (d) Autumn

Table 4.2: Overview aquarium consumption and peak power

	Winter	Spring	Summer	Autumn	Annual
Consumption one week (kWh)	33.41	16.91	16.32	17.47	1093.3
Maximum power (W)					439

Compensating load

The compensation load in this thesis covers the small appliances, who are not separately described. The compensating load is a load that is always present and requires the same amount of energy at any time. Some energy users in a household are minimal and are not taken into account separately. Examples of those energy users are: TV standby mode, router, the clock on microwave/oven, mobile phone charger and printer. The estimated load that is always present is set on 125 Watt.

Total base load

The total base load in a regular household is simulated as the combination of the load pattern of an aquarium, a fridge-freezer and an always present compensating load. The compensating load is to compensate for household appliances that are not specifically explicitly treated in the load chapter. The base load is never zero, which is likely because of all appliances that have a stealth consumption like almost everything with a transformer.

In figure 4.5 the total base load as used in this thesis of a nowadays situation is displayed. It can be seen that the consumption in the winter time (figure 4.5a) is higher than in the rest of the seasons. This is a possible load pattern and not the load pattern of every household in The Netherlands. The maximum power of the base load does not exceed 782.1 Watt. The corresponding numbers are in table 4.3.

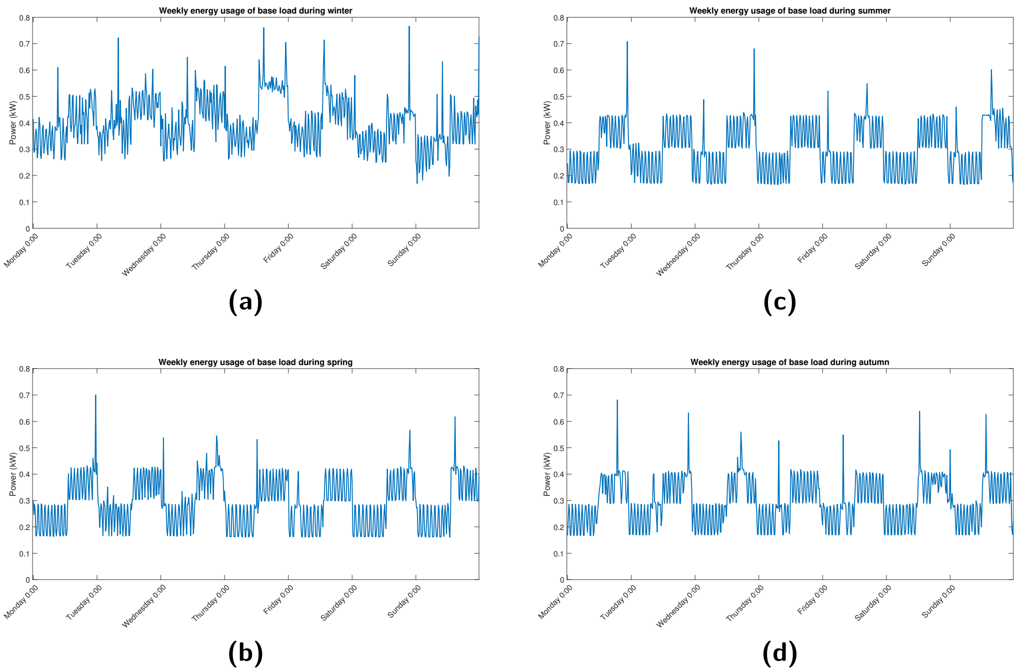


Figure 4.5: Load pattern base load for all seasons: (a) Winter (b) Spring (c) Summer (d) Autumn

Table 4.3: Overview base load consumption and peak power

	Winter	Spring	Summer	Autumn	Annual
Consumption one week (kWh)	67.4	49.3	49.8	50.3	2818.8
Maximum power (W)					782.1

4.2.2 Stochastic load

Stochastic loads are loads that are present in a household, but their consumption is not predetermined. In theory, a stochastic load can be switched on at any time. However, the probability that a specific appliance is switched on at a particular time can be low or high. Examples of stochastic loads are a stove, microwave, oven, television, computer and lights. This part describes stochastic loads that are significant contributors to the load pattern of the house.

Stove

A kitchen stove is essential in a household for preparing food. Food is prepared multiple times per day. The stove is not always used during those preparations, but can be used if necessary. Figure 4.6a corresponds to the power demand during a week in the winter and figures 4.6b, 4.6c and 4.6d for a week in spring, summer and autumn respectively. The data for these figures is created as dataid 1310 by the Pecan Street Project in Austin, Texas. This data is compared (and scaled) to common Dutch standards for maximum power and annual consumption of a stove. As can be seen in figures 4.6a-4.6d the use of the stove often happens at similar times. At two hours after midday and and around 18.00. The stove is not a very big load, because the use is limited in time and occurrence. Seasonal differences are not immediately visible and also not likely for using a stove. In table 4.4 the data used for the stove is listed.

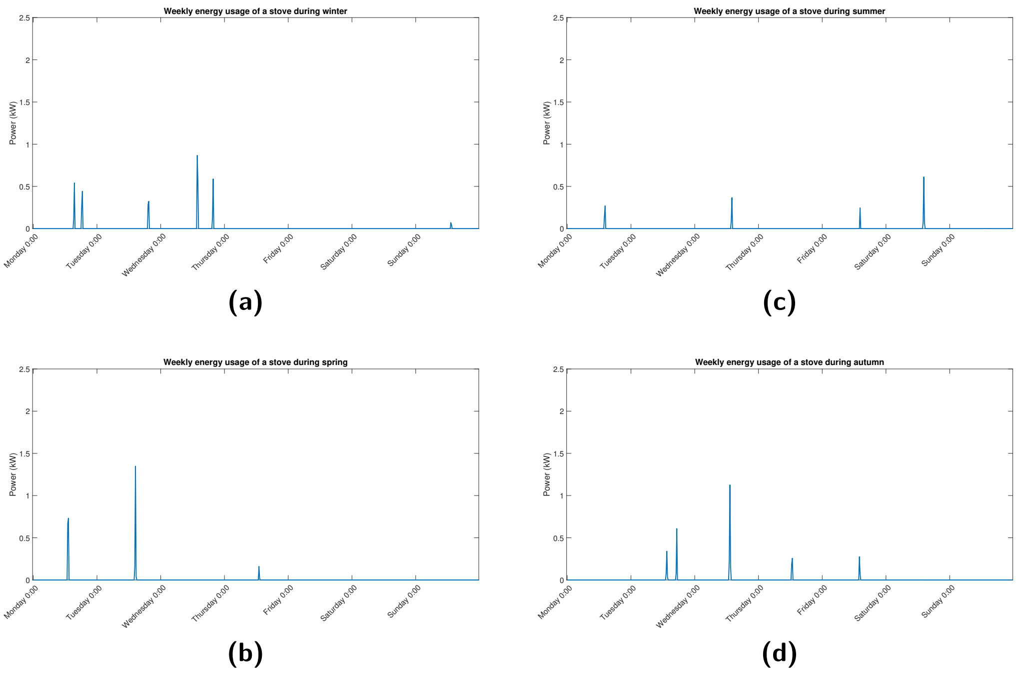


Figure 4.6: Load pattern stove for all seasons: (a) Winter (b) Spring (c) Summer (d) Autumn

Table 4.4: Overview stove consumption and peak power

	Winter	Spring	Summer	Autumn	Annual
Consumption one week (kWh)	1.06	0.78	0.86	0.47	41.3
Maximum power (W)					1360

Oven

An oven has a significant impact on the load pattern when it is used frequently. In most households this is not the case. Figure 4.7a corresponds to the power demand of an oven during a week in the winter and figures 4.7b, 4.7c and 4.7d for a week in spring, summer and autumn respectively. The data for these figures is created as dataid 26 by the Pecan Street Project in Austin, Texas. This data is compared (and scaled) to common Dutch standards for maximum power and annual consumption of an oven. In table 4.5 immediately stands out that the consumption is not regularly, in the winter the oven is used more frequently than during the summer. It is safe to say that this is not a standard use for an oven. However, it is interesting to implement a load with high peaks in the load pattern to simulate seasonal volatility of a load. The maximum power required by this oven is 2423 Watt (see table 4.5).

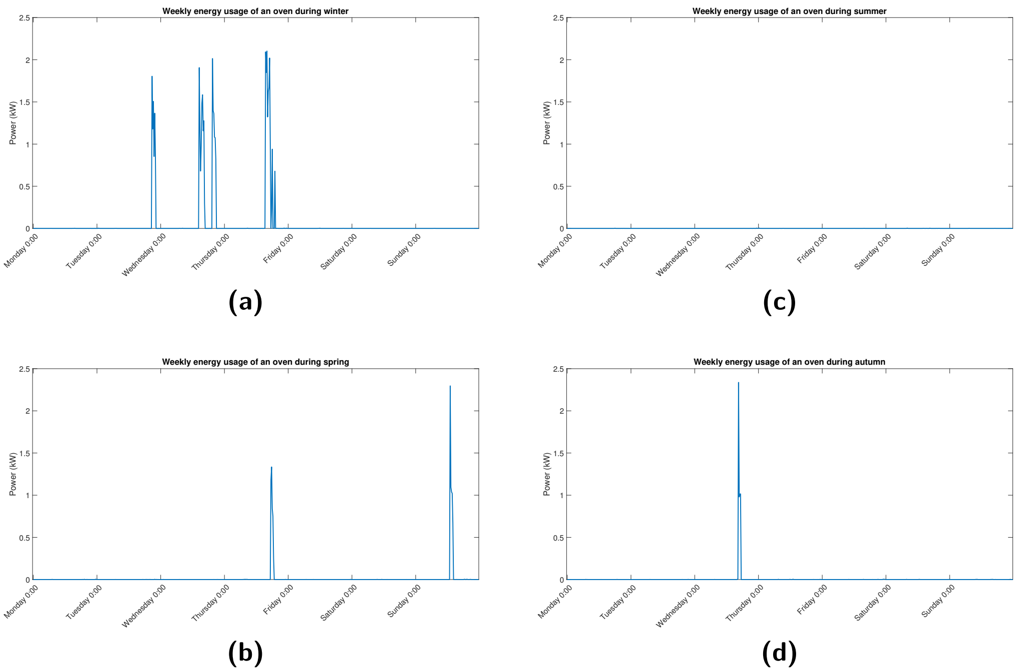


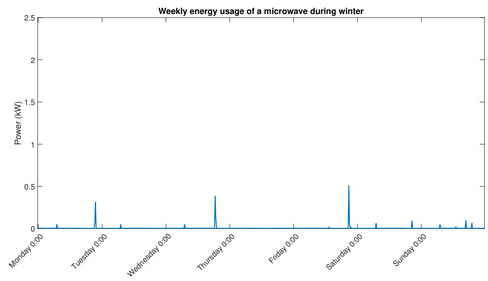
Figure 4.7: Load pattern oven for all seasons: (a) Winter (b) Spring (c) Summer (d) Autumn

Table 4.5: Overview oven consumption and peak power

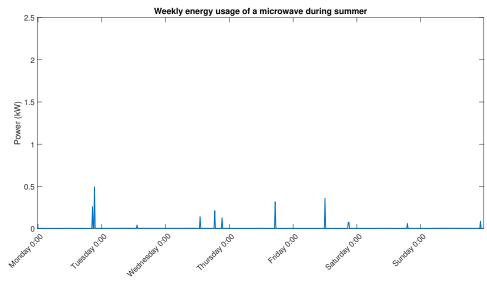
	Winter	Spring	Summer	Autumn	Annual
Consumption one week (kWh)	10.38	2.63	0.01	1.35	186.98
Maximum power (W)					2423

Microwave

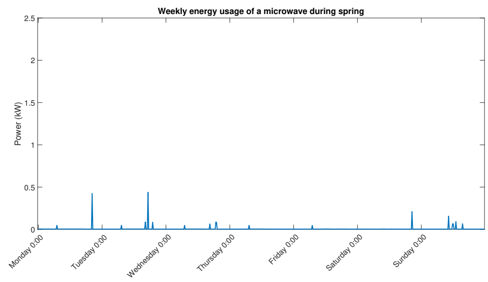
Another kitchen appliance is the microwave. A microwave is used to heat products for food preparation. Figure 4.8a corresponds to the power demand during a week in the winter and figures 4.8b, 4.8c and 4.8d for a week in spring, summer and autumn respectively. The data for these figures is created as dataid 26 by the Pecan Street Project in Austin, Texas. This data is compared (and scaled) to common Dutch standards for maximum power and annual consumption of a microwave. The occurrence is much higher than for the stove and oven, but the consumption is lower. As can be seen in figures 4.8a-4.8d the use of the stove happens at random times. It can only be concluded that (also for other appliances) the occurrence during the night (24.00-06.00) is lower than for other hours. Seasonal differences are not immediately visible and also not likely for using a microwave. The impact of the microwave is not that high as can be seen in table 4.6.



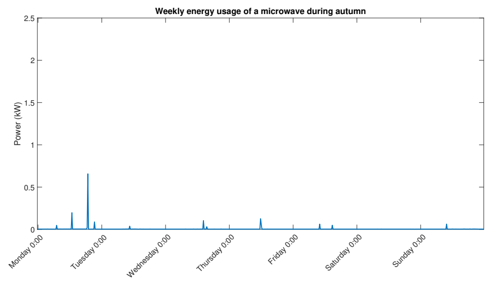
(a)



(c)



(b)



(d)

Figure 4.8: Load pattern microwave for all seasons: (a) Winter (b) Spring (c) Summer (d) Autumn

Table 4.6: Overview microwave consumption and peak power

	Winter	Spring	Summer	Autumn	Annual
Consumption one week (kWh)	1.09	1.08	1.09	0.90	53.94
Maximum power (W)					657

Total stochastic load

The total stochastic load in a regular household is simulated as the combination of the load pattern of a stove, microwave and oven. Those are not the only stochastic load appliances in a household, many other appliances can also be counted as a stochastic load. For simplicity reasons the total stochastic load consists of those three appliances. To account for a lower total stochastic load, the base load is added with an always present load of 125 Watt.

In figure 4.9 the total stochastic load as used in this thesis of a nowadays situation is displayed. It can be seen that the consumption in the winter time (figure 4.9a) is higher than in the rest of the seasons. This is a possible load pattern and not the load pattern of every household in The Netherlands. The maximum power of the stochastic load does not exceed 2427 Watt. The corresponding numbers are in table 4.7.

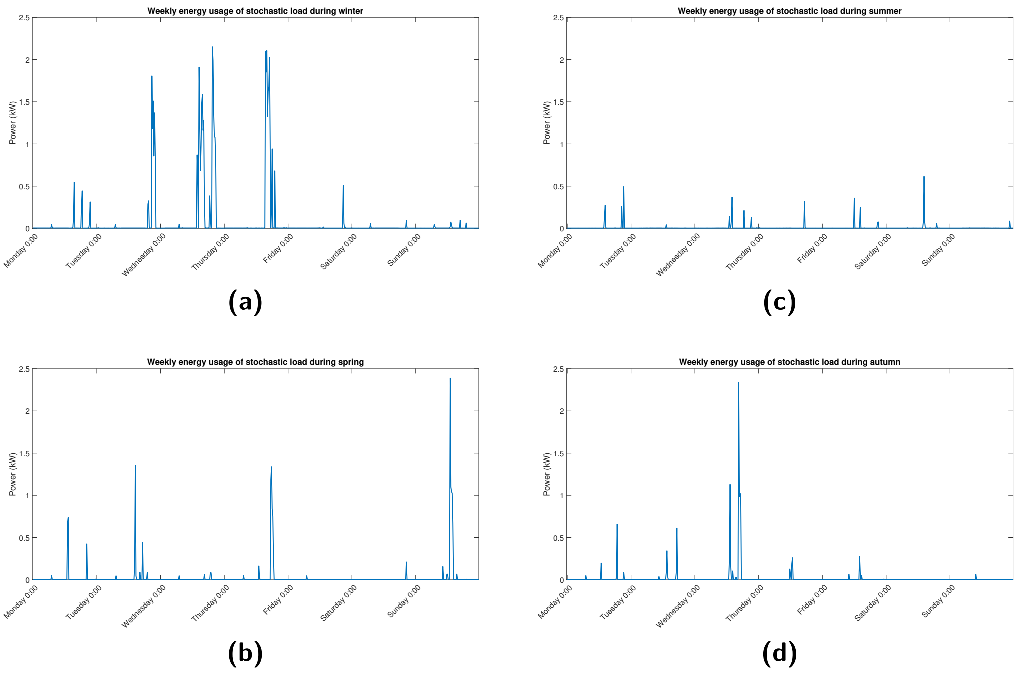


Figure 4.9: Load pattern stochastic load for all seasons: (a) Winter (b) Spring (c) Summer (d) Autumn

Table 4.7: Overview stochastic load consumption and peak power

	Winter	Spring	Summer	Autumn	Annual
Consumption one week (kWh)	12.5	4.5	3.1	1.6	282.2
Maximum power (W)					2427

4.2.3 Shiftable load

Some household appliances are very suitable to participate in a demand-side management (DSM) system. These appliances are (entirely) shiftable and can be used to create a more efficient load pattern. In a regular household are three appliances that are suitable for shifting. Those appliances need to be finished at a particular time, but the actual moment that the appliance is switched on can be changed. The three appliances treated in this part are a washing machine, dishwasher and dryer.

Washing machine

A washing machine is the first shiftable appliance that is described. A washing machine is used several times a week depending on the household formation. The consumption of a wash is very depended on the temperature of the wash cycle. A lower temperature has a lower consumption than a program with a higher temperature. The load pattern for a wash cycle can be found in figure 4.10. For simplicity reasons the number of washes per week is set to three. In figure 4.11 are displayed the uses of a washing machine when used three times a week. In table 4.8 the corresponding numbers of the figures are shown.

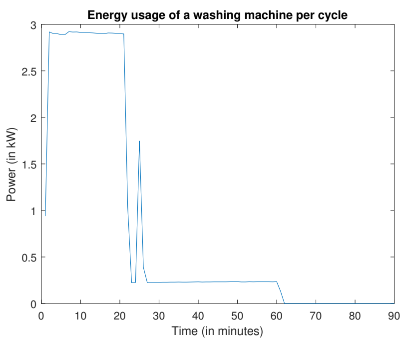


Figure 4.10: Standardized washing machine load pattern for one cycle

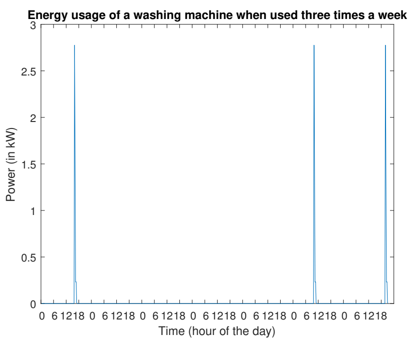


Figure 4.11: Distribution of washing machine consumption when used three times a week

Table 4.8: Overview washing machine load consumption and peak power

	One Cycle	Three times a week
Consumption one week (kWh)	1.18	3.53
Maximum power (W)	2921	2921

Dryer

A dryer is the second shiftable appliance that is described. A dryer is used several times a week depending on the household formation in accordance with a washing machine. The load pattern for a dry cycle can be found in figure 4.12. For simplicity reasons the number of dry cycles per week is set to two. In figure 4.13 are the uses of a dryer for two displayed. In table 4.9 the corresponding numbers of the figures are shown.

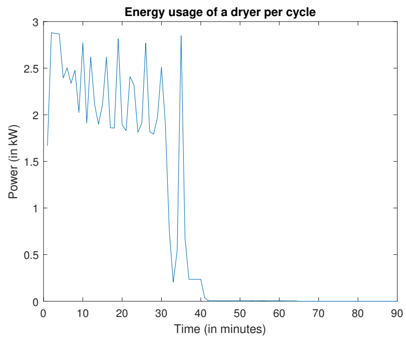


Figure 4.12: Standardized dryer load pattern for one cycle

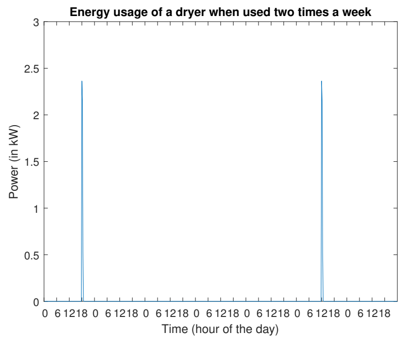


Figure 4.13: Distribution of dryer consumption when used two times a week

Table 4.9: Overview dryer load consumption and peak power

	One Cycle	Two times a week
Consumption one week (kWh)	1.26	2.52
Maximum power (W)	2881	2881

Dishwasher

A dishwasher is the last shiftable appliance that is described. A dishwasher is used several times a week depending on the household formation. Two times a day can also occur. The load pattern for a dishwasher cycle can be found in figure 4.14. For simplicity reasons the number of dishwasher cycles per week is set to five. In figure 4.15 are the uses of a dishwasher displayed for five times a week. In table 4.10 the corresponding numbers of the figures are shown.

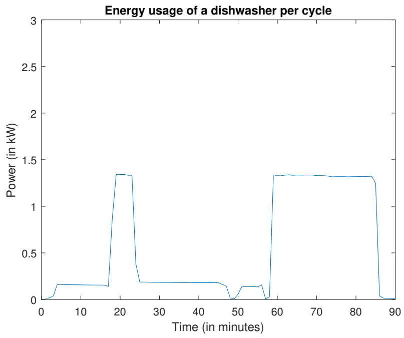


Figure 4.14: Standardized dishwasher load pattern for one cycle

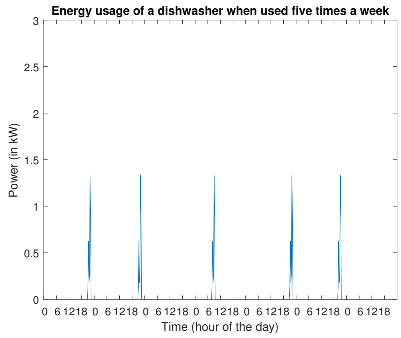


Figure 4.15: Distribution of dishwasher consumption when used five times a week

Table 4.10: Overview dishwasher load consumption and peak power

	One Cycle	Five times a week
Consumption one week (kWh)	1.34	6.72
Maximum power (W)	1343	1343

Total shiftable load

The total shiftable load in a regular household is simulated as the combination of the load pattern of a washing machine, dryer and dishwasher. Those are not the only shiftable appliances in a household, many other appliances can be shifted as well. However, those appliances have a low consumption or do not often occur in ordinary households. An example is charging a mobile phone. Within limits it can be shifted to a different time. When a mobile phone is connected to its charger just before the night, the only demand is that it is fully charged when the owner wakes up. It does not matter when the phone is charged during the night hours. Nonetheless, the impact on the load pattern of the total shiftable load is minimal.

In figure 4.16 the total shiftable load as used in this thesis is displayed. The total shiftable load pattern is a possible pattern and is not valid for every household in The Netherlands. The maximum power of the shiftable load does not exceed 2921 Watt. The corresponding numbers are in table 4.11.

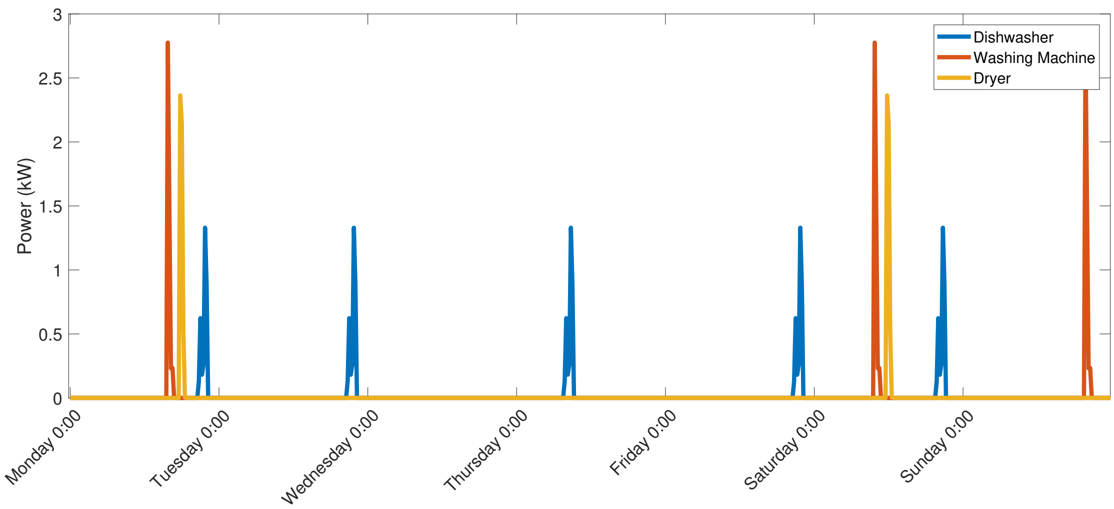


Figure 4.16: Distribution of shiftable load uses when DW(5), WM(3) and DM(2) are used

Table 4.11: Overview shiftable load consumption and peak power

	532 case
Consumption one week (kWh)	12.77
Maximum power (W)	2921

4.3 Home Battery

Without a fixed home battery, energy has to be stored on the main grid. In this thesis the house has a home battery, where solar energy can be stored. The simulation investigates multiple energy configurations for the balance between the PV panel installation and the home battery. It is always a cost trade-off. The higher the capacity of the battery, the higher the investment in the battery.

The battery technology that is used for this thesis, is based on Li-ion. Nowadays the most common storage technology for home batteries and batteries in EVs. There are already Li-ion home batteries on the market, as stated in chapter 2. The cost of a Li-ion battery is fixed on €500/kWh.

4.4 Analysis of EV batteries

The battery is the fuel tank in an EV. Tesla reinvented the EV and made people enthusiastic about their EVs. Several other car manufactures followed and it is likely that the EV wins the first war against other powered cars like hydrogen-based cars for example. The capacity of the batteries used in EVs ranges from a few kWh (plug-in hybrid) up to hundred kWh for the top model from Tesla Motors.

For this part eight EVs are chosen, who are very popular these days. The selected cars are:

- Tesla Model S Long Range
- Jaguar I-Pace
- Audi e-tron 55 Quattro
- Tesla Model S Standard Range
- Tesla Model 3 Long Range
- Opel Ampera-e
- Nissan Leaf
- Volkswagen e-Golf

All the EVs have their specific battery capacity and consumption per kilometre. To get an estimation of the battery capacity left, that can potentially store energy for the house, the commuting traffic is set to 35, 50 and 65 kilometres one way. At this point, a reserve is introduced, which is the value of driving a hundred kilometres in the EV. This reserve prevents (too much) discomfort for the EV owner, so he can take detours and for any arising emergencies.

In table 4.12 the battery capacity and consumption for each EV is listed. Immediately noticeable is that the battery capacity varies from 32 to 95 kWh, which is quite a difference. The consumption of the EVs are closer together; only the Jaguar and Audi are outliers when comparing the consumption.

Table 4.12: Overview battery capacity and consumption of eight EVs

EV	Capacity (kWh)	Consumption (kWh/100km)
Tesla Model S Long Range	95	19
Jaguar I-Pace	84.7	22.3
Audi e-tron 55 quattro	83.6	22.3
Tesla Model S Standard Range	75	18.8
Tesla Model 3 Long Range	74	16.4
Opel Ampera-e	58	16.8
Nissan Leaf	38	16.5
Volkswagen e-Golf	32	16.8

As stated earlier the commuting traffic is set to 35, 50 and 65 one way. When the commuting traffic consumption and the reserve is taken into account, the storing potential of the several EVs is displayed in figures 4.17a-4.17c. The differences as a result of the increased commuting traffic are visible. The storage potential of the EV with the smallest battery capacity is close to zero, when the commuting traffic is 130 kilometres. Before the simulation can already be concluded that not all EVs are suitable to be part of an EMS. Another conclusion that the commuting traffic determines if the EV can help the house, can also already been drawn.

In 2016 the average commuting traffic in The Netherlands was, according to the Statistics Netherlands (CBS) [58], 22.3 kilometres one way. This is an average, so also many commuters drive more. The case with a total of hundred kilometres is used to make a safe assumption.

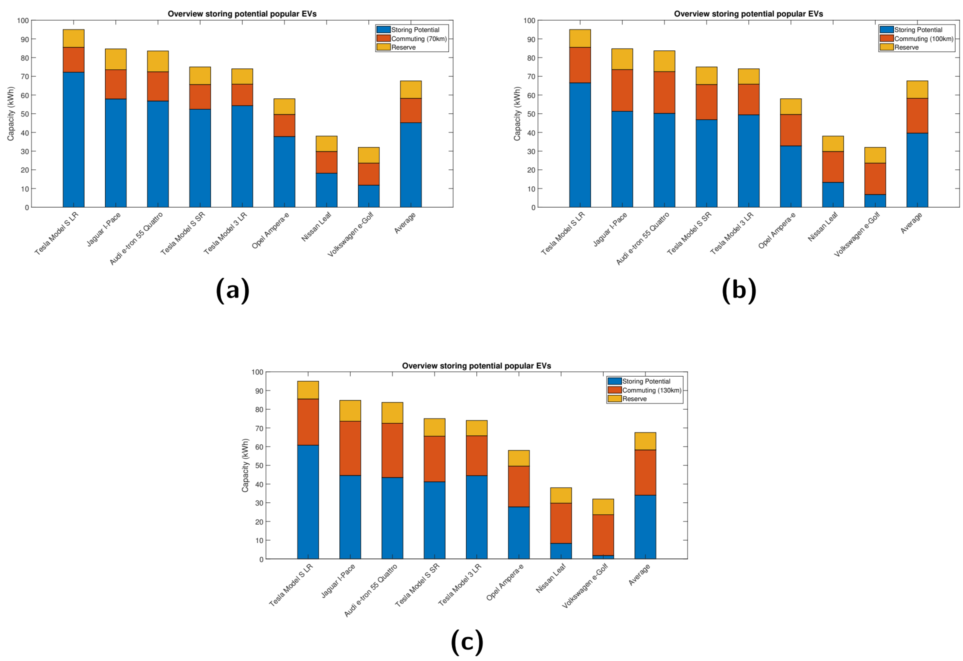


Figure 4.17: Breakdown battery capacity (a) 70km commuting traffic (b) 100km commuting traffic (c) 130km commuting traffic

As can be seen in figure 4.17 the average storing potential is 45, 39, 34 kWh for 70, 100, 130 kilometres commuting traffic respectively. The potential of the battery is one side of the case. The amount of energy that the EV can be charged on a day and the amount of energy that is needed at home are equally important. Those two aspects are later discussed in this thesis.

4.5 Miscellaneous

This section covers the parts that are worth mentioning but are too small for an own paragraph. This section contains pricing, location and grid connection.

4.5.1 Pricing environment

The choice of the pricing environment is an important one. For this thesis the pricing is done with a two tariff strategy. One tariff of €0.2202/kWh for the period between 7 AM and 9 PM and a tariff (night tariff) of €0.2062/kWh between 9 PM and 7 AM. The price for selling a kWh to the grid is specified for each case in the next chapter.

4.5.2 Location of the smart house

The location of the simulation is fixed and is located in The Netherlands. The azimuth (185) and altitude (28) are optimised for a solar panel installation in The Netherlands. The differences between places in The Netherlands are marginal since it is a flat country without much surface. It can be assumed that the simulation results are valid for the entire country.

4.5.3 Grid connection

The simulated house is grid-connected at all times, the microgrid does not have the goal to be able to run in islanding mode. The simulation is allowed to buy and sell energy from/to the grid. Buying cheap energy with the only intention to sell it back to the grid for a higher price at a later time, is not allowed.

Chapter 5

System Sizing Optimisation Results

This chapter covers the simulation results of the models described in the previous chapter. All cases are evaluated by the system sizing optimisation program, except the house without locally produced PV energy. In that case the house does not have a PV installation, and without an installation the optimisation program has no advantage. The chapter focuses on the following cases:

- Case A: house without locally produced PV energy
- Case B: house without locally produced PV energy with load shifting
- Case C: house with PV installation and home battery
- Case D: house with PV installation and home battery with load shifting
- Case E: house with PV installation, home battery and standard EV
- Case F: house with PV installation, home battery and standard EV with load shifting
- Case G: house with PV installation, home battery and smarter EV
- Case H: house with PV installation, home battery and smarter EV with load shifting
- Case I: house with PV installation, home battery and charged EV
- Case J: house with PV installation, home battery and charged EV with load shifting

To judge the results of each case, except case A and B, the cases are evaluated on three classifications. All these classifications are related to the capital cost.

- Grid energy autonomy (GA)
- Peak shaving capability (PSC)
- Electricity cost (EC)

5.1 Case A/B: house without locally produced PV energy

Case A and B are the cases to simulate a house that has no PV installation, EV or own storage facility. This is still valid for the majority of the households in The Netherlands. These cases are included for comparison reasons, no new aspects are applied. The shiftable loads are distributed throughout the week in a way that the shiftable appliances are used at various times. The dishwasher, washing machine and dryer are used five, three and two times respectively each week. In the Netherlands many households have a double tariff energy meter in their homes. This is taken into account for both cases. The overview of the specifications for case A can be found in table 5.1.

Table 5.1: Overview specifications case A and B

	Case A	Case B
Annual energy consumption 7AM-9PM (kWh)	2394	2038
Annual energy consumption 9PM-7AM (kWh)	1256	1612
Total annual consumption (kWh)	3650	3650
Peak power (W)	2891	2891
Annual EV consumption (kWh)	0	0

The load profile for case A can be seen in figure 5.1. The load pattern of case B (figure 5.2) is created to apply load shifting to the load pattern of case A. All shiftable appliances are shifted to a lower electricity price window case, this is only the case when households have a double tariff energy meter in their homes. It depends on the location of the house if the electricity tariff is lower between 11PM and 7AM or between 9PM and 7AM. For this thesis the shiftable loads are shifted with the 9PM-7AM time frame taken into account.

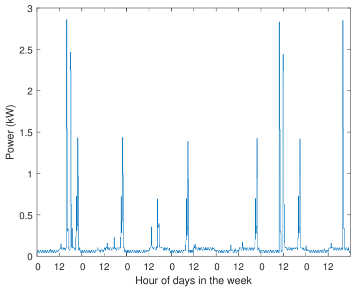


Figure 5.1: Standard load pattern of case A

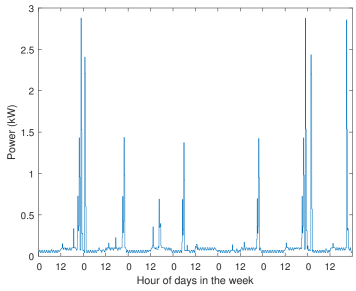


Figure 5.2: Shifted load pattern of case B

Cost Analysis

The two-tariff system in The Netherlands has been invented to reduce the difference between the daily and night energy usage. Fossil fuel power stations work more efficient when evenly used throughout the day. With the recent developments of RES penetration the concept is a bit old fashioned, because solar energy is mainly generated during daytime. Using energy during daytime is then more desirable. Reducing the overall cost for case A is only possible when the shiftable appliances are using energy between 9PM and 7AM (case B). The day kWh tariff used is €0.21654 and for the night tariff €0.20183 per kWh. In table 5.1 the annual cost of case A and B can be found.

	Case A	Case B
Annual EC (€)	772.03	766.66

Conclusion

In this part the total electricity bill has been reduced by 0.70% when applying tariff based shifting on the shiftable appliances. The household does not have any solar power installed and thus all shiftable appliances that are used during the daytime are shifted to the nighttime. For a house without PV energy and home battery the cost reduction is marginal with a reduction of €5.37 (0.70%).

5.2 Case C/D: house with PV installation and home battery

The first step for a household to become a smart house with a microgrid is the generation of electricity with RES. In this thesis the focus is entirely on a PV integrated house, which is the most common energy source for a single household. Case A and B are about a house that has no PV installation and battery. Compared to those cases, case C and D vary on a few aspects. Now the house does have a PV installation and battery. Also the load shifting algorithm is not directly based on the price anymore, but takes the solar generation into account. The specifications for case C and D can be found in table 5.2.

Table 5.2: Overview specifications case C and D

	Case C	Case D
Yearly consumption 7AM-9PM (kWh)	2394	2535
Yearly consumption 9PM-7AM (kWh)	1256	1115
Total yearly consumption (kWh)	3650	3650
Peak power (W)	2891	2891
Yearly EV consumption (kWh)	0	0

The load profile of case C is equal to the one used in the previous section (case A). To make a fair comparison between the case, the load profile is kept the same. The standard load pattern (case C) can be found in figure 5.3. The load pattern in figure 5.4 is the pattern of case D with the shiftable appliances shifted to their best place, according to the algorithm as described in chapter 3. The shiftable appliances are mostly shifted to noon every day. This is a direct impact of the solar radiation for the location in The Netherlands. When a different location is used the shiftable appliances will be shifted into the morning or evening, depending on the distance from the equator.

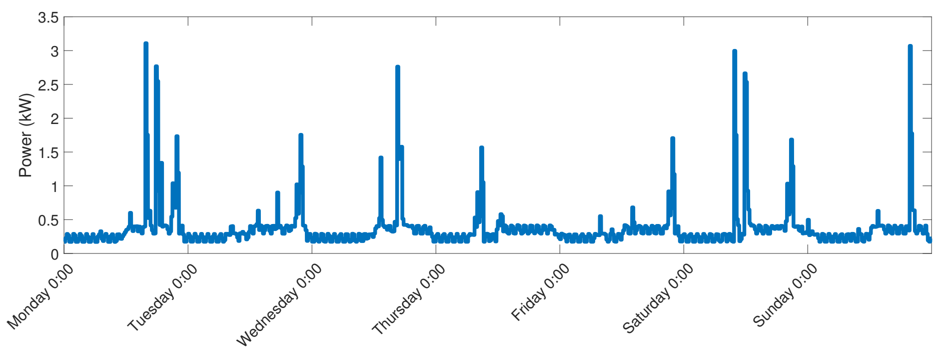


Figure 5.3: Standard load pattern of case C

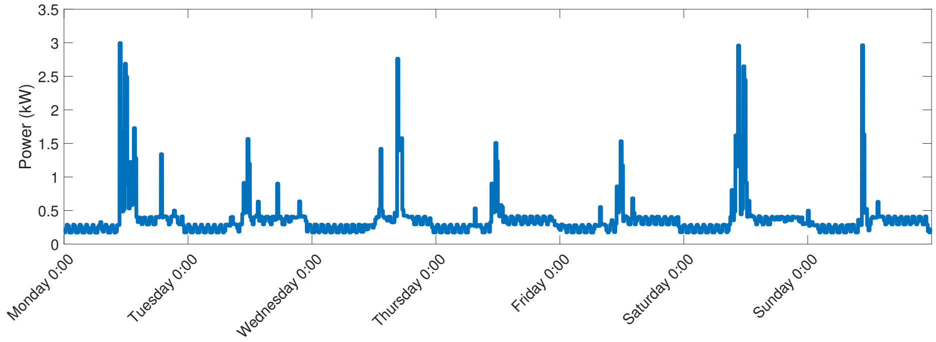


Figure 5.4: Shifted load pattern of case D

Optimisation result

In figure 5.5 the grid energy autonomy is displayed for case C and D. The differences between the two cases are marginal. However, it is still visible that the shifted case D has a higher grid energy autonomy than the standard case C for the same capital cost (PV with battery system). When case C and D are compared on peak shaving capability in figure 5.6, the shifted load pattern of case D leads to a significant increase in the peak shaving capability. Case C and D can reach high levels of grid energy autonomy and peak shaving capability when the PV system and home battery capacity is increased. The capital cost is increased significantly in those cases.

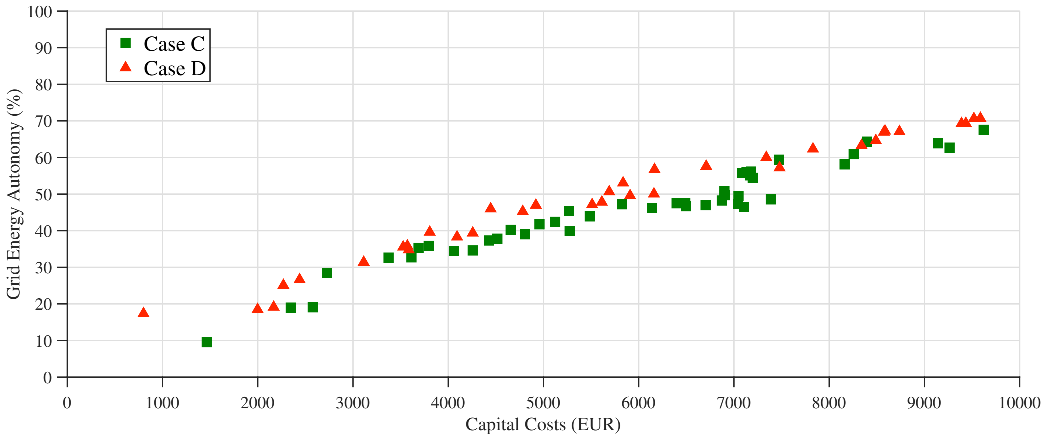


Figure 5.5: Grid energy autonomy for case C and D

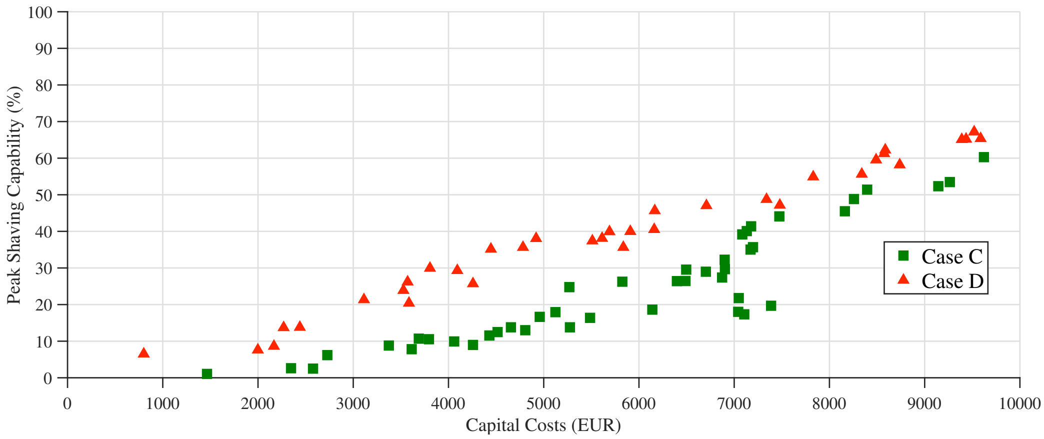


Figure 5.6: Peak shaving capability for case C and D

Shifting leads to a higher grid energy autonomy and peak shaving capability for the same system. In tables 5.3 and 5.4 the grid energy autonomies and peak shaving capabilities for four systems are displayed in more detail. Shifting leads in grid energy autonomy to a relative increase of 5-34% (3-11% absolute). The peak shaving capability compared between case C and D ranges from relatively 8-431% with absolute increases of 5 to 22%.

Table 5.3: Grid energy autonomy comparison of case C and D

Capital Cost	Case C(%)	Case D(%)	abs. increase(%)	rel. increase (%)
2350	19	26	7	34
4250	34	39	5	14
6150	46	57	11	23
9600	68	71	3	5

Table 5.4: Peak shaving capability comparison of case C and D

Capital Cost	Case C(%)	Case D(%)	abs. increase(%)	rel. increase (%)
2350	3	14	11	431
4250	9	26	17	187
6150	19	41	22	118
9600	60	65	5	8

Cost Analysis

The market cost is the annual electricity cost for a load pattern. If the system is generating more electricity than the yearly consumption, the energy is sold to the main grid. When the capital cost (and thus the number of PV panels or battery capacity) increases, the surplus of energy grows and is sold to the main grid. The market cost can become negative in that way. In figure 5.7 the market cost is given for case C and case D. Shifting leads to a reduced cost of electricity for every PV with battery system. The extra cost reduction that is achieved when load shifting is applied, varies from 3.7-10.6% (see table 5.5).

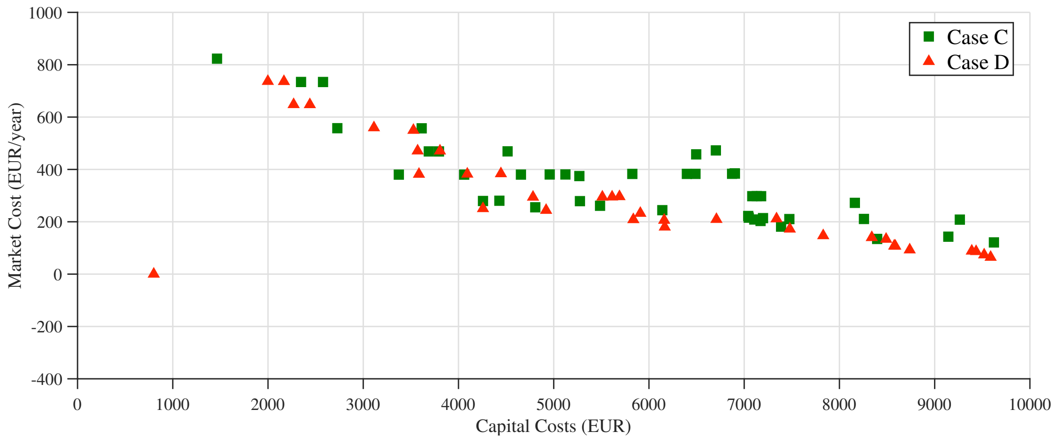


Figure 5.7: Case C and D: market cost

Table 5.5: Market cost case C versus case D

Capital Cost	EC Case C(€)	EC Case D(€)	shifting cost reduction(%)
2350	734	648	10.6
4250	279	251	3.7
6150	244	206	4.9
9600	121	65	7.3

Conclusion

In this part the case of a house with PV and battery is investigated. In case D the shifting algorithm leads to better overall performance for the house based on grid energy autonomy, peak shaving capability and market cost. The grid energy autonomy increases by 5-34%. Even larger relative increases are seen with the peak shaving capability, namely 8-431%. Shifting also leads to a reduction in the cost of electricity (3.7-10.6%). Intelligent load management is beneficial for a house with PV and battery.

Comparing the cost of electricity of case D for a €4,250 system to case A with the same capital cost, gives an annual savings of €521 (with a market selling price of €0.092/kWh and no grid storing costs for using the utility grid). This corresponds to a payback time of 8.2 years.

5.3 Case E/F/G/H: house with PV installation, home battery and EV as load

The smart house of tomorrow consists, besides a PV installation and battery, also an EV. The EV can be charged in different ways. This case is to show that the EV is has a significant impact on the grid energy autonomy and peak shaving capability when it is charged at home in combination with a PV installation and battery. Case E simulates that the EV starts immediately charging when plugged in at home. Case F is the shifted version of case E.

Charging an EV can be done at many different power rates and times. To simulate a more intelligent way of charging an EV, the charging curve is flattened for the entire time of the curve. To get that different charging curve, the start and end time of the charging cycle is taken into account. In combination with the required energy needed, the power rate for the entire time window is calculated. This has as downside that the EV is only fully charged when the assumed departure time is kept the same or postponed. The load pattern is different than for the cases with the standard EV. However, in this way the impact of the charging curve can be made transparent. This is definitely not the optimal way to charge an EV, but it indicates if an improvement can be achieved by tweaking the EV's charging load curve. The specifications for case E, F, G and H can be found in table 5.6.

Table 5.6: Overview specifications cases E/F/G/H

	Case E	Case F	Case G	Case H
Annual consumption 7AM-9PM (kWh)	7536	7676	5408	5548
Annual consumption 9PM-7AM (kWh)	6635	6475	8753	8613
Total annual consumption (kWh)	14161	14161	14161	14161
Peak power (W)	8132	7528	6528	6528
Annual EV consumption (kWh)	10510	10510	10510	10510

The charging curves are added to the load profiles of cases C and D. The peaks in the load pattern increase immensely in comparison with the cases where no EV was present. In figure 5.8 the load is displayed for the case E when no shifting algorithm is applied. The load peaks are going up to 7.5kW when the EV is charged and one of the household appliances is used. In figure 5.9 is the load pattern of case F displayed, the peaks are lower after applying the load shifting algorithm. For case G and H the load patterns are represented in figure 5.10 and 5.11 respectively. It can be noticed that the peaks are lower than the peaks of case E and F in figures 5.8 and 5.9.

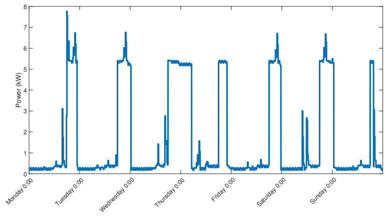


Figure 5.8: Standard load pattern of case E

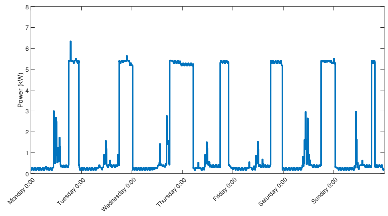


Figure 5.9: Shifted load pattern of case F

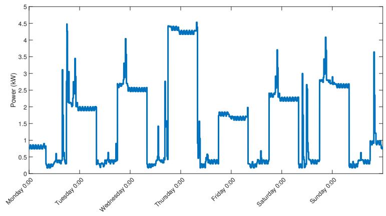


Figure 5.10: Standard load pattern of case G

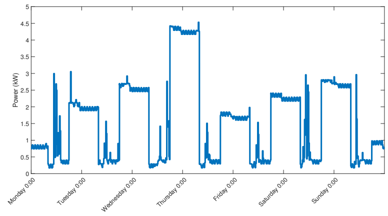


Figure 5.11: Shifted load pattern of case H

Optimisation result

In this part the optimisation of the battery and solar panel system is done to evaluate the shifting algorithm for this case. When figure 5.12 is studied the low grid energy autonomies are immediately noticeable. The massive load as the EV is, has a high influence on the load pattern and therefore has a negative impact on the grid energy autonomy. To charge the EV at home with a solar panel installation leads to high investments when the grid energy autonomy level of case C and D is the goal. The space for a solar installation is limited for an ordinary household to generate a large amount of PV energy for charging the EV. There are no clear differences when the standard (case E and G) and shifted cases (case F and H) are compared on grid energy autonomy. The impact of the EV is too significant and that influences the results of the shifting algorithm. The shifting algorithm controls the dishwasher, washing machine and dryer, but have a much lower consumption in comparison to the EV load.

The peak shaving capability in figure 5.13 does not have a better result than the grid energy autonomy. When comparing case E and F, it can be noticed that case E is equal to the shifted case F or even has a slightly higher peak shaving capability. This is not a desired result of the shifting algorithm. That case E results in a higher peak shaving capability is a result of how the peak shaving capability is calculated. The calculation can be found in chapter 3. The optimisation is not capable of reducing all peaks in the load pattern with the solar installation. The EV is charged with a power of 5 kW, which is the highest power of one load in the load pattern of the house. In case F the highest peaks are only from charging the EV. In case E the peaks are sometimes an addition of the EV charging power and one or more shiftable appliances. Those peaks are reduced by the optimisation program. Hence, the worse result of shifted case F.

The optimisation of cases G and H are comparable with cases E and F. Compared to the grid energy autonomy, the peak shaving capability is more influenced. The peak shaving capability for the smarter EV case is displayed in figure 5.13. The peaks from the load pattern in figure 5.10 can be taken care of by the solar panel installation. The optimisation finds the best sizing of the PV installation and is able to shave some peaks.

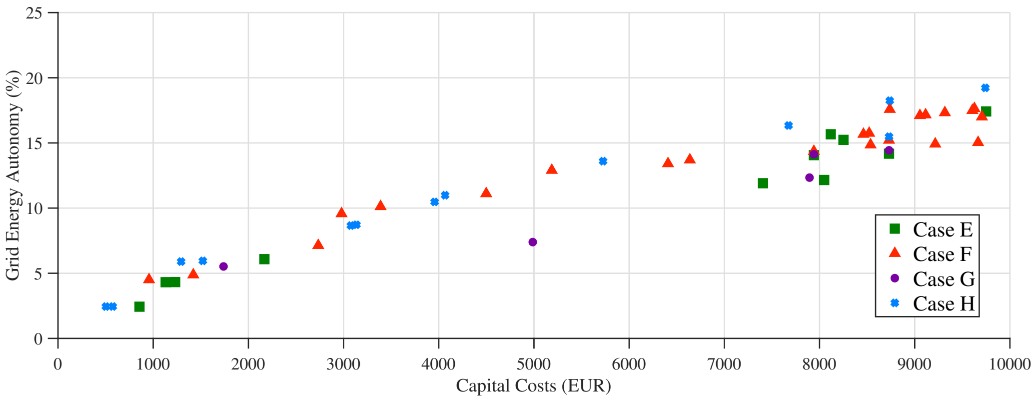


Figure 5.12: Grid energy autonomy for case E,F,G and H

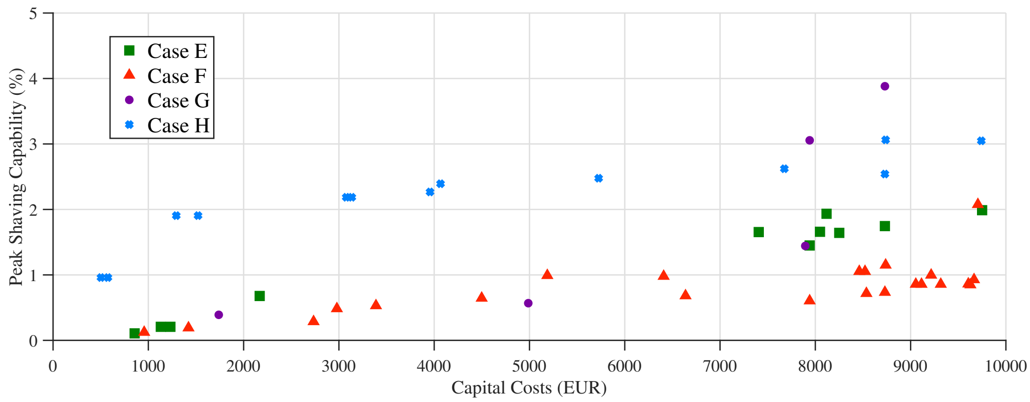


Figure 5.13: Peak shaving capability for case E,F,G and H

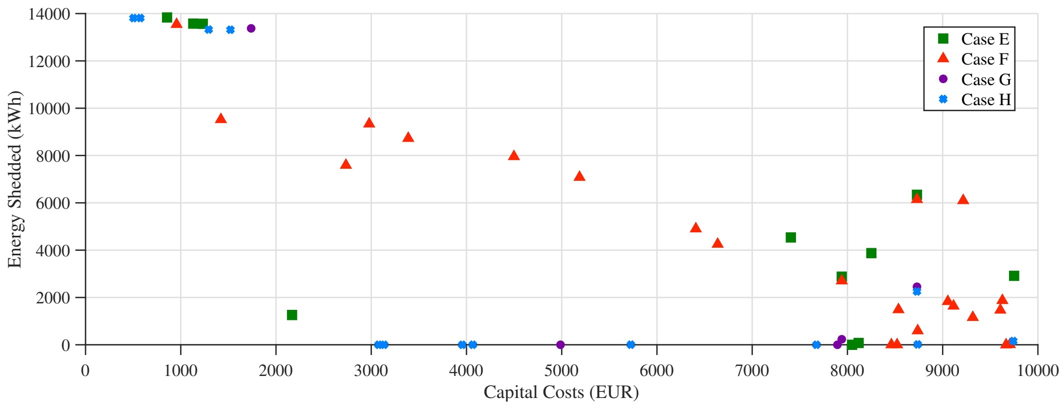


Figure 5.14: Energy shedded for case E,F,G and H

Table 5.7: Grid energy autonomy of case E, F, G and H

Capital Cost	Case E(%)	Case F(%)	Case G(%)	Case H(%)
2350	6	7	6	7
4250	8	11	5	11
6150	12	13	12	15
9600	17	18	17	19

Table 5.8: Peak shaving capability of case E, F, G and H

Capital Cost	Case E(%)	Case F(%)	Case G(%)	Case H(%)
2350	0.7	0.25	0.5	2.1
4250	9	0.65	0.6	2.4
6150	1.5	0.97	1.5	2.5
9600	2.0	2.1	4	3

Cost Analysis

For the cases when the EV is charged at home, a cost analysis is harder to make in comparison to the previous cases. Already with the peak shaving capability and grid energy autonomy the impact of the EV is very striking. In the cost analysis it is not different. In figure 5.15 the market cost for cases E-G are displayed. The zero market cost for low capital cost immediately stands out. To understand this phenomenon, figure 5.14 is included. From that figure it can be concluded that the SSO program sheds the load, instead of trying to power it. The impact of the EV with an energy consumption of 10,510 kWh is too massive. A proper cost analysis (in comparison to the previous case) cannot be made.

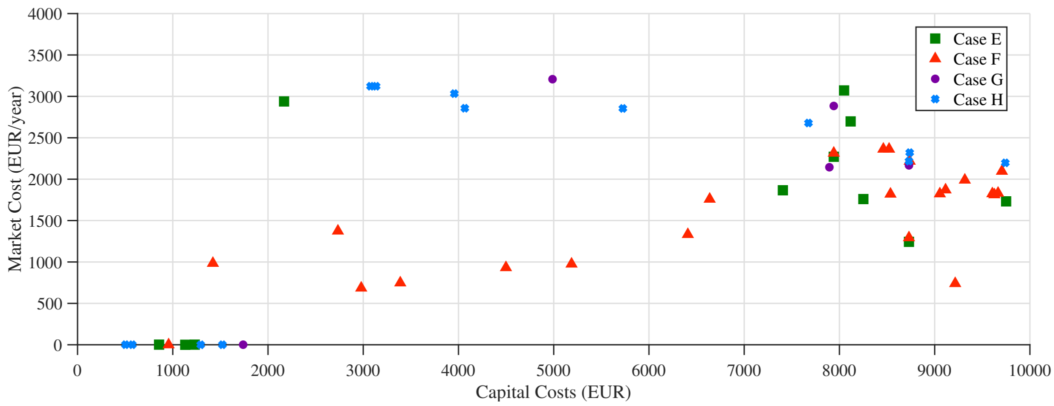


Figure 5.15: Market cost for case E,F,G and H

Conclusion

In this part the case of a house with PV, home battery and EV is investigated. This case is very different compared to the previous case without an EV involved. The differences between the standard and shifted load patterns are marginal when the grid energy autonomy and peak shaving capability is compared. The impact of the EV load is simply too large. Also a cost analysis does not make sense for this system.

5.4 Case I/J: house with PV installation, home battery and charged EV

In this section the results of cases I and J are given and discussed. In these cases is the EV charged at work and provides the house (V2H) with energy from its battery when the EV is at home. The energy needed when the EV is not at home is provided by the solar panel installation, battery or utility grid. The specifications of case I and J can be found in table 5.9.

Table 5.9: Overview specifications cases I and J

	Case I	Case J
Annual consumption 7AM-9PM (kWh)	1599	1367
Annual consumption 9PM-7AM (kWh)	2052	2284
Total annual consumption (kWh)	3651	3651
Peak power (W)	3198	2763
Annual EV consumption (kWh)	0	0

The load patterns for the cases with a charged EV are not like the other load patterns used in this thesis. The use of the EV as an energy source for the house is quite clear. When the EV is at home the load is provided by the EV, as is determined by the load shifting algorithm. Energy is not needed from the utility grid or home battery during those hours. This is the case between 6PM and 8AM (when the EV is at home). The EV itself is not charged at home. In figure 5.16 (case I) the peaks from the household appliances are well observable. The load pattern of case J in figure 5.17 does not have that many power peaks anymore. The two major power peaks that are still present are from the non-shiftable stochastic load. All power peaks from the shiftable loads are taken care of by the EV.

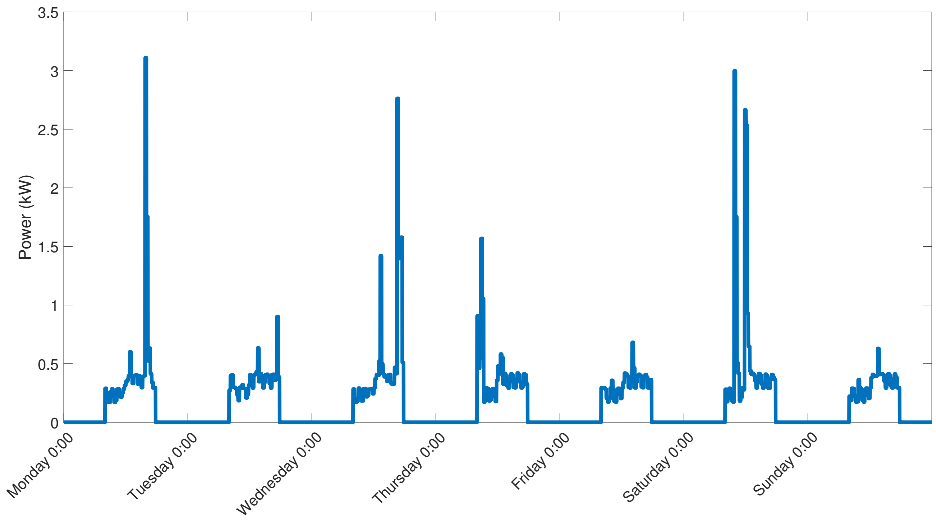


Figure 5.16: Standard load pattern of case I

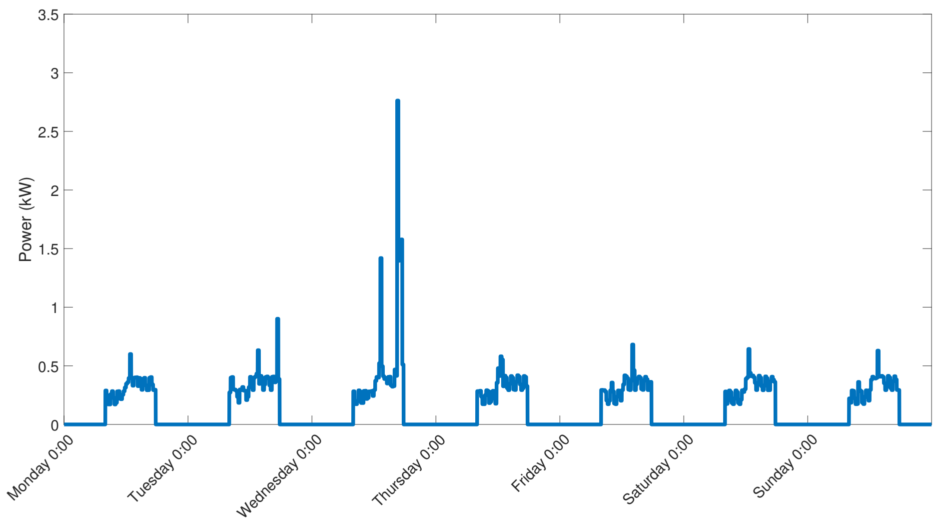


Figure 5.17: Shifted load pattern of case J

Optimisation result

Powering the house with an at work charged EV is the final case that is simulated. The optimisation is done for the house with a solar installation and battery for the times when the EV is not at home. When the EV is at home the EV provides the energy of the house, and the optimisation program does not have to power the demand for those times. It should be noted that the grid energy autonomy and peak shaving capability are for the entire day. Using the EV as an extra power source does not influence (negatively or positively) the grid energy autonomy and peak shaving capability. The cost of charging the energy at work influences the electricity cost, as is discussed in the cost analysis. The impact of the shifting algorithm is clearly visible. The shifted case J has an increased peak shaving capability and grid energy autonomy than compared to the standard case I. The algorithm has a positive effect on the grid energy autonomy and peak shaving capability. The EV provides the energy for all shiftable loads.

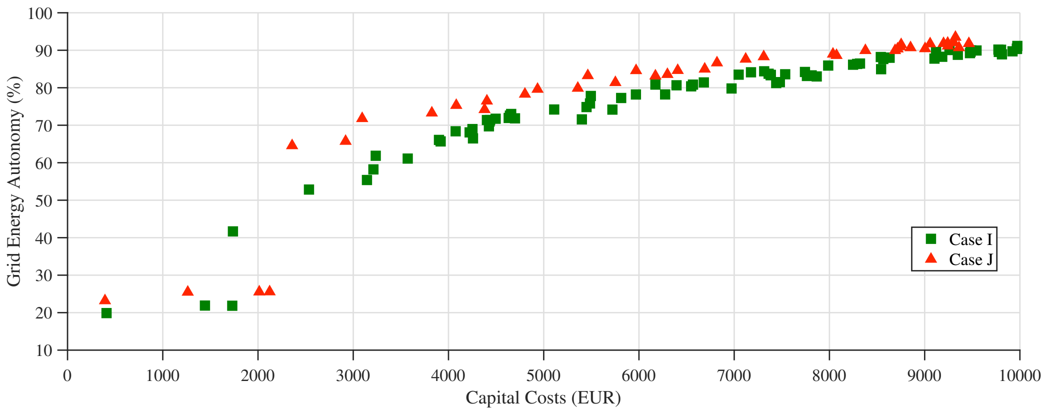


Figure 5.18: Grid energy autonomy for case I and J

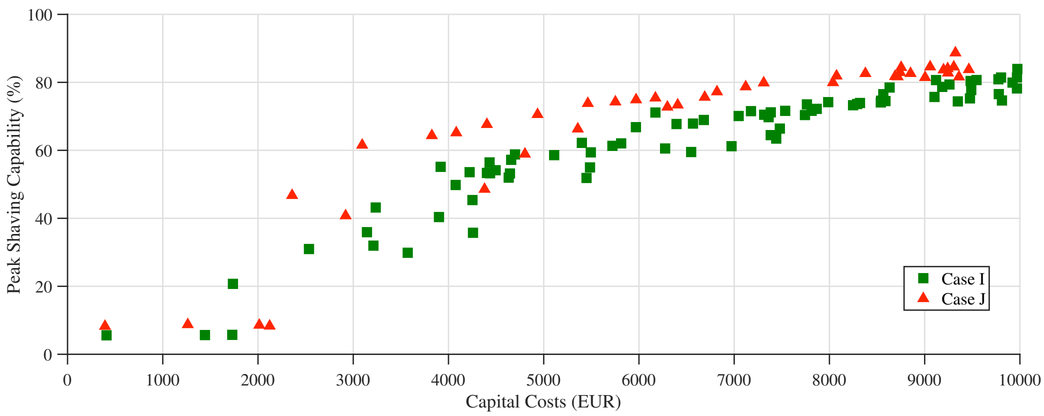


Figure 5.19: Peak shaving capability for case I and J

Shifting also leads for the charged EV cases to a higher grid energy autonomy and peak shaving capability for the same system. In tables 5.10 and 5.11 the grid energy autonomies and peak shaving capabilities for both systems are displayed in more detail. Shifting leads in grid energy autonomy to a relative increase of 3-49% (3-21% absolute). The peak shaving capability compared between case I and J ranges from relatively 11-137% with absolute increases of 8 to 28%.

Table 5.10: Grid energy autonomy comparison of case I and J

Capital Cost	Case I(%)	Case J(%)	abs. increase(%)	rel. increase (%)
2350	44	65	21	49
4250	66	74	8	11
6150	79	83	4	6
9600	89	92	3	3

Table 5.11: Peak shaving capability comparison of case I and J

Capital Cost	Case I(%)	Case J(%)	abs. increase(%)	rel. increase (%)
2350	21	49	28	137
4250	36	55	19	54
6150	65	75	10	15
9600	76	84	8	11

Cost Analysis

The cost analysis is focused on the market cost. The market cost is the annual cost of electricity for the given load pattern with the sized PV installation with home battery. In figure 5.20 the market cost for case I and J are given. The shifted load pattern has a lower market cost than the standard load pattern, although the difference is not large for every PV with battery system (capital cost). When the energy bought from the utility grid is equal to the energy sold to the grid, the net energy bought and sold to/from the grid is zero. This is called net metering and can be done up to the consumption of the house. For larger PV system the energy sold to the grid is also higher, the energy is sold for €0.092/kWh. When the market cost is negative, it means that the owner earns money. Shifting leads to a reduced cost of electricity for every PV with battery system. The extra cost reduction that is achieved when load shifting is applied, varies from 1.2-29.9% (see 5.12).

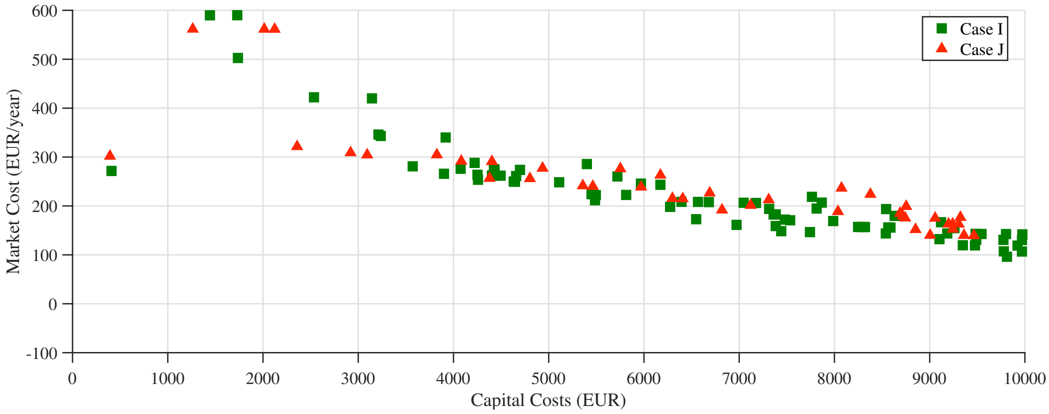


Figure 5.20: Market cost for case I and J

Table 5.12: Market cost case I versus case J

Capital Cost	EC Case I(€)	EC Case J(€)	extra cost reduction after shifting(%)
2350	230	-1	29.9
4250	-29	-49	2.6
6150	-65	-110	5.8
9600	-173	-182	1.2

Conclusion

In this part the case of a house with PV, battery and charged EV is investigated. Shifting of household appliances leads to better overall performance based on grid energy autonomy, peak shaving capability and market cost. The peak shaving capability and grid energy autonomy are increased for both cases. This can be beneficial when power peaks are charged extra and storing on the main grid is no longer free for homeowners. Comparing the results of the €4,250 system of case J to the regular house (case A), gives an annual savings of €954. This corresponds to a payback time of 4.5 years (with market selling price of €0.092, no grid storage cost and no charging tariff at work). However, the comparison with the house with PV installation is not fair when the energy provided by the EV is not paid for. Also the impact on the battery for using it and charging cost at work has to be considered. For case C and D storing on the grid is no longer free. These costs are implemented in the next section to make a fairer comparison.

5.5 Introducing grid storage cost, charging tariff at work and battery degradation cost of the EV battery

To evaluate the charged EV case, the conditions of the cases compared have to be as equal as possible. The charged EV case is compared to the other cases, but has to be adjusted to make a fair comparison. The cases where the EV is charged at home are not suitable for comparing.

The variables of the cases are altered to cover a broad variety of future pricing environment. Changing these variables give many results, due to the many possibilities. To limit the possibilities only cases B, C, I and J are investigated in detail. The variables (with values per kWh) altered are:

- Selling price to the main grid (€0.03)
- Grid storage cost (€0.00, €0.042, €0.082)
- Charging tariffs at work (€0.05, €0.09, €0.13)

The selling price to the main grid is set on €0.03 per kWh. This tariff is a prediction of the future price and currently already used by certain energy suppliers when the solar generation is higher than the consumption of the house. This lower tariff is expected with the upcoming surplus of energy from RES. On a higher level (country to country) are negative prices already used for energy trading. This is unlikely for consumers, but a lower tariff for feeding the surplus of energy to the grid is realistic.

The grid storage cost is a result of the high penetration of RES. Currently the energy of RES can be "stored" on the utility grid. However, when more and more consumers feed energy into the grid, this becomes a real challenge for the grid and its operator. Storage on the grid can no longer be free of charge, so the grid storage cost is introduced. To see the impact of the grid storage cost, three tariffs are used. No cost, a cost of €0.042/kWh and a storage cost of €0.082 per kWh.

The third term is the charging tariffs at work. The energy that the EV provides to the house, is not free of charge at work. This tariff is set on €0.05,€0.09 and €0.13 per kWh. In combination with the degradation of the EV's battery with €0.042/kWh, those tariffs become €0.092,€0.132 and €0.172 per kWh. A higher price is also possible, but then the total price is too close to the market price (around €0.22). In that case using the EV as a power source is not beneficial anymore. The charge and discharge efficiency (Li-ion batteries have a round trip efficiency of 95%) of the EV's battery are not taken into account.

Influence of grid cost for cases D and J

This section investigated the influence of increasing the grid storing cost on the electricity cost of the various cases. In tables 5.13 and 5.14 the electricity costs for several PV with home battery system are displayed for different grid storing costs.

The influence of grid storing is more substantial for smaller PV with battery systems. When the battery capacity is lower, more energy has to be stored on the grid. In that way the energy can later be used for powering household load when energy cannot be generated by solar energy at night.

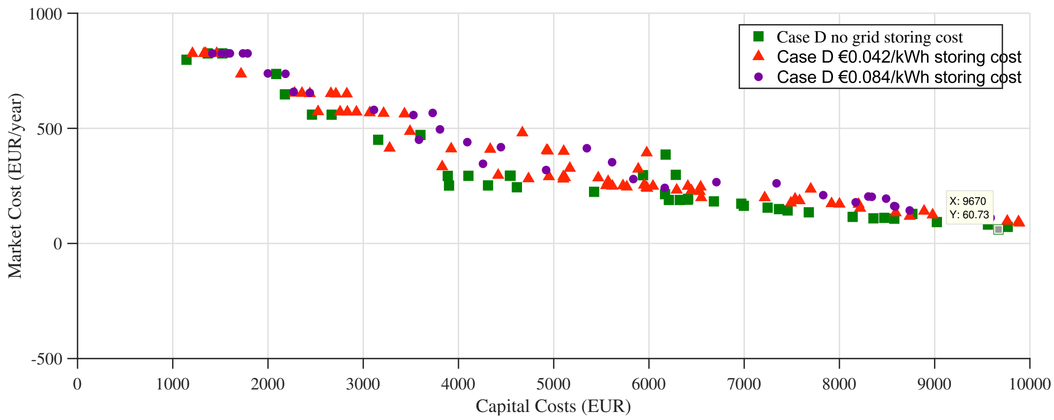


Figure 5.21: Annual electricity cost for case D for different grid storing costs

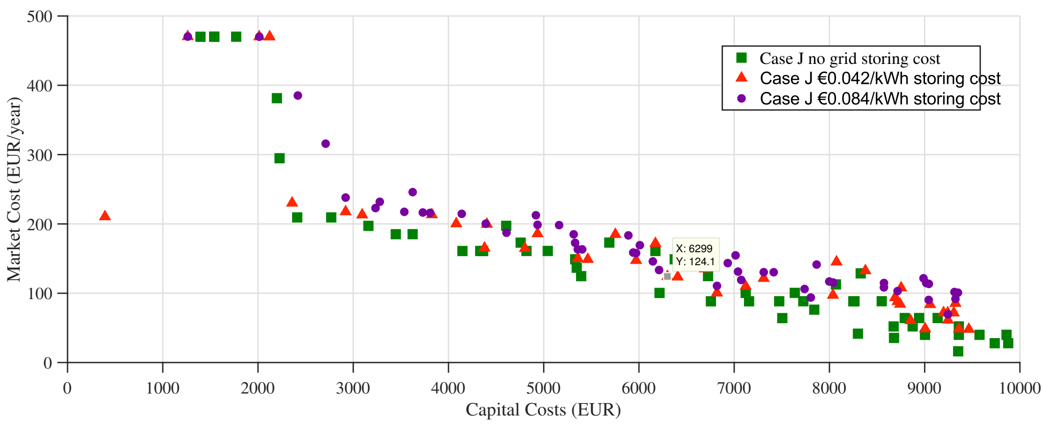


Figure 5.22: Annual electricity cost for case J for different grid storing costs

Table 5.13: Relative cost increase of grid storage cost (GS) for case D

Capital Cost	€0.042/kWh GS (%)	€0.084/kWh GS (%)	absolute increase
2350	12	12.4	0.4
4250	5.8	12.2	6.4
6150	2.3	3.5	1.2
9600	4.7	7.9	3.2

Table 5.14: Relative cost increase of grid storage cost (GS) for case J

Capital Cost	€0.042/kWh GS (%)	Cost increase €0.084/kWh GS (%)	absolute increase
2350	2.7	22.8	20.1
4250	0.6	6.9	6.3
6150	3.1	5.9	2.8
9600	1.0	3.8	2.8

Influence of charging at work cost

This section investigated the influence of increasing the charging at work cost per kWh on the electricity cost of the various cases. Charging costs only occur in cases with a charged car (case I and J), in the other cases the EV does not power the house. The electricity cost decreases when the capital cost increased, see figure (5.23). The difference between the three different charging tariffs is clearly visible in the figure. In table 5.15 the electricity cost reduction compared to case A for several PV with home battery system are displayed for different charging tariffs for charging at work. An increase of €0.04/kWh in the charging tariff at work results in a 12% increase in cost of electricity for case J.

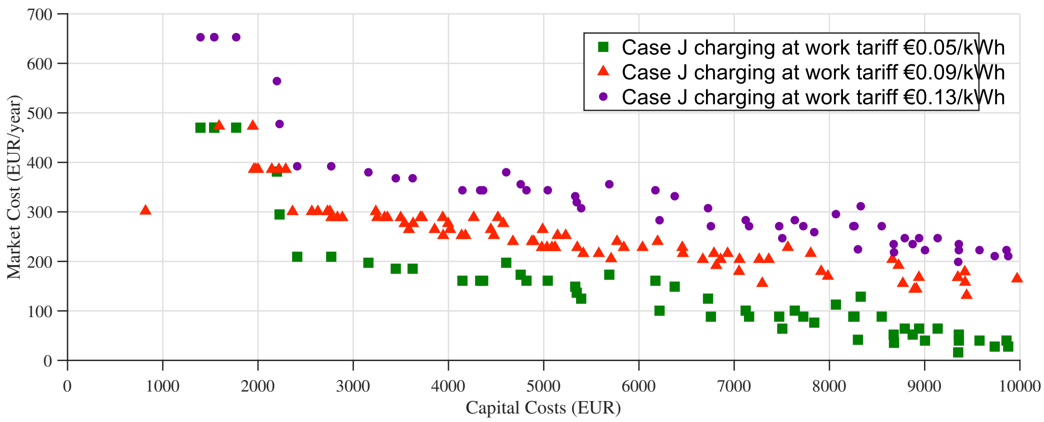


Figure 5.23: Annual electricity cost for case J for different charging tariffs at work

Table 5.15: Cost reduction of charging at work cost (W) for case J relative to case A

Capital Cost	€0.05/kWh (%)	€0.09/kWh(%)	€0.13/kWh (%)
2350	73	61	49
4250	79	67	55
6150	87	69	63
9600	95	83	71

Cost analysis with grid storing costs and charging tariff at work included

In figures 5.24, 5.25 and 5.26 the optimisation results for various scenarios are displayed. For the simulated cases in figure 5.24 the market selling price and grid storage cost are kept the same. The charging tariff at work is varied. It can be seen that the house without the charged EV is between the charging tariff of €0.05/kWh and €0.09/kWh. When the charging tariff at work is increased to €0.13/kWh case D has a lower market cost after a capital cost of €4,000. Case J outperforms case D on electricity cost for charging tariffs less or equal than €0.05/kWh at work.

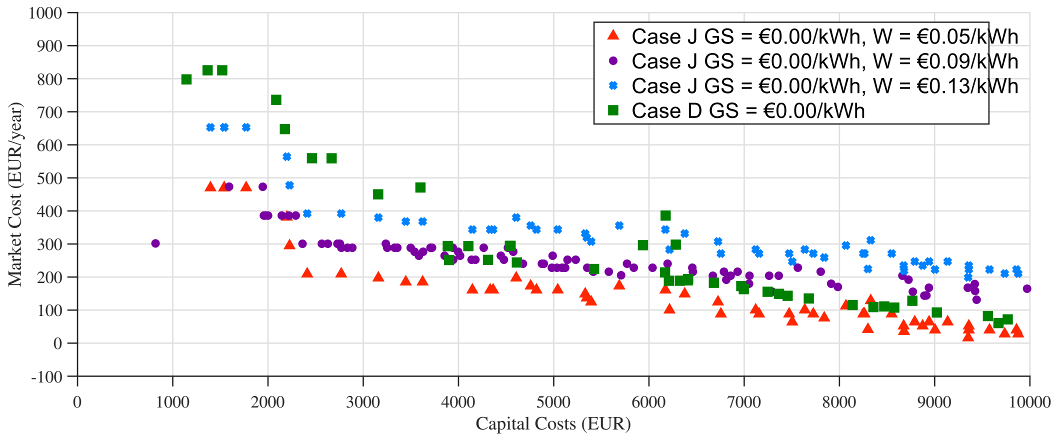


Figure 5.24: Market cost comparison (GS=€0.00): Case D versus case J

Including the storage fee of the main grid is another term to make the comparison more realistic and accurate. In figure 5.25 the results of the scenarios are displayed when grid storage cost is set to €0.042/kWh. Case J with charging tariff at work of €0.05/kWh and grid storing cost of €0.042 still outperforms case D for all systems with a capital cost lower than €10,000.

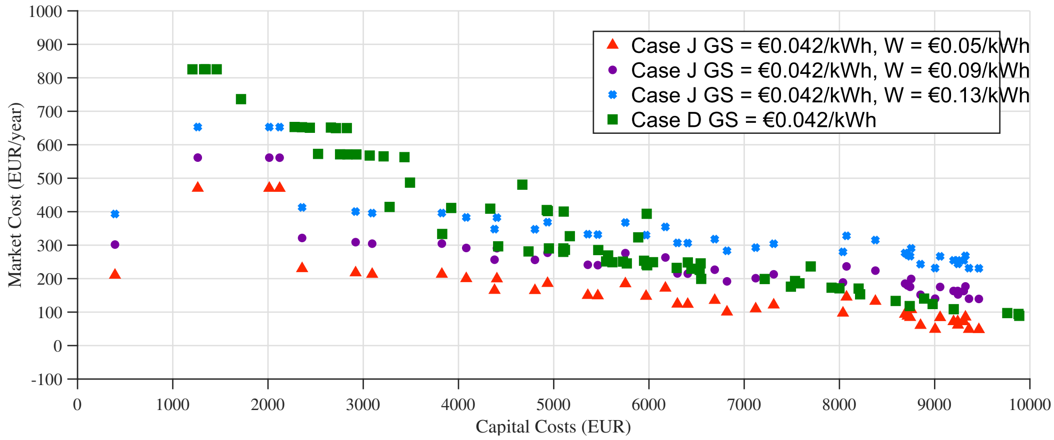


Figure 5.25: Market cost comparison (GS=€0.042): Case D versus case J

Now the market cost is further increased to €0.084, so doubled in proportion to the previous scenario. The results can be found in figure 5.26. In this scenario case D and J are closer together for different charging tariffs. A capital cost higher than €7,500 leads case B has lower annual electricity cost than case J with charging tariff of €0.09. The charged EV cases are less beneficial in the long run. This is a result of that the charged EV is still charged at work for a charging tariff. This tariff never reaches zero. In case J the cost for charging the EV at work always have its impact.

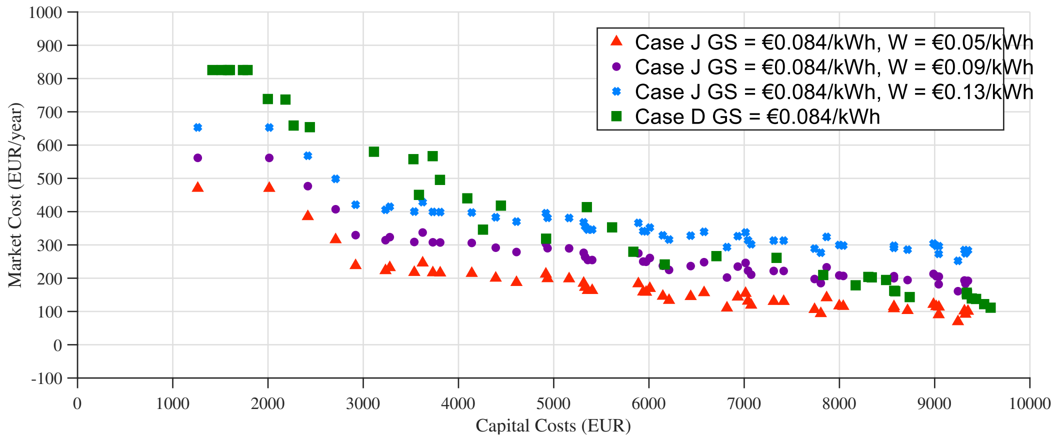


Figure 5.26: Market cost comparison (GS=€0.084): Case D versus case J

Conclusion

In this section the charged EV is examined in more detail to evaluate the case. The shifted charged EV case (J) is compared with the shifted case without EV (D). The impact on the EV's battery, the charging tariffs at work and grid storage cost are added to the equation. The peak shaving capability and grid energy autonomy are not affected when these costs are added. When the main grid storage cost is increased, the tipping point (when the case without an EV has lower electricity costs costs) is also at a higher capital cost.

5.6 Overview case results

In this part the results of all cases are summarised. Table 5.16, 5.17, 5.18 and 5.19 are the results for a house with integrated PV and battery with a capital cost of €2350, €4250, €6150 and €9600 respectively. The results in this section are with a charging tariff at work of €0.09/kWh and grid storage cost of €0.042/kWh. In figure 5.29 the annual electricity cost are displayed for cases C, D, I and J. It can be seen that case I has the overall lowest market cost for capital cost lower than €10,000. However, for capital cost around €9,000 and above case D is more or less equal to case I. When comparing case I and J, it can be concluded that shifting load is not always cost beneficial for cases with a charged EV (in a pricing environment where only the actual consumption is charged by the energy supplier, instead of also charge power peaks). On the other hand, shifting for grid energy autonomy (figure 5.27) and peak shaving capability 5.28 reasons is beneficial.

Table 5.16: Case comparison (CC=2350, GS=€0.042/kWh, W = €0.09/kWh)

	A	B	C	D	E	F	G	H	I	J
GA (%)	0	0	19	26	6	7	6	7	44	65
PSC (%)	0	0	3	14	0.7	0.25	0.5	2.1	21	49
EC (€)	772	767	653	652	>3000	>3000	>3000	>3000	460	321
CC (€)	0	0	2350	2350	2350	2350	2350	2350	2350	2350

Table 5.17: Case comparison (CC=4250, GS=€0.042/kWh, W = €0.09/kWh)

	A	B	C	D	E	F	G	H	I	J
GA (%)	0	0	34	39	8	11	5	11	66	74
PSC (%)	0	0	9	26	9	0.65	0.6	2.4	36	55
EC (€)	772	767	440	409	>2500	>2500	>2500	>2500	264	256
CC (€)	0	0	4250	4250	4250	4250	4250	4250	4250	4250

Table 5.18: Case comparison (CC=6150, GS=€0.042/kWh, W = €0.09/kWh)

	A	B	C	D	E	F	G	H	I	J
GA (%)	0	0	46	57	12	13	12	13	79	83
PSC (%)	0	0	19	41	1.5	1	1.5	2.5	65	75
EC (€)	772	767	270	232	>2000	>2000	>2000	>2000	243	216
CC (€)	0	0	6150	6150	6150	6150	6150	6150	6150	6150

Table 5.19: Case comparison (CC=9600, GS=€0.042/kWh, W = €0.09/kWh)

	A	B	C	D	E	F	G	H	I	J
GA (%)	0	0	68	71	17	18	17	19	89	92
PSC (%)	0	0	60	65	2	2.1	4	3	76	84
EC (€)	772	767	167	97	>1800	>1800	>1800	>1800	107	139
CC (€)	0	0	9600	9600	9600	9600	9600	9600	9600	9600

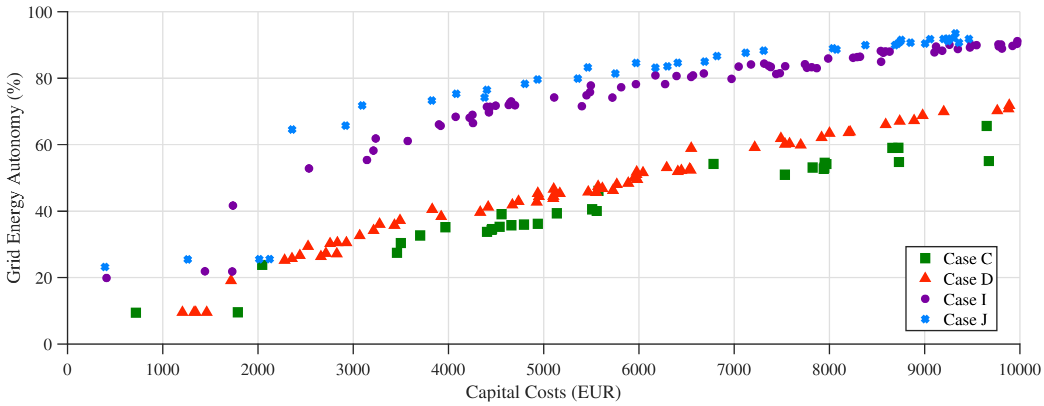


Figure 5.27: Overview grid energy autonomy case C, D, I and J

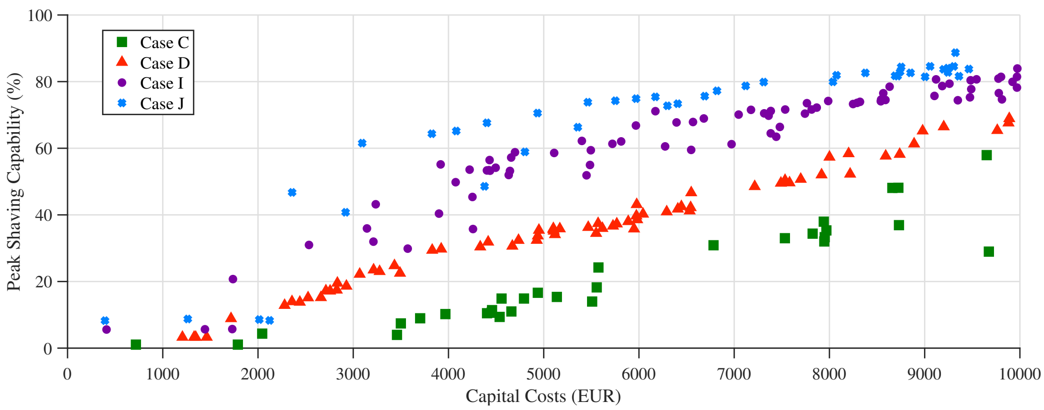


Figure 5.28: Overview peak shaving capability case C, D, I and J

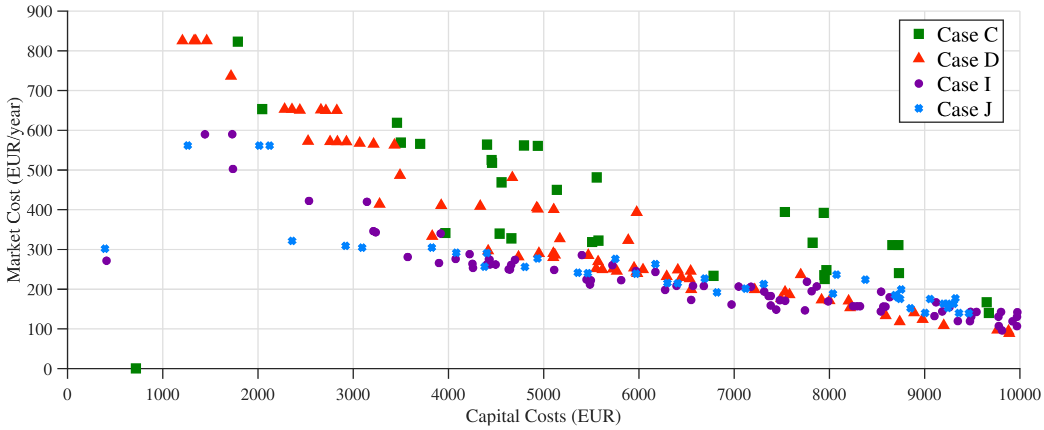


Figure 5.29: Overview market cost case C, D, I and J with W = €0.09 and GS = €0.042

Chapter 6

Conclusions and recommendations

6.1 Conclusion

Tomorrow's house electricity grid is designed as a DC microgrid with a PV panel installation, battery and an EV. The upcoming increase in household consumption comes mainly from the electrification of heating and charging an EV at home. This extra consumption has to be controlled to minimise the impact. In this thesis the benefits of integrating the EV in the EMS have been investigated. The house can use the unused capacity of the battery in the EV for powering the house and storing options. The extra energy needed for the house is charged at the workplace. Using the battery of an EV has an impact on the degradation of that battery. This thesis has investigated the potential and economic feasibility to use the EV as an energy source for the house.

The targets of the simulation results are the following terms:

1. Capital cost (CC): all investments that are related to the PV system with storage. Like PV panels, home battery and converters (for the grid connection, solar panels and home battery).
2. Grid energy autonomy (GA): the system is evaluated on grid energy autonomy, not to be confused with grid power autonomy. A grid energy autonomy of 100% means that the house does not need to buy from the main grid anymore. However, the house does still have interaction with the main grid for selling the surplus of energy from the PV generation.
3. Peak shaving capability (PSC): the peak shaving capability is the term to show what the impact of the system is on the peaks of the house load

pattern. A system that reduces or lowers the household peaks, has an increased peak shaving capability.

4. Annual electricity cost (EC): the cost analysis of a system is essential to identify the benefits and shortcomings of a system. The focus is on the cost of electricity. The cost of electricity can be negative when the surplus of energy is sold to the main grid.

In this thesis the capital cost has been limited to €10,000 for the PV panel installation, home battery and converters (for PV, home battery and grid connection). This limit has been chosen to investigate reasonably priced PV home battery systems for homeowners.

Cases

Ten cases have been researched to evaluate the impact of load shifting on household load patterns and the contribution of using a charged EV in a house with integrated PV and battery. The ten cases that have been researched:

- Case A: house without locally produced PV energy
- Case B: house without locally produced PV energy with load shifting
- Case C: house with PV installation and home battery
- Case D: house with PV installation and home battery with load shifting
- Case E: house with PV installation, home battery and standard EV
- Case F: house with PV installation, home battery and standard EV with load shifting
- Case G: house with PV installation, home battery and smarter EV
- Case H: house with PV installation, home battery and smarter EV with load shifting
- Case I: house with PV installation, home battery and charged EV
- Case J: house with PV installation, home battery and charged EV with load shifting

For a better comparison between case C, D, I and J the following costs have been included/altered: grid storage cost, lower market selling price and different charging tariffs at work.

Main conclusions

1. When the charging tariff at work is €0.13 or higher, the benefits of integrating the EV as power source are minimal. For charging tariffs up to €0.05, integrating the EV in the house is always beneficial in terms of grid energy autonomy, peak shaving capability and annual electricity cost.
2. Using the EV for improving grid energy autonomy, gives an increase from 30% up to 154% relative to the cases without charged EV.
3. Using the EV for improving peak shaving capabilities, gives an increase from 28% up to 252% relative to the cases without charged EV.
4. Using the EV for reducing the annual electricity cost is not always beneficial. The electricity cost increases by 18% for capital cost and decreases by 55% relative to the cases without charged EV, depending on the market selling price, charge tariff at work and grid storage costs.
5. Applying load shifting to a household load pattern is beneficial for the grid energy autonomy (increase of 2.6% up to 21.2%) and peak shaving capability (increase of 5.1% up to 28%) for all cases. Shifting load in the charged EV case leads to a higher or equal electricity cost.

The most important contribution of this thesis is the conclusion that a charged EV is beneficial, in terms of grid energy autonomy and peak shaving capability, to implement it into a house with integrated PV and a home battery. The electricity cost, in a two-tariff pricing environment, is lower for houses with integrated PV and home battery when the PV system is oversized. In table 6.1 the results for a system with a capital cost of €4,250 are given. The grid storage cost is €0.042/kWh for cases C, D, I and J. Cases I and J charge the extra needed energy to power the house for a price of €0.09/kWh.

Table 6.1: Comparison cases (GS=€0.042/kWh, W = €0.09/kWh)

	A	B	C	D	E	F	G	H	I	J
GA (%)	0	0	34	39	8	11	5	11	66	74
PSC (%)	0	0	9	26	9	0.65	0.6	2.4	36	55
EC (€)	772	767	440	409	>2500	>2500	>2500	>2500	264	256
CC (€)	0	0	4250	4250	4250	4250	4250	4250	4250	4250

6.2 Recommendations

In every research the boundaries are limited due to a few factors. In this thesis the following aspects can be extended or done differently in future work.

The following recommendations are given for further research:

1. Further research on using the outcome of the optimisation program as feedback for the load shifting program can be beneficial. Due to the long simulation run time of the system sizing optimisation program, this was outside the scope of this thesis.
2. Heating of a house will be electrified in the future. Additional research is needed to investigate the impact of heating electrification on the outcomes of this thesis.
3. Another topic that needs additional research is the feasibility of the proposed idea in this thesis on a broader view. The scalability of the proposed idea can be limited.

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