The Impact of Emerging Technologies and Energy Management Systems on a Neighbourhood

C.A. Post
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Faculty of Electrical Engineering, Mathematics and Computer Science (EEMCS)

Master's Thesis, M-SET

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Abstract

The energy transition is crucial to mitigate climate change. However, problems, such as grid congestion and low power quality, in the Dutch electricity grid arise due to the increase in electricity demand and the implementation of renewable energy sources. A solution is needed to not only mitigate climate change, but also to be able to continue connecting new buildings in the Netherlands to tackle the house shortage. One solution is using an Energy Management System (EMS) to control the flexibility of devices to resolve peak-load problems. However, there is a lack of long-term studies on the impact of emerging technologies and different control methods for an EMS on a neighbourhood scale in the Netherlands. The goal of this study is to look at the impact of different ways to control devices in a Dutch neighbourhood: an individual approach based on price steering and a community approach based on profile steering are evaluated. This study specifically looks at the impact on the grid load, self-consumption, costs and societal consequences.

The used modelled neighbourhood consists of 17 houses and a smart charging parking lot. These houses can have a baseload, PV panels, Heat Pump (HP), Electric Vehicle (EV) charging station and a home battery. Three cases are researched: The base case does not use any control and investigates the impact of adding these devices to the houses. The realistic scenario looks at the impact of the different control algorithms when only 7 houses own an EMS, home battery and EV. The futuristic scenario researches the impact of different control methods when all houses have 100% penetration of all abovementioned devices. The impact on individual households is also shown to discern any discrepancies between households.

The simulation results show that emerging technologies greatly increase the demand load on the grid, for example, with a factor of 4.1 with the use of uncontrolled HPs and EVs. The use of price steering decreases the costs significantly, however, it also causes the grid limit to be exceeded for 10 full days of the year in the realistic scenario. The batteries are mainly responsible for this. When some houses use price steering, there is unfairness between the households due to the way the Dutch grid costs are divided amongst its users. The use of the community-based control method, profile steering, results in the highest self-consumption of 75% and keeps the maximum demand load peak at 46% of the grid limit. Moreover, the costs are also still 23% lower compared to the uncontrolled scenario and are more equally divided amongst the households.

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Contents

Acronyms

DHW Domestic Hot Water.

DR Demand Response.

DSM Demand Side Management.

DSO Distribution System Operator.

EMS Energy Management System.

EPC Energy performance coefficient.

EV Electric Vehicle.

HEMS Home Energy Management System.

HP Heat Pump.

PV Photovoltaic.

RES Renewable Energy Source.

SoC State of Charge.

V2G Vehicle to Grid.

Introduction

1

Chapter Objective: In this chapter, the background and scope of this thesis and the research questions are introduced.

Chapter Contents

1.1 The Energy Transition

Currently there is an increasing pressure being put on the Dutch energy system due to an increasing electricity demand and a higher penetration of Renewable Energy Source (RES). The increasing pressure originates from the incentives to reach the climate targets. The Netherlands signed the Paris Agreement, which aims to limit global warming to 1.5°C. To reach this goal, the Dutch government made a Climate Plan for the period of 2021-2030 [1]. This plan includes stimulating the implementation of RESs such as wind and solar energy, the use of EV and making houses gas-free. As a result, there has been a big increase of Photovoltaic (PV) panels on rooftops, EVs, houses using a HP for heating, and large-scale RESs such as wind parks in the North Sea.

The increase in electricity demand in the residential sector is mainly caused by the electrification of energy-intensive applications, such as transport and heating systems. Higher penetration of RESs gives problems to the grid due to their intermittent unpredictable generation of energy. Furthermore, the generation of energy by RESs, for example, PV panels (during the day), typically does not match peak demand periods in the morning and evening.

The current system is designed in a centralised way, where matching demand and supply is done by using the flexibility of changing the output of generators. However, as we are working towards becoming CO2 neutral, the number of RESs and electric loads will increase even more and the generators based on fossil fuels will decrease [2]. In addition, these new generators and loads will be installed in a decentralised fashion in the low-voltage grids instead of in a centralised fashion. The current grid constraints are limiting the implementation and connections of more RESs, EV charging stations and other extra connections in the future.

To adhere to future demand the Dutch Distribution System Operator (DSO) Alliander already mentions the need to break open a third of all streets to reinforce the low voltage grid, which is a big task and can not be performed at the speed with which the demand is increasing due to limited materials, technicians and high societal costs [3].

The waiting time for a new grid connection is already a limiting factor to being able to perform more construction work [4]. The Netherlands has a housing shortage, hence a solution to keep a reliable energy supply, while being able to continue to connect new houses, more RESs and handle the increase in the residential load is needed.

One possible solution is the use of the flexibility of devices to alleviate grid problems and enable more implementation of RESs and new devices. For example, by turning on the washing machine when PV panels are generating energy, most energy stays "behind the meter" and will not affect the grid. By properly managing flexible devices, the matching of demand and generation can be improved. This way, flexibility offers the possibility to increase the self-consumption rate, to benefit from variable pricing, to obtain a more robust system, less stress on the grid and a higher usage rate of renewable energy generation [5]. There are new regulations planned and expected to be put in place to motivate end-users to implement and use flexible devices to help solve the grid problems. In short, this would probably boil down to having a different pricing mechanism in order to decrease the demand peaks and increase consumption while there is renewable energy being generated. More about these expected regulations are described in Section 1.5. A common trend seen in the planned or already implemented regulations is that most incentives are targeting individual parties or households. Barely any incentive motivates working together as a community to alleviate the grid and share assets for reducing costs, needed assets and grid issues.

From the viewpoint of a house owner, these new regulations can make flexibility profitable. Using more of their own generated solar energy and using energy while prices are low will result in lower energy bills, less dependency on fluctuating energy prices and lower CO2 emissions, however, households are limited in the amount of flexibility they can offer, since they are stuck to their schedules and the limited devices they own. Thus, they might not be able to use their solar energy at the moment it is generated, resulting in either injection of the electricity into the grid or having to curtail their generation. However, their neighbour without PV panels be able to use energy at that moment. Since all households have different consumption patterns and different penetration levels of EV, HP, PV and batteries, the consumption planning of the households could be matched in order to coordinate their energy consumption to maximise self-consumption and profits. More houses together have more flexibility to offer and thus working together could benefit all participants. Furthermore, not all houses have their own parking space and depending on regulations on energy trading it might (not) be possible to charge their own EV with their own locally generated solar energy.

The goal of this research is to find out what the impact of different control algorithms is in a newly built smart neighbourhood on the grid load, self-consumption and energy costs. We compare a situation where each household is controlled to maximise its own gains to a situation where the whole neighbourhood is coordinated to maximise the gains for everyone.

However as not all households are the same and, thus, one household might benefit from certain control methods, while others do not or even lose more. Thus aside from the technical goal, also the (social) impact of control strategies on the individual households is investigated.

The studied neighbourhood consists of 17 houses, which are designed and built by Heijmans. Heijmans is a real-estate development and construction company in the Netherlands. They recently started an energy department because sustainable energy became an integral part of their work. The energy department not only designs, develops and realises sustainable energy systems for the built environment, but they also do the exploitation of these systems. They are therefore also an energy service company (ESCo). Heijmans provides data for this study, since Heijmans Energie would like to develop new propositions based on smart energy services in the buildings they build, with the goal to provide sustainable and affordable energy to all.

1.2 Flexibility

As mentioned before, the flexibility of devices can be used as a solution for grid problems and to lower energy bills. Flexibility is an often used term but its significance may change dependent on the context. In this section, the definition of flexibility is discussed, including a description of what the flexibility of residential loads is and what it depends on.

1.2.1 What is Flexibility?

Multiple studies use slightly different definitions when it comes to flexibility: "Flexibility is seen as the ability to modulate demand over a certain time" [6]. "Changes from usual patterns of interaction with the electricity systems" [2]. Within the context of this research, we argue that flexibility is the ability to shape the power and energy profile over time.

1.2.2 Flexibility of Different Devices

Multiple devices can provide demand side flexibility. This flexibility is determined by the characteristics of the load and storage, such as their maximum and minimum amount of power, their capacity, State of Charge (SoC), whether they can be interrupted and how well the devices react to control signals [2]. The flexibility can be controlled by using different starting times, interrupting the process, ramping up or down the device and skipping or replacing a process entirely [6]. What the exact possibilities are and how much of the flexibility can be controlled depends on the device. Furthermore, the consumers generally have their limits in the amount of comfort they are willing to sacrifice, further limiting the usable flexibility of a device. For example, whether a change of 0.5°C or 2°C in temperature within a house is acceptable, makes a difference in the usable flexibility of a HP and thermal storage. In the following, the flexibility of some devices is described more elaborately: EV, HP, PV panels and a home battery. These devices are deemed to have the most significant flexibility in a household.

- **Electric vehicle**
  EV drivers typically do not use the full capacity of their EV daily, since most cars are used for commuting relatively short distances. When connected to a charging station at home an EV mostly charges for only around 30 or 40% of the total time it is connected [5]. This means there is some flexibility it can offer to a management system for the time it is connected to a charging point. It can reduce the demand by postponing charging or by reducing the charging power. On the other hand, it is also able to increase the charging power or duration and thus increase the demand. In the case of being able to also use Vehicle to Grid (V2G), the battery can also provide electricity to the grid [6]. However, the time the vehicle is connected to the charging station is variable and its usable flexibility is dependent on its SoC. For residential charging stations, the behaviour is relatively predictable since people arrive and leave home around the same time almost every day. Dependent on how the system is designed, the consumers do not have to adjust a lot in their behaviour or comfort for a smart system for EVs, as long as they connect it to the charging station and accept that their EV is not always charged immediately once it is connected [5].

- **All electric heat pump**
  The energy use of heat pumps is caused by the heating and cooling demand of the house and the Domestic Hot Water (DHW) demand. The flexibility of the heat pump is mainly interesting for the consumer to optimise based on grid tariffs and self-consumption. However, in cold periods the heat pump is often operating, decreasing its flexibility. Furthermore, an HP without seasonal thermal storage is not a very useful solution for optimizing the self-consumption of solar energy as the main generation is in the warm months and the main heat demand is in winter. For the energy system the flexibility of the heat pump can be used to prevent grid congestion by shifting the peak load [5]. An HP provides flexibility firstly by being able to reduce the demand by turning it off, especially when having a thermal storage that can provide for a certain period of time, or by accepting temperature changes. An HP can increase the demand by heating the buffer or room to temperatures above the setpoint, for example by increasing the room temperature by 0.5°C or the water in the buffer by 5°C [6], [7].

- **PV panels**
  PV panels generate electricity when there is irradiance and otherwise do not. Their only flexibility is to reduce the feed-in through curtailment. This is mainly useful to prevent overloading of the grid during sunny days when all PV panels generate simultaneously at maximum power.

- **A home battery**
  A battery alongside PV panels provides flexibility by being able to lower the demand by not charging the battery and using PV-generated electricity directly instead, or by feeding both the PVs and the battery's electricity into the grid. The battery can also increase the demand by charging from the grid. Its flexibility is limited by its SoC, capacity and by the allowed charging and discharging power [6]. Even when not owning PV panels, a battery can be used to lower energy costs when using a dynamic pricing scheme and help peak reduction.

1.3 Energy Management Systems

As mentioned before, there is a need to efficiently use the flexibility of high energy-consuming devices, such that the energy transition can continue forward. Problems from the uncertainty of production and the mismatch of production and demand can be achieved by using energy storage systems. However, especially for large-scale solutions, this is simply not feasible, since using only energy storage becomes too costly, inefficient and/or loaded with environmental constraints [8]. Another approach is using the flexibility of demand-side resources through the use of an EMS. Demand Side Management (DSM) entails the activities that intend to modulate, in time and/or shape, the demand profile of the consumer in order to match supply and demand [9]. Typical goals of DSM are

- Lower the energy bills of the end-user;
- Decrease CO2 emissions;
- Improve self-consumption;
- Decrease load peaks on the grid;

An EMS for a house is called a Home Energy Management System (HEMS). A neighbourhood EMS can be implemented when there are multiple houses with HEMSs in a region, such that they can collaborate to reach a common goal.

1.4 EV Charging

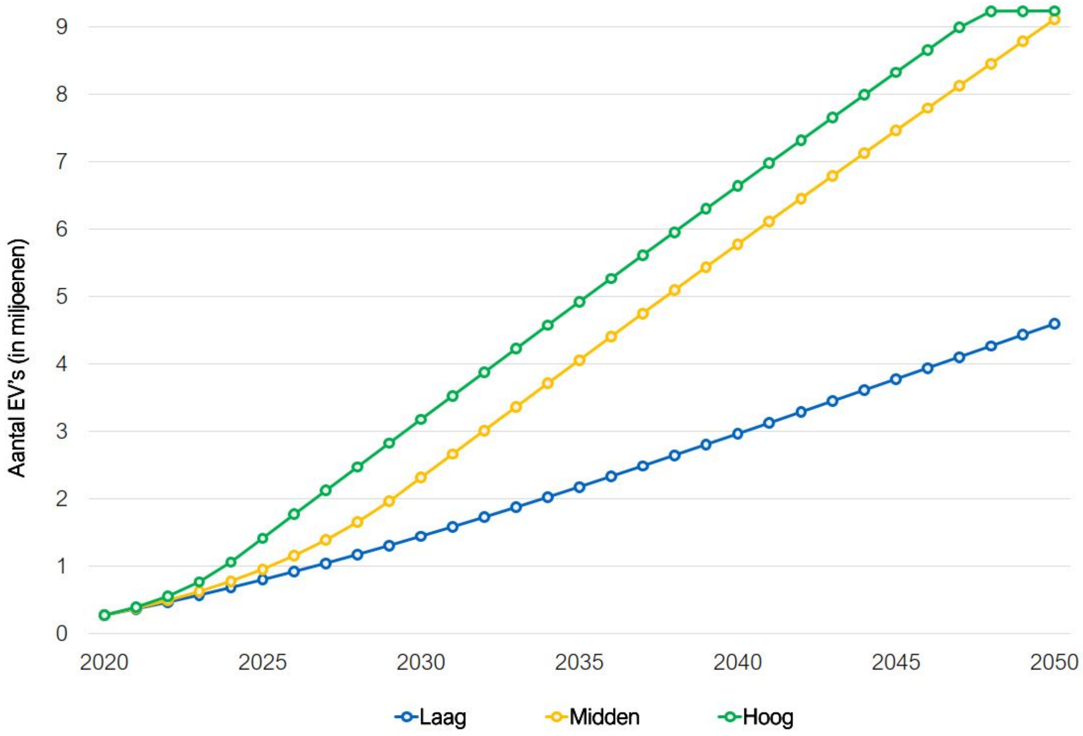


Fig. 1.1: Expected number of EVs (in millions) in low (blue), medium (yellow) and high (green) scenario [10]

In the upcoming years, a steep rise in the number of EVs in the Netherlands is expected as can be seen in Figure 1.1 [10]. Regulations state that from 2030 all newly sold cars should be emissions-free, and it is expected that these will be mainly battery electric vehicles. However, all these EVs need to be charged and our current grid is not designed for large numbers of EVs charging at the same time. On the other hand, EVs also provide an opportunity to help stabilize the current grid. By using smart charging they can help prevent grid congestion, match demand and renewable energy generation and prevent grid imbalance. To provide enough charging possibilities, parking lots with multiple charging stations are already being placed in industrial, commercial and residential parking spaces. These public charging stations are usually owned by a third party that tries to make a profit from the charging sessions.

1.5 Current Regulations & Expected Changes

Due to the energy transition, the current grid in the Netherlands already has to deal with congestion issues, the electricity grid needs to be expanded. However, the DSOs cannot upgrade the physical grid as fast as is deemed necessary due to the lack of manpower, space, costs and materials, thus new solutions such as making use of flexible systems are needed and should be incentivized by policies and regulations. Currently, there is a lack of incentives for end users to invest in solutions due to, among others, the net metering scheme, uncertain future energy prices, uncertain government regulations, uncertain future technological developments, and the low price of natural gas. In the following, some of the most relevant changes that are recommended to be implemented in order to resolve the grid issues, while keeping the energy transition going in the Netherlands are given [11],[12]:

- **Reduction of the net metering scheme**
  The "salderingsregeling", translated to the net metering scheme, gives households in the Netherlands the possibility to feed electricity back into the grid and deduct that amount of energy from their consumption meter, such that they practically get the same price for their generated electricity as when they buy the electricity from the grid. The percentage of electricity that can be netted into the grid will slowly decrease from 2025 onwards until no netting is left in 2031. As a replacement, there will be some form of compensation that energy providers need to pay for the electricity that the customer feeds back into the grid [13].
- **Subsidising battery systems**
  Implementing a subsidy or regulation to motivate the placement of smart controlled batteries next to solar systems will make it possible to add more PV panels to the same connections and alleviate the grid during sunny time periods. This also provides the possibility to use green energy during the evening peak hours, and prevent large-scale curtailment in the future when there is little demand during very sunny hours. This would be mainly recommended for large-scale systems where it should be clear that it is meant to alleviate the grid and maximise the use of renewable energy. There is a smaller chance that home batteries will get subsidies, since in practice it is hard to

predict how the households will use their batteries and their limits in preventing the high peaks caused by the PV panels [11], [12].

- **Curtailment of small scale solar energy generation**
  Since the peak generation of PV panels is only a small part of the total generated solar energy in the Netherlands, a regulation could be made that forces people to have a smaller inverter than the actual possible peak power the PV panels can generate. If the inverter can handle only 70 or 50% of the maximum solar peak, the generated energy will become only 2% or 10% lower, respectively [11]. So these regulations can have only a small impact on the totally generated energy per year but will have a big impact on the overloading of the grid in the residential sector.

- **Take into account the grid impact to giving away SDE++ subsidies**
  The grid connection costs are not taken into account for the calculations of the SDE++ subsidies yet. If these calculations are added to the SDE++ base costs calculations, it would give a more realistic view of the complete costs of the renewable energy system. This can motivate people to among others use the energy more locally, store the energy and combine different generation methods, such that the extra societal grid costs are also represented in providing subsidies to individuals and organisations [12].

- **Charging stations**
  Charging stations are generally connected to the common 3x25A connection due to the relatively low costs compared to a bigger connection, however, the costs calculation for such a small connection is based on 4kW, which is lower than the maximum power over such a connection, namely 17kW. Adding a charging station to such a connection is cost-effective for the owner but not for the grid operator. However, a larger connection is around four times as expensive per kW grid capacity. This is why a new grid tariff specifically for charging stations is important. Furthermore, it is recommended that small charging parking lots would be proactively installed. Currently, the charging stations are being requested uncontrolled at different moments in time and placed as separate units. Compared to single charging stations, a small smart charging parking lot is more space, time and labour efficient by decreasing the number of streets to be opened up and the number of new cables to be installed. Furthermore, regulations on smart charging should be implemented such that the potential flexibility of EVs can be used in favour of the grid. A new tariff for smart charging could be implemented by grid operators to lower the grid load [11].

- **Non-firm net capacity**
  The Dutch grid operators are only allowed to provide a grid connection in which the full capacity is always available. However, for most flexible implementations, full capacity is not always needed. So a solution for adding more connections quicker is to allow non-firm connection and transportation agreements where a client will

not always have the full capacity, but might get it at a specific time. Such a non-firm contract would be cheaper for the end-users. Systems that could be suitable for such a scheme are, for example, batteries, electrolysers or EV charging parking lots [11] [12].

- **Different construction of energy pricing**
  The energy taxes could be changed dependent on the type of energy used (gas, or electricity e.g.), which will further stimulate the use of renewable energy resources. Also, a progressive tax or capacity tariff based on energy usage might be implemented, such that high-energy users pay more for their connection to the grid. Furthermore, dynamic tariffs are already offered to improve the matching of supply and demand. This way the energy prices will fluctuate more, making flexible systems more attractive to invest in [11].

1.6 Energy Communities

Energy communities are "legal entities that empower citizens, small businesses and local authorities to produce, manage and consume their own energy" [14]. Their purpose is to have all its members and the local area where they operate benefit socially, economically or environmentally from cooperation. The EU has made a regulatory framework around energy communities to overcome the barriers of decentralizing the energy system and add possibilities for citizens to actively aid in the energy transition. The EU directive 2019/944 [15] states that energy communities should be able to take on multiple forms like a cooperative, an association, a non-profit organisation or a limited liability company. As the energy communities are a legal entity, they can access all suitable energy markets and even benefit from support schemes, capacity building, information and additional financing based on the strict participation criteria from the EU.

1.7 Research Questions

The objective of this study is to create insight into what happens when emerging technologies are implemented in a newly built Dutch neighbourhood and the impact of EMSs controlling these devices using different control methods. By looking at the impact on self-consumption, grid load, costs, and societal consequences, a possible solution can be found to prevent grid congestion and grid balancing problems while keeping electricity affordable. The main research question of this thesis is:

What is the impact of individualistic-oriented incentives versus community-based incentives on the grid load, self-consumption, costs and societal consequences of a smart neighbourhood?

The following sub-questions are formulated to deal with this main question:

- *What is the impact of a high penetration of emerging technologies on a Dutch neighbourhood?*
- *What is the effect of controlling the emerging technologies on self-consumption, minimize costs and prevent grid overloading for the neighbourhood?*
- *What is the effect of a smart charging parking lot in the neighbourhood?*
- *Are there any discrepancies on a household level between the costs, grid impact and self-consumption?*
- *What are the social implications of different control algorithms in a smart neighbourhood?*

1.8 Contributions

State-of-the-art research is shown in Chapter 2. From the literature study, a lack of knowledge on the realistic long-term impact of relevant emerging technologies and different control methods for EMSs in a Dutch neighbourhood is noticed, both in realistic scenarios and in futuristic scenarios. The main contributions of this thesis to the already existing studies done on this topic are:

- Showing the impact of both the increase of emerging technologies as well as different control mechanisms on these devices on a realistic newly built Dutch neighbourhood taking into account all common emerging technologies in the Netherlands: HPs, PVs, Batteries and EVs.
- Comparing a price-steered individualistic control mechanism to a community-based load-flattening control mechanism.
- Simulating over a time period of a year on a 15 min basis, looking both at the aggregated load and the individual households load.
- Considering the impact of the emergence of a smart charging parking lot in the neighbourhood, since not all houses can have their own charging station.
- Looking not only at the technical impacts but also at the social implications for the different households of using different control strategies.

1.9 Thesis Outline

The structure of the remainder of this thesis is as follows. First, the relevant literature on the impact of emerging technologies, EMSs and smart charging parking lots is discussed in Chapter 2. The control methods used for the EMS in this study are described in Chapter 3. Chapter 4 details the model used for the simulations in this study. Chapter 5 presents the results obtained from the simulations. The social implications of the results are discussed Chapter 6. Lastly, the research questions are answered in Chapter 7 and recommendations for future works are presented.

Literature Review

2

Chapter Objective: This chapter serves to review the literature relevant to the presented research.

Chapter Contents

- Impact of Emerging Technologies and Device Flexibility (2.1)
- Home Energy Management Systems (2.2)
- Neighbourhood Energy Management Systems (2.3)
- Energy Communities (2.4)
- Smart Charging Parking Lots (2.5)

2.1 Impact of Emerging Technologies and Device Flexibility

Multiple studies have been performed on the impact that emerging technologies and their flexibility, such as HPs, EVs, PV-panels and battery systems, can have when implemented on a large scale.

In order to compare the flexibility of emerging technologies, Gerards et al. [16] show a methodology to determine the value of flexibility. Thus making it possible to compare the impact of smart devices for different objectives. They research a scenario with no control, with peak shaving and with maximising self-consumption as the objective. They show that a small battery greatly helps with flattening the load curve when the house has no PV, whereas with PV installed a bigger battery can make it possible to shift the energy from one day to another. They also show that the flexibility of white goods devices in practice is quite small. EVs using smart charging can prevent the charging peak and PV peak, dependent on when it is connected. They are only useful for peak shaving when PV panels are installed, assuming there is no V2G option.

Another study focuses on a practical example of available flexibility in the residential sector: Fischer et al. [6] studies the power and energy flexibility in the residential demand profile for two scenarios in Germany: The individual devices in a multifamily house and a future 2030 typical residential area scenario, where some houses have an EV, PV panels, batteries and an HP, but not all of them. The study shows that HP and PV-battery systems offer great flexibility but are season dependent, whereas an EV also offers flexibility but is limited by the time it is connected (at home). The household appliances offer very little flexibility, they start to become significant only when the penetration levels of the other devices are low and the household appliances are very high in number.

Also in [17] the impact of these emerging technologies is studied. This study is focused on the change in the electric load profiles due to the impact of PV panels, EVs and HPs in the residential sector. They use a bottom-up approach to simulate a part of a German city consisting of 1550 houses of different types in one-minute resolution. They use a 2017, 2030 and 2050 scenario with different levels of device penetration. In an efficient 2030 scenario, they show that the annual peak load increases by a factor of 1.31. They also show that adding batteries does smooth the peak during evening hours but does not affect the feed-in peak if constant tariffs over time are used. In an inefficient 2030 scenario, the annual electricity demand is increased by 30% compared to 2017, the peak load is increased by a factor of 1.76 and the load in winter by a factor of 1.48. The houses that replace their boiler with an HP have an electricity demand increase of a factor of 2.8 on average. In winter this is a factor 4, with a load peak increase of up to 7 times (since they assume the use of a backup electric heater during the coldest days). The influence of PV shows that all houses equipped with PV aggregated are net consumers during winter but become net producers during summer, even when they have a battery. The aggregated net electricity demand of this group of houses (without batteries) changes from 870MWh to -214 MWh and has an annual self-consumption of 440MWh. When an EV is added to a household the annual electricity consumption is increased by a factor of 1.63, but does not lead to any seasonal changes. The annual peak load becomes almost three times as high with the addition of an EV to the household, dependent on the installed charging infrastructure. By using more energy-efficient devices in the future the annual demand of household devices can be reduced by 28%.

Proper usage of the available flexibility in the residential sector can also help reach sustainability goals. Mata et al. [18] show that using the potential of flexibility in the residential sector, 2-18% of the electric loads can be shifted in Germany, UK, Sweden and France. If this amount of flexibility would be used for peak shaving, 10MtCO2 emissions could be saved, whereas using it for optimizing the use of renewables could save 24MtCO2 per year.

In short, studies show that EVs offer great flexibility when connected. PV-battery systems and HPs also offer flexibility, which value is dependent on the season, whereas white goods only offer little flexibility. The increase of HPs and EVs being used in households greatly increases electricity consumption and the annual peak load. PV systems implemented on a large scale make houses become net producers in summer, even when they are equipped with batteries. When the potential flexibility in the residential sector is used, it could greatly decrease CO2 emissions and help minimize peak loads. The different ways to use and control the available flexibility are described in the following.

2.2 Home Energy Management Systems

The abovementioned studies have shown the impact emerging technologies can have in different scenarios. HEMS can make use of DSM in order to reach their objective as mentioned in Section 1.3. Many studies have already surveyed researched methods to effectively control the demand side electrical loads [9],[19],[20],[21],[22]. First, in Subsection 2.2.1 different ways to model the loads are described. Afterwards, in Subsection 2.2.2 the common different techniques to shape the load are described and one of the most popular used strategies for load shaping, namely Demand Response (DR) is elaborated on.

2.2.1 Load Modelling Techniques

A good model of a house, including all its devices, is needed to test a HEMS design and its impact on the energy consumption of a household. Two main approaches are used: top-down and bottom-up. The top-down looks at each house or even a neighbourhood as a single unit, whereas the bottom-up approach looks at the consumption of the individual loads and combines these to get the energy consumption of an entire house or neighbourhood.

A top-down approach is simpler as it uses aggregated data which is more commonly available. It is mainly used for long-term load profile changes. Precise control strategies cannot be used nor developed for this approach.

A bottom-up approach uses the energy consumption of each device separately. The load curve of a single house or multiple houses can be determined by adding these curves. It is not easy to obtain all the data on the consumption of all devices, since rarely measurement units are being used on all devices. Thus, a validation is needed e.g. by comparing the combined loads to the results of the top-down approach. Household devices are subdivided into categories, namely the non-controllable baseloads, fully controllable burst loads, which can be shifted in time and paused at specific cycle times, and partially controllable regular loads. When modelling these devices it is important to take the behaviour of the users into account, such as house occupancy, geographic location, climate conditions, and economics. By grouping devices and knowing which can be controlled by how much, the flexibility of the whole household demand can be determined. The bottom-up approach is the most suitable to use DR and related techniques.

2.2.2 DSM Load Shaping Techniques

There are different methods used to shape loads. DSM has six major load shaping techniques: peak clipping, valley filling, load shifting, load reduction, strategic load growth and flexible load shape [23]. An overview is given in Figure 2.1.

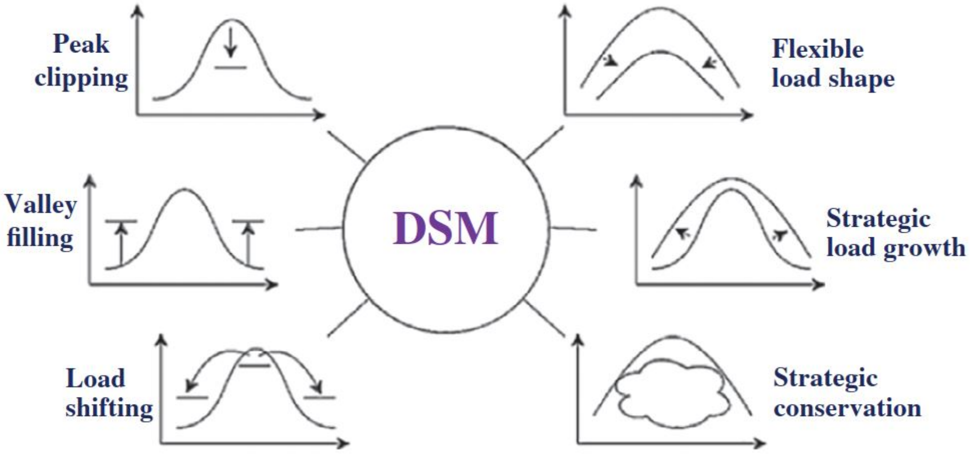


Fig. 2.1: Overview of DSM load shaping techniques [24]

Peak clipping
Peak clipping focuses on decreasing the demand peak, usually done by direct load control. This means that at times when there is a high peak the energy supplier is able to remotely turn off loads of consumers [24]. This is a useful technique to avoid having to install a very expensive new power generator [23].

Valley filling
This technique attempts to maximise energy usage during off-peak moments. This is mainly achieved by motivating consumers to use their appliances during this time by reducing the energy prices at that time period [23]. This technique is very useful when the long-term cumulative costs are lower when using energy in these off-peak moments than when the average electricity price is paid, for example by using a dynamic pricing scheme [24].

Load shifting
Load shifting combines peak clipping and valley filling to move load from peak periods to off-peak periods [24]. This generally uses cheaper tariffs as motivation for the consumer and is very beneficial for utility applications [23]. A popular strategy to achieve this is Time of Use which uses fixed tariffs for different times of the day. So it divides the 24 hours into different time periods in which each gets assigned a different tariff. This keeps the peak load periods tariff and seasonal pricing under control [23], [24].

Strategic energy conservation

This technique focuses on diminishing the load demand during every time period by using efficient appliances and uses the planning, distribution and management of the network system to obtain the desired load profile [24],[23]. A common strategy to achieve this is called energy efficiency. This strategy focuses on improving the efficiency at device level in order to permanently reduce the load profile, as less energy is consumed per device [23].

Strategic load growth

As implied by the name, load growth focuses on increasing the power generation for consumers in order to maintain a stable grid beyond the valley filling approach. This is achieved by the enhancement of the market share of loads, electrification in industry and guaranteeing an infrastructure that can handle the increased load demand [24]. A common strategy to achieve this is spinning reserve: This refers to a backup in power generation that can be started within a few minutes upon receiving a signal. Frequency-responsive spinning reserve reacts within 10 seconds to sustain the right frequency. Thus when there is an imbalance between demand and generation due to e.g. an unexpected failure of a generator, this spinning reserve can be started to help balance the grid [23].

Flexible load shape

Customers who have flexible loads are identified and when they are willing to offer their flexibility to the electricity generation company during peak periods they receive various incentives. This technique is used for securing the reliability of the smart grid [24].

Demand Response

An often-used strategy to achieve different load shaping, such as peak clipping, load shifting, and valley filling is DR. It motivates changes to the energy consumption of the end-users in response to a signal given by the system operator. The motivation is cost related, as either the prices change over time, or incentive payments are given to lower the energy usage at times of peak demand and/or high market prices. These are the two main types of DR programs based on offered motivation: incentive-based and price based [9].

Incentive-based DR

Incentive-based programs offer payments to the consumers to motivate them to decrease their demand during a specific time period, e.g. when the electricity system is stressed [9]. This can be done on a voluntary basis (demand reduction bids) or by using mandated commands given by the service operator. For example, in the case of direct load control, certain devices are enrolled which can be remotely shut down when required, and the customers get paid an incentive [23].

On a single household scale, an incentive-based program can help satisfy grid requirements and save costs for the consumer, however, the cost reduction depends on the availability of an incentive and is thus not guaranteed. Also, the user needs to hand over some comfort in return for the price reduction so when this happens too often the consumer may choose to discontinue the agreement. It is also very hard to determine the baseload profile for just one house [8].

Price-based DR
Price-based programs, also known as time-based DR or dynamic pricing, grant time-varying electricity prices to the consumers [9]. On a single household scale, price-based DR gives more frequent possibilities to consumers to reduce their energy bills, however, they can choose for themselves how much comfort there are willing to give up. For the energy providers, this results in more uncertainty about how much load reduction will be achieved by the price changes. Dependent on how it is implemented, the price variations could change frequently making it hard to predict and difficult for the end-users to adapt to [8].

Many of these DSM load shaping techniques are already used in the Netherlands or planned to further be implemented as mentioned in Section 1.5. For Dutch households specifically, the dynamic pricing scheme is the most relevant. Using this scheme in combination with DR can help the household lower their energy bills, and help balance the grid.

2.3 Neighbourhood EMS Coordination

Most proposed solutions on household level control their loads while ignoring the effects of the energy consumption of other households. All consumers typically get the same signals from the utility when using DR. This means that if all devices are programmed the same way in a neighbourhood, everyone might switch on or off their devices at the same time, causing new problems such as synchronization effects and rebound peaks, which might be even higher than the peak the system was trying to prevent. Coordination between the households by using a neighbourhood EMS could help prevent such problems.

Assume that a smart neighbourhood consists of smart houses that are connected by an electrical grid and a communication network. This network can communicate with the houses and thus coordinate their actions. The coordination structures used for the neighbourhood level can be centralized or decentralized [8].

A new entity called an aggregator can be used to aggregate the energy and power from multiple households and sell the total capacity on the energy markets [19]. This way the aggregator may help to reduce the energy bills of participating households and can be the middle-man between the utility and the customers.

Centralized
In a centralized structure, one central operator manages (a part of) the energy usage of all houses. It optimizes the loads by using the information communicated by the HEMS and scheduling the devices accordingly. Studies show that a centralized approach can lead to efficient electric energy use and maximum use of RESs. However, the computational burden can be quite high, so centralized control is not yet suitable for large-scale applications where computational time matters in general [8].

Decentralized
In the decentralized structure, the consumers schedule their own devices. To successfully do this the houses do need to communicate to get enough information about the neighbourhood's electricity profile. They can communicate directly with each other or via a central entity, or with both each other and a central entity. Research shows that this approach quite often achieves 20% cost reduction and/or peak load reduction [8]. The aggregated costs for decentralized control tend to be higher than using a centralized approach, but the end users have more freedom of choice. Also, households that have more flexibility may be gaining more than those that have less. The convergence time and necessary bandwidth may be significantly higher for the decentralized approach as many iterations are generally needed to reach convergence and therefore frequent communication is needed [8].

2.3.1 State of the Art Solutions

Some studies on the impact of neighbourhood EMSs compared to individual EMSs are shown below [25],[26],[27], [28],[19].

Mascherbauer et al. [25] show the influence of EMSs on the residential load of both individual houses and on a national scale using an hourly optimization model for a single house to minimize costs for the consumer by also maximising self-consumption. A household in their model includes the building parameters, thermal and battery storage, PV panels on the rooftop, an HP and an airconditioner for cooling. Furthermore, the indoor thermometer is set dependent on the household's preference. A reference case without optimisation is compared to an optimisation to minimise the household's electricity bills, by including the electricity prices and feed-in tariff. For the national influence, they used a realistic current scenario for the types of houses and penetration levels of devices in Austria. A well-insulated building with 10kWp PV, an airconditioner, ground source HP and thermal storage, and no home battery showed the biggest annual decrease in electricity consumption from the grid through the use of a HEMS. Thermal storage has a limited impact on the optimization as space heating is not needed when there is a lot of solar energy (in summer). For the reference case, the use of home batteries lowered the demand from the grid due to being able to store the surplus electricity and use it later, however, for the optimization case, it does not have that big of an impact due to being able to use other storage potential in the form of pre-heating/cooling. Both fixed and variable electricity prices are researched. For all building types, it is shown that the use of the EMS improves the self-consumption significantly. A limitation of this study is that they only included building stock data for buildings up to 2011, but not for newly build houses nor did they take into account the evolution of new buildings and the installation of more emerging technologies.

Nizami et al. [26] developed a neighbourhood EMS using an aggregator to minimize costs, while also reducing the demand peaks in the grid. They modelled 20 houses with PV panels and battery systems for a single day using the TOU tariff while allowing energy trading. Moreover, they also take into account the battery degradation in the cost function. The results show that everyone in the neighbourhood profits from the energy sharing, however, there is quite a difference in the profits (0.07-3.96$/day) of a single house dependent on the capacity of the battery and the load demand of the house. Note that only the battery is used by the EMS for scheduling purposes.

Rafique et al. [27] propose EMSs for a neighbourhood with 20 houses in 5 apartment blocks that have EVs (allowing V2G), PVs, and batteries in order to minimize costs. One EMS uses an aggregator for the modelled apartment buildings to minimize aggregated costs and the other EMSs try to minimize costs for the individual households. They show that the net energy consumption lowers by 39% in both cases compared to not using any control and the cost savings are around 57 and 59% compared to the uncontrolled case. Furthermore, the aggregated EMS shows an additional cost saving of 8% compared to the individually controlled households.

Paterakis et al. [28] studied three houses with an EMS under a dynamic pricing scheme, equipped with PV, batteries, V2G EV and time-shiftable devices. They allow the households to sell energy to each other and to the grid for the same price as the buying price and simulate for one day with a 5-minute optimization interval. To prevent overloading of the grid they introduce constraints and propose a strategy to fairly distribute the grid capacity at low price periods over the houses. The costs are minimized and the transformer overloading is also minimized. This is mainly achieved by the V2G option for evening peak hours. They assume the feed-in price is the same as the buying price. Model predictive control is used to deal with estimation uncertainties. The model is simulated for one cold winter and one hot summer day. By controlling the EVs and HVAC the costs for an individual household can be minimized, and when controlling the community as a whole, the performance gain is 20% compared to when each household optimizes its own energy use separately.

Celik et al. [19] summarises more studies that have used coordination techniques for multiple smart houses, showing that optimization is the most popular technique, especially to minimize costs. Most studies do not take uncertainties on load and consumer behaviour into account. Furthermore, Celik et al. show that most management techniques are only tested on small-scale systems with less than 100 devices and storage systems, which are almost only tested on a community scale and very little on individual houses.

The trend seen in these studies shows that using EMSs does improve self-consumption and minimize energy costs significantly. Everyone benefits when using an aggregator and by allowing energy sharing, however, not everyone has equal profits. Furthermore, using an aggregated EMS increases the gains significantly compared to using individual EMSs.

2.4 Energy Communities

A way to use the decentralized approach in practice is through an energy community, where the members control the energy in the community themselves or they could use an aggregator or service provider to do this [29]. This can have different objectives. For example, by lowering the overall load on the grid coupling point, they can reduce transport losses and costs of the grid infrastructure due to less stress, resulting in a longer lifetime of the assets. In such a setting, the goal is to keep everything behind the grid coupling points instead of behind the meter. This can be achieved by sharing energy amongst the members of the community. Dependent on pricing structures and legislation it could be beneficial to optimize either the individual load profile or the communities energy profile. Reijnders et al. [29] show that household batteries can reduce the peaks on the overall energy profile of a neighbourhood by up to 36%. Furthermore, in a field test Reijnders [30] obtained a peak reduction of 25% together with annual savings of € 1400 using batteries and his proposed community hybrid pricing mechanism. This pricing mechanism might not be optimal, however, the study showed that participants' understanding was needed for social acceptance of the implementation of the pricing mechanism. Ghiani et al. [31] show an expected reduction of energy purchased from the grid of 38% in a village of 5000 inhabitants by using EMSs in the houses and installing additional PV- and battery systems as an energy community.

2.5 Smart Charging Parking Lots

Households do not have to be the only flexible entities in a neighbourhood. Smart charging parking lots can also provide a significant amount of flexibility. Smart charging is proven to work for alleviating the grid and can also lower energy bills, dependent on the pricing schemes used. For residential smart charging, the Electric Nation project found that using a smart ToU tariff prevents stressing the substations and limiting the peak evening demand [32]. However, the use of cost optimisation, with a lower tariff after the typical demand peak, resulted in a rebound peak at 22:00, which is an even higher peak than would happen when the cars would arrive home gradually and start charging immediately. Little research was found on parking lots specifically for residential areas and especially in combination with HEMS.

Almeide et al. [33] model and simulate the coordination between EV parking lot management systems and HEMS. The HEMS is modelled to minimize costs and the houses have PV panels, their own charging station and battery system. The EV smart charging parking lot is situated at work and also has PV panels and aims to minimize costs for the parking lot owner. One week in winter in Portugal is used for the analysis. The research shows that having a HEMS significantly decreases the electricity bills of the EV owner, whereas the smart parking lots have an adverse effect on the energy bills. The effect on the grid of a similar set-up is researched in [34], where a 33-bus system is used to showcase the reduction of active power losses in case of having only HEMS, having only an EMS for the parking lot and having both. The influence of the HEMS (reduction of 1.749MW power losses) is significant whereas the influence of only a smart parking lot was very low (0.004MW). When both used an EMS, the results were the most significant with a total reduction of 2.670MW.

2.6 Summary

Research shows that emerging technologies significantly influence the demand load on the electrical grid. Using different strategies this higher demand load can be shifted to for example prevent overloading the grid during peak moments. One of the most popular strategies to do this is DR. Households or other entities can use EMS in order to control their available flexible devices to use the DR programs to make a profit and help grid balancing. Studies show that households using an EMS for controlling their EV, PV-battery system, HP, HVAC system and/or shiftable devices can greatly improve their self-consumption and minimize their energy costs. All houses can use their EMS to optimize for themselves, but multiple households can also optimize their load profiles together, by e.g. using an aggregator. In such a case, studies show that all participating households will make a profit and the total gains will be higher compared to all households only having their own EMS. However, these gains might not be equally divided over all households. By forming an energy community, energy can be shared amongst participants and as such the aggregated load profile can be optimized in practice. The emergence of smart charging parking lots is expected and studies have shown that these can also help in alleviating the grid and lowering the energy bills, of course, dependent on who the owner is and what the EMS is optimized for.

Smart Home Control Algorithms

3

Chapter Objective: This chapter describes the control algorithms that are considered for the simulation of the smart houses and smart charging parking lot.

Chapter Contents

3.1 Introduction

A futuristic vision of a sustainable city could be one, where all houses, apartments, industry and other types of buildings and energy-consuming resources work together to match the electricity demand with the RES generation. As mentioned before, this control of the flexible devices is needed in order to keep up with the increasing electricity demand in congested grids and match it with RES generation. Looking at the residential sector only, it may be that many houses get a HEMS, which are however not communicating with their neighbours. Consumers are expected to steer these HEMS price based in order to lower their energy bills. In the upcoming years, the way to achieve the lowest energy costs in the Netherlands, as described in Section 1.5, will most likely be a combination of increasing self-consumption while following a dynamic pricing scheme.

Multiple smart houses can communicate either through a central entity or directly with each other to gain a good energy profile. This way the houses can work together and, dependent on the policies in place, can exchange their own generated energy. This could decrease the upfront and the societal costs by reducing the needed grid connection, and thus prevent the need to reinforce the grid. Looking at the probable future developments described in Section 1.5, it will be beneficial to increase the self-consumption of solar energy and to use electricity at low-demand times. Using the flexibility of the whole neighbourhood can help work towards these goals. In this context requirements of a good energy control system for a smart house and neighbourhood are:

- Scalable, so being able to add not only more devices and/or houses but also other types of buildings and parking lots;
- Guaranteeing the users comfort;
- Transparent communication to the users about how the system works;
- Robust against prediction errors and malfunctioning;
- Modular in adding/removing devices and able to control many different devices;
- Guarding the privacy of the user;
- Taking into account physical limits of devices and the grid.

In this research, we consider three different control schemes to show the impact of each scheme on each household separately and on the neighbourhood as a whole. The first considered control scheme is without using an extended EMS, but where only the battery is controlled by charging when there is solar energy and discharging when there is demand. The second control scheme is using dynamic pricing to minimize electricity costs, where each house has its own HEMS controlled without communicating with the other houses (see Section 3.2). In the third scenario, there is a controller that is connected to each participating HEMS and is aiming to achieve an aggregated profile, which is as flat as possible such that as much as possible energy is used locally, and to optimize the grid connection (see Section 3.3).

3.2 Individual-Based: Price Steering

In the individual-based price steering is used. Meaning that households control their devices based on day-ahead prices, such that they can save money on their energy bills. This is the most common control type at the moment and its usage is expected to increase in the future. These households only take their own gains into account and not their effects on the grid. Thus, this control method is considered an individual-based control scheme. The used prices for this individually based control case are the dynamic prices from 2020-2023 in the Netherlands. The steering is greedy and schedules the devices such that as much electricity as possible is consumed during the cheapest periods. Due to net metering in the Netherlands, the feed-in tariff is the same as the buying electricity price at the moment. This will change when the net metering subsidy is removed, making it often more profitable to use the own generated solar energy. However, there is still much uncertainty about the exact pricing schemes in the future. It might also be possible to buy and sell locally generated electricity to and from your neighbours. So for now the same prices for buying and selling electricity are assumed for the control algorithm.

3.3 Community Based: Profile Steering

In order to use most of the generated renewable energy locally in the neighbourhood and by that optimize the grid usage, the houses can steer their devices to keep the aggregated profile of the neighbourhood as flat as possible. This can be done by sharing information about their planned energy usage and adjusting their schedule to optimize the aggregated load of the neighbourhood. Profile steering is a suitable method for this [35]. Profile steering is a heuristic scheduling-based approach, which gives transparency to the user about how and when electricity is planned to be used. It is based on the assumption that a desired profile of the whole neighbourhood is specified (e.g. a load profile as flat as possible).

In this approach, the devices have to control their flexibility such that an overall profile is achieved, which is as close as possible to the desired profile. The flexibility of the available devices in a future time period is derived from a prediction based on historical data. As the desired profile is also based on predictions, errors herein may cause unobtainable schedules. This is resolved in the realization phase, wherein an asynchronous and event-driven approach is used to update the schedule when needed. This is done in such a way that not all calculations have to be re-done, making it computationally viable. The advantage of this method is that it avoids the known negative effects of only price-based steering, such as rebound peaks at low price periods. In the following the profile steering approach is explained in more detail.

3.3.1 The Algorithm

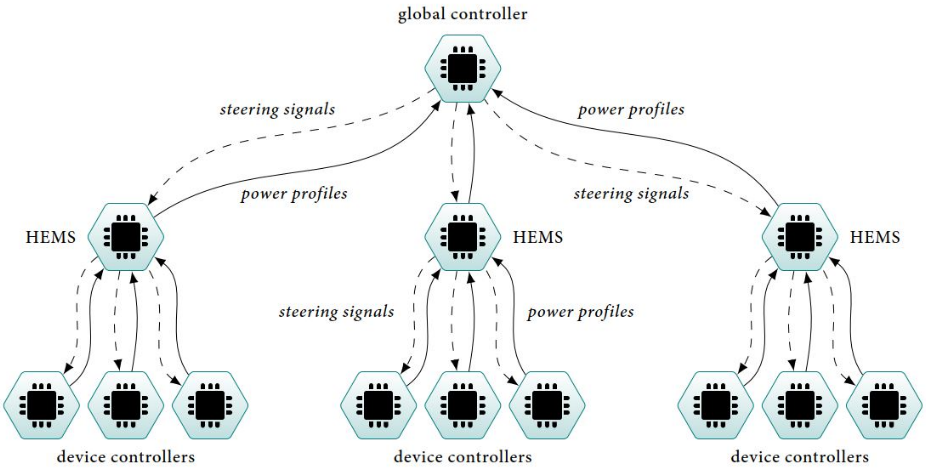


Fig. 3.1: Hierarchical structure of the profile steering algorithm [36]

The first phase of profile steering consists of synchronous scheduling, where each device optimizes its flexibility such that a new schedule is created for a certain time period in the future. Figure 3.1 shows the used hierarchical structure. By using a tree structure of control nodes, excessive communication is avoided and the process is split into sub-problems. This makes the process computationally feasible and allows to adhere to all different device and grid constraints. A higher-level controller enables a set of devices to work together towards a global optimum. This controller coordinates the energy usage of connected children (devices) by sending steering signals and an objective function. Hereby, each control node only has one parent and each controller creates its own new scheduled power profile and sends it to its control parent. This means the system is scalable and robust against communication failures.

Profile steering uses bi-directional communication between the controllers. Figure 3.2 shows the core structure of how the algorithm works: First, each device sends an initial planning to the higher-level controller, which creates an aggregated schedule of these plannings. These controllers send their aggregated profiles to their parent controller until all information is at the top controller. Next, the top controller sends a steering signal down via the mid-level controllers until it reaches the device controllers. Each device controller now optimizes its own scheduled profile and returns the new power profile and obtained improvement. The higher-level controller selects the device that can make the biggest improvement and replaces its scheduled profile with the updated version and gives the chosen device the signal to change its schedule accordingly. This process is repeated until none of the devices can make a significant improvement anymore or a given maximum number of iterations is passed.

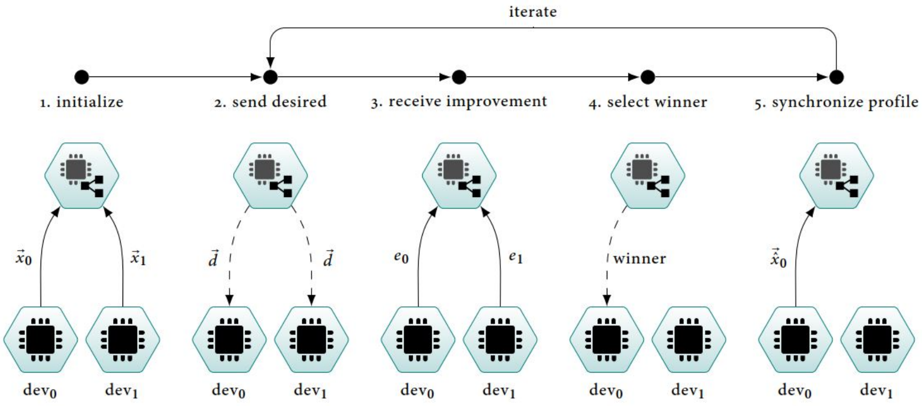


Fig. 3.2: Profile steering algorithm overview [36]

By only sending the resulting aggregated profiles, privacy-sensitive information is not passed to the higher-level controller from the HEMS, so it adheres to the privacy requirement. For a more elaborate explanation and overview of what happens when the schedule needs to be updated in case of an event, see Chapter 4 in [36].

3.4 Summary

In this chapter, we presented the control schemes used in this study. The first control scheme is not using any control. The other two control schemes are individual and community-based. In the individual-based control scheme, the households do not communicate with each other and use greedy price steering to minimize their own energy costs. The community-based control uses profile steering, where the houses work together to achieve an as flat as possible aggregated neighbourhood load profile. Optimizing for a flat overall load profile helps achieve a high self-consumption and prevents peak loads in the grid.

The implemented control algorithms are based on those already implemented in DEMkit [36].

Models

4

Chapter Objective: This chapter describes how the neighbourhood and EMS discussed throughout this thesis is modelled.

Chapter Contents

4.1 Introduction

A good and realistic model is required to properly investigate the impact of different devices and the effects of different control mechanisms. Based on this, we research the influence of different levels of penetration of the devices on the grid load, costs and self-consumption of the households and of the neighbourhood. Hereby, the used model should be designed in such a way that new devices and households can easily be added or removed. A suitable simulation environment for this is DEMKit, which is further explained in Section 4.2.

For testing the developed approach, we use a newly built neighbourhood in the Netherlands built by Heijmans as a test scenario. Heijmans provided the construction data of the houses and the expected devices within those houses, such that the test case can be considered representative of newly built neighbourhoods. The studied neighbourhood consists of 17 houses. The implementation of HPs and PV panels in newly built houses is the standard, whereas installing a home battery or charging station is the decision of the buyers. Thus the model needs to be able to simulate houses with and without batteries and charging stations. As the houses still need to be sold at the time of writing, nothing is yet known about the exact future inhabitants of this neighbourhood and their choices regarding equipment. Thus, assumptions of the type of people and what type of car they might own have to be made based on expectations from Heijmans. These expectations are based both on the location, the target group, and on general statistical information from the Netherlands.

Most of the houses are expected to be used by families with children. Furthermore, four houses are built especially for older people. Moreover, some houses will not be able to have their own parking space, hence are unable to receive a personal charging station in case they own an EV. For these households, there are enough public parking spots available in the neighbourhood for parking these cars, which also offer the opportunity to install public charging stations. In the future, it is assumed that a smart charging parking lot is built to provide charging opportunities for the EVs of these households. The model is made based on all provided data on the technical aspects of the houses as well as the expected inhabitants, which should be a proper representation of the real neighbourhood. It should be noted that grid restrictions are not taken into account in the model. However, the DSO intents to install a grid connection dimensioned for 4kW per house in this neighbourhood.

The remainder of this section first elaborates on the toolkit used for the model in Section 4.2. Then the variables and constraints of all modelled devices, and their in- and outputs, as well as how these devices are integrated into the house model are described in Section 4.3. Additionally, the model for the smart charging lot is disclosed in Section 4.4. Finally, Section 4.5 shows how the houses and smart charging parking lot are integrated into the neighbourhood model. Also, the exact input and output data for the studied neighbourhood based on the abovementioned assumptions are given. The used control system is as described in the previous chapter.

4.2 DEMKit

The model is made using the Decentralized Energy Management Toolkit (DEMKit), described in [36]. This is a tool that is able to test different optimization algorithms on a multi-energy system. It contains device, grid and control components and based on its modular design, different control algorithms can be tested on the same scenario. It uses a bottom-up modelling approach, meaning that each component is modelled individually. DEMKit is thus very suitable to implement a model with multiple devices and scalable to a whole neighbourhood, while still the profile of every device can be integrated. DEMkit works with device classes and for each of these device classes, there are different control and optimization components. Furthermore, multiple control algorithms are already implemented within the simulation tool. Additionally, due to the modular approach, it is easy to add new control methods and compare them on the same scenario if needed. The exact components and their parameters as implemented in the model are described in the next section. Moreover, it is also possible to replace the modelled device components with adapters to control real hardware, making it possible to test the system on a real smart house in the future.

4.2.1 ALPG

Realistic load profiles are necessary as input to the model to properly test our approach. There is very limited to no data available on the exact load profiles and flexibility of houses which have PV panels, HPs, batteries and EVs. To overcome this, an artificial load generator algorithm (ALPG) can be used to provide input for DEMKit. It generates electricity and heat profiles and the corresponding constraints [37]. For example, to get realistic data on the DHW consumption, the ALPG takes into account occupancy profiles of the houses and generates thermostat setpoints to come up with profiles for DHW usage and ventilation. The generation of the heat demand profile is based on [38] and is verified by comparing it to field test data.

In order to get reasonable profiles for the expected inhabitants of the newly built houses, the household types given in Table 4.1 are used as input to the model:

Tab. 4.1: Input of household types in the ALPG

Household type	Housenumbers
Fulltime & parttime working duo with 2 kids	0,1,2,3,4
Fulltime working duo with 2 kids	6,7,8,9,10,15,16
Fulltime & jobless duo with 2 kids	5
Retired duo	11,12,13,14

4.3 House Model

As mentioned before, the neighbourhood consists of 17 houses. These houses all have different occupants with different behaviour and thus different load profiles, generated by the ALPG. It should be possible to add or remove devices from the houses to test our approach. This is achieved by using a bottom-up approach, meaning that all devices are modelled individually and are aggregated in the house model. When a house does not have a specific device, it can simply not be added to the house model. An overview of all possible loads for a house is given in Figure 4.1, including all variables that need to be entered in the corresponding device model. In the following, the models for the different load types are elaborated upon, including the variables, flexibility and constraints corresponding to each device and the used input data for the test case.

4.3.1 Baseload

All houses have a baseload. This is an uncontrollable load consisting of devices such as the lights, fridge, TV and dishwasher. The baseload profile of a household is determined

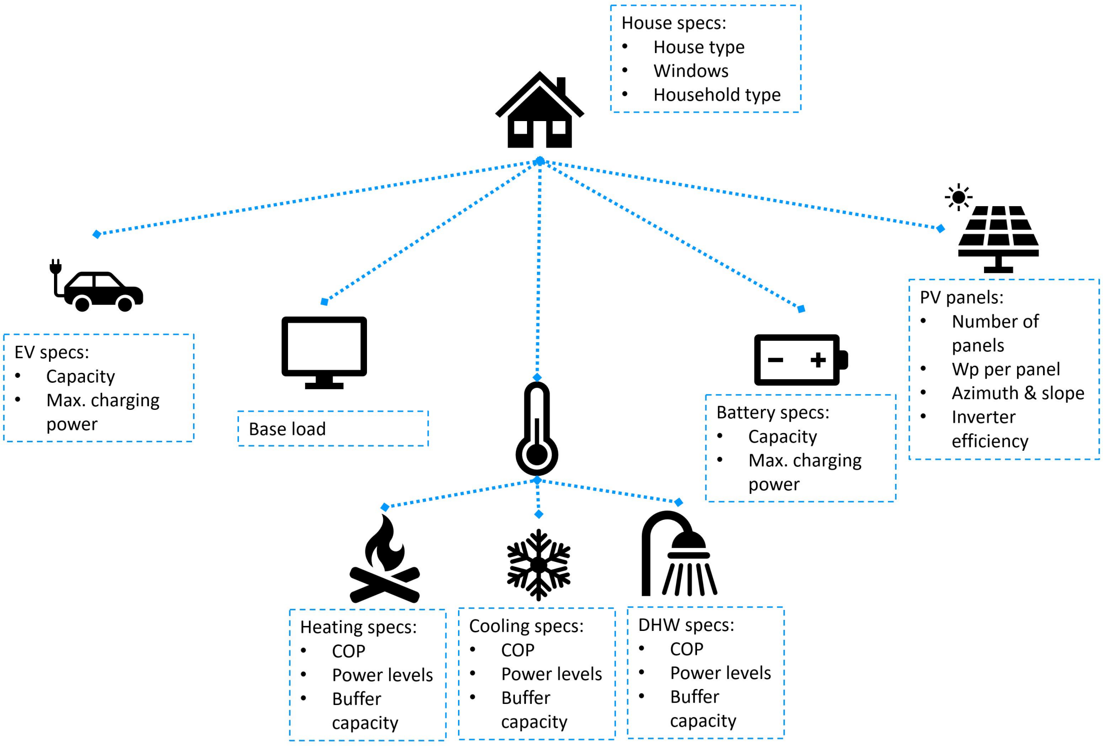


Fig. 4.1: Overview of the house model including the variables per device

by its inhabitants and their behaviour. For a household consisting of 2 people the average electricity demand in the Netherlands is 2850 kWh and for 4 people it is 4010 kWh [39]. The baseload of the modelled houses is randomized around these values. The modelled yearly loads per household are shown in Table 4.7.

4.3.2 Thermal Model

Not only do all houses have an uncontrollable baseload, but all Dutch houses also need heating. In this study, only HPs are used to provide space heating, cooling and DHW. The modelled HP provides flexibility to the control scheme used since the heating and cooling can be shifted in time and changed in power, within the constraints of the thermostat temperatures it has to reach. The size of the buffer of especially DHW adds more flexibility by being able to heat before actually using the hot water.

The thermal model for the houses in this study is based on the research of van Leeuwen et al [38], who present a thermal network model that can be used for simulation studies of house heating and cooling systems. The house's thermal properties are modelled using two resistance and two capacitance values and are based on a house using floor heating. Different parameter values are given for different types of houses, namely terraced houses, corner houses, semi-detached and detached houses. The houses in the test case are modelled as either the heavy semi-detached or terraced houses [38].

Tab. 4.2: Heat pump specifications

Heat pump parameter	Value
Producing powers	0, 1500, 2500, 3500, 4000 W
COP heating	5
COP cooling	27
COP DHW	2.5
Buffer capacity DHW	10000 Wh
Buffer capacity heating/cooling	2000 Wh

The thermal model as implemented in DEMkit [36] is based on [38] and takes into account the inside and outside temperatures, area of the house, heat flow, windows and their location with respect to the sun, the envelope of the house, the solar irradiance and gains from appliances and present people. Both the heating and cooling of the house and the DHW usage are in the model. The windows are also added to the houses at their respective places (note that only the windows on the first floor are taken into account). The exact values of the windows per modelled house are shown in Table 4.6.

The other input data to the thermal model are the heat gain profile, the thermostat start times, the airflow profile of the ventilation and the heat demand profile, which are generated by the ALPG. The outside temperature input is obtained from the hourly weather data in Eindhoven from KNMI [40].

The inside temperature is set using a value for when the heating or cooling should start, which is typically between 18.5 and 23 °C. The thermal model uses the operating power levels and COP of the heat pump as input variables. Furthermore, a buffer is also added for the DHW, which has a capacity, SoC and initial SoC.

All houses in the test case use the same heat pump and have a DHW buffer of 180L, which contains 55°C hot water. The modelled HPs specifications are shown in Table 4.2. The buffer capacity of the heating and cooling is used to model the water in the pipes of the floor heating. The heating, cooling and DHW are modelled as separate devices with an overlapping controller, together forming the heat pump. The HP is in practice only able to provide either heating, cooling or DHW at a certain time. However, since discrete modelling is used, it is allowed in the model to have overlapping producing periods during the 15-minute time intervals.

The expected yearly HP consumption is between 1800-2400 kWh dependent on the expected heat loss of the house, the expected number of occupants and the expected heating/cooling hours. The simulated yearly consumption of the modelled houses is shown in Table 4.7.

4.3.3 PV Model

As mentioned before, the implementation of both HP and PV panels is standard for newly built houses. The PV panels are, just like the baseload, uncontrollable in the model. The only flexibility they can offer is curtailment. However, this is not taken into account since there is currently no reason for homeowners to curtail their solar energy, as explained in Chapter 1.

The variables in the PV model are the Wattpeak, inverter efficiency, number of panels, panel size, azimuth and inclination angle. Furthermore, global irradiation values are needed to determine the solar energy generated at each time period.

The modelled PV panels have an area of $1.95m^2$ and 395Wp. The inverter efficiency is set at 0.77, which is chosen to get a similar generation as calculated by the PVGIS tool in Eindhoven using the same slope, azimuth and installed peak PV power, using a loss of 14% [41]. The inclination, azimuth and number of panels depend on the house and the exact data per house is given in Table 4.3. The azimuth uses 0 to indicate the north and 90 to indicate the east. The irradiation data is from "uurgegevens knmi" for 2020 until 04-2023 in Eindhoven [40].

Tab. 4.3: PV houses specifications

House number	Total number of PV panels	Number of PV panels 1	Azimuth PV 1	Slope PV 1	Number of PV 2	Azimuth PV 2	Slope PV 2
0	20	8	294	45	12	114	45
1	12				12	114	45
2	20	8	294	45	12	114	45
3	12	0			12	128	45
4	12	0			12	128	45
5	12	0			12	128	45
6	20	12	244	45	8	64	45
7	20	12	244	45	8	64	45
8	20	12	244	45	8	64	45
9	18	18	154	45			
10	18	18	236	15			
11	18	18	236	15			
12	18	18	236	15			
13	18	18	236	15			
14	20	12	288	45	8	108	45
15	12	12	288	45			
16	20	12	288	45	8	108	45

4.3.4 Battery Model

Home batteries are very suitable to store the energy generated by the PV panels. Batteries offer a lot of flexibility since they are always available to be used. In the model they are constrained by their SoC, so they cannot charge when they are full or provide energy when they are empty. The other constraint is its charging and discharging power. It should be noted that the degradation of the battery is not included in the model. The values for the maximum charging and discharging power, the battery's capacity and its initial SoC are input for the battery model.

The batteries used in the modelled houses consist of two types. Their specifications and in which houses they are optionally placed are described in Table 4.4 and Table 4.6, respectively.

Tab. 4.4: Battery specifications

Battery parameter	Value	Based on
Capacity 1	6390 Wh	Pylontech Force L1 7.10kWh
Capacity 2	9590 Wh	Pylontech Force L1 10.65kWh
Charging/discharging power 1	3000 W	Solis S5-EH1P3K
Charging/discharging power 2	5000 W	Solis S5-EH1P5k
Initial SoC	3195 Wh	
Initial SoC	4795 Wh	

4.3.5 EV Model

An EV in theory has similar flexibility as a battery, however, V2G is not allowed in the model, so it cannot provide energy to the house. Moreover, it is constrained by the moments it is connected to the charging station, which on a typical workday results in only having the flexibility to be charged between the homeowner arriving home from work and going to work in the morning.

Tab. 4.5: Specifications of different EV models

EV model	Capacity (kWh)	Max. charging power (kW)
Tesla model 3	57.5	11
Hyundai Kona	64	11
Nissan Leaf	40	6.6

The variables of the EV model are the capacity and charging power of the EV. The used parameters are based on the constraints of the chosen charging station Heijmans will offer, which means charging up to a maximum of 11kW. Furthermore, the capacity and charging power of the modelled EV are based on the most common EVs in the Netherlands right now [42]. These are the Tesla model 3, Nissan Leaf and Hyundai Kona, see Table 4.5 for their specifications.

It is assumed that 70% of the charging sessions will be at home and around 13000 km is driven on average per car per year, resulting in around 30 km a day for commuting [42]. The electricity usage of the car is generated by the ALPG and is around 5.5kWh/km, which is very close to the consumption of the three types of cars. Other input data are the EV start- and end times, which are generated by the ALPG based on the type of household and occupancy profiles.

4.3.6 Example Load Profile

All the abovementioned models provide a load profile as output. The smart meter of the house aggregates all these profiles. Figure 4.2 shows an example of these profiles for the abovementioned device models of house 2 on the 12th and 13th of October 2022.

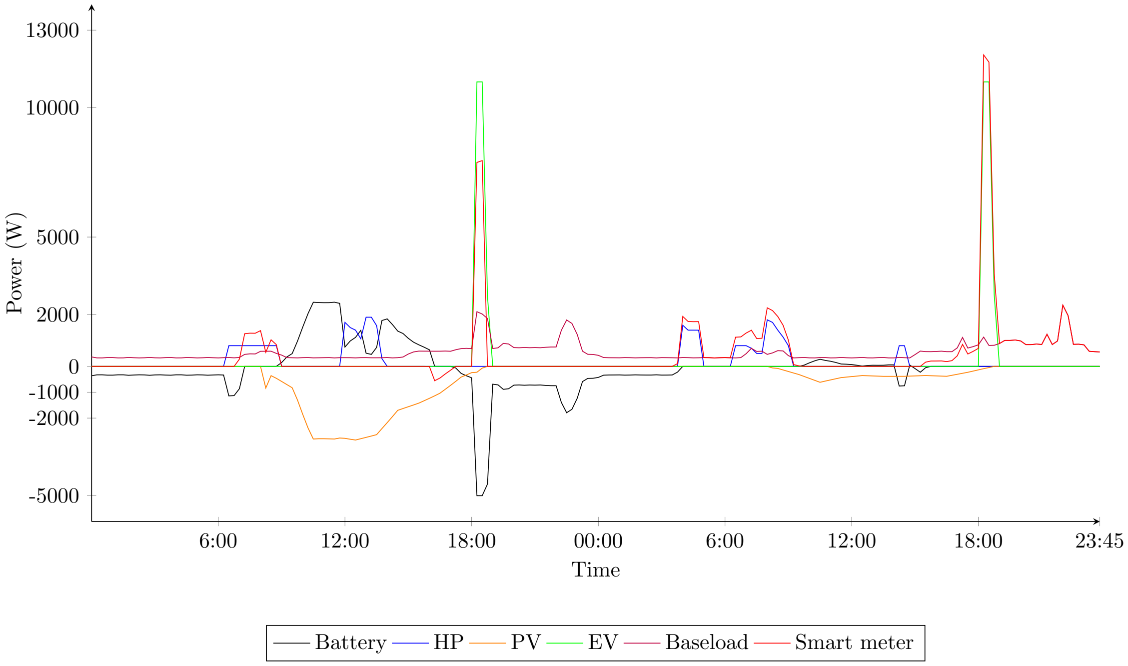


Fig. 4.2: The load profiles of house 2 for 2 days in October

4.4 Smart Charging Parking Lot Model

The households that own an EV, but cannot have their own charging station need to use the smart charging parking lot. This means that a certain number of EVs needs to be added to the smart charging parking lot. Thus the input is a list of EVs with all the variables described in Subsection 4.3.5. The model uses the EVs driving patterns of the households that do not have their own charging station possibility at home. The charging profiles are thus similar to those of EVs which are connected to private home charging stations and correspond to the user behaviour. All cars connected to the charging stations are being controlled in the same way by the smart charging parking lot owner. The used input of this model is the EVs as specified by the ALPG for the houses that do not have their own parking lot, but it is also possible to add guest cars to the model. The EV types and consumption of the relevant cars are shown in Table 4.6 and Table 4.7, respectively.

4.5 Neighbourhood Model

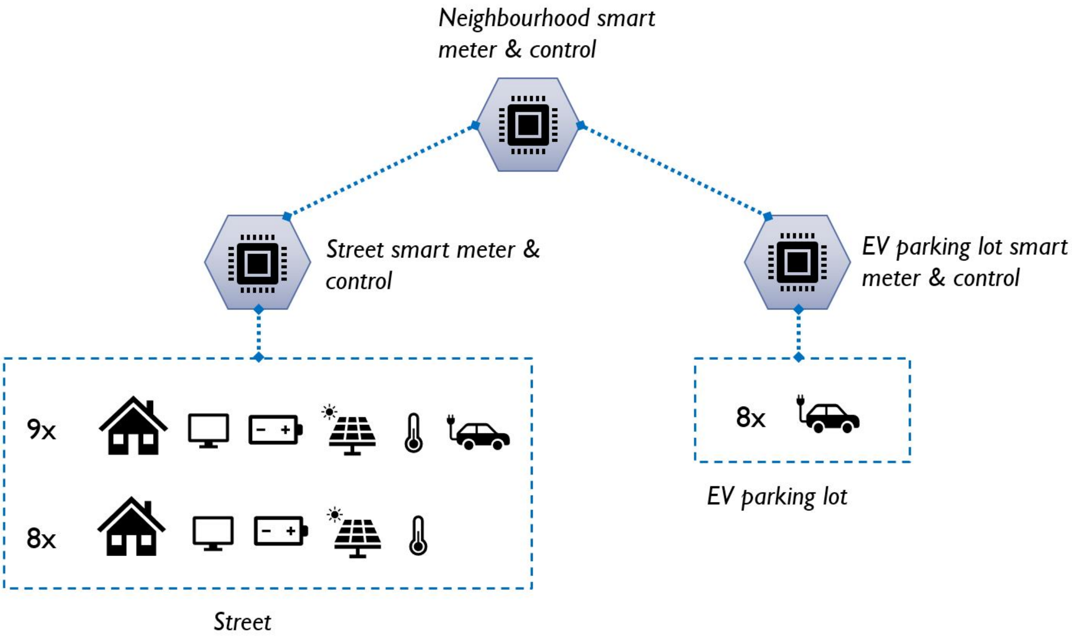


Fig. 4.3: Overview of the neighbourhood model

The neighbourhood model combines the smart charging parking lot and the houses with their corresponding devices. The houses are connected to a street controller, and the smart charging parking lot also has its own controller. Consequently, a different control scheme can be used for the houses than for the parking lot. Moreover, they can also be connected to the neighbourhood controller and communicate with each other. Figure 4.3 shows an overview of the neighbourhood model, in the scenario where every house has a baseload, battery, PV panels, HP and EV. An overview of the input data of the houses for the used neighbourhood model is shown in Table 4.6. Table 4.7 shows the output yearly consumption of the houses individually, which are close to the expected values as described above.

Tab. 4.6: Houses specifications

House number	Number of occupants	Type of household	windows: (m^2), Orientation	Own charging pole	EV Type	Battery Capacity (Wh)
0	4	Householdfamilydualparent	3.75, 294, 6, 114, 6, 24	no	Tesla model 3	9590
1	4	Householdfamilydualparent	3.75, 294, 6, 114	no	Hyundai Kona	6390
2	4	Householdfamilydualparent	3.75, 294, 6, 114	yes	Tesla model 3	9590
3	4	Householdfamilydualparent	3.75, 310, 6, 130	yes	Hyundai Kona	6390
4	4	Householdfamilydualparent	3.75, 310, 6, 130	no	Tesla model 3	6390
5	4	Householdfamilydualparent	3.75, 310, 6, 130	yes	Nissan Leaf	6390
6	4	Householdfamilysingleparent	3.75, 244, 6, 64, 2.25, 334	yes	Tesla model 3	9590
7	4	Householdfamilydualparent	3.75, 244, 6, 64	no	Tesla model 3	9590
8	4	Householdfamilydualparent	3.75, 244, 6, 64	no	Hyundai Kona	9590
9	4	Householdfamilydualparent	3.75, 244, 6, 64, 7.125, 154	no	Tesla model 3	9590
10	2	retireddual	6, 326, 6, 146	yes	Nissan Leaf	9590
11	2	retireddual	6, 326, 6, 146	yes	Tesla model 3	9590
12	2	retireddual	6, 310, 6, 130	yes	Nissan Leaf	9590
13	2	retireddual	6, 310, 6, 130	yes	Tesla model 3	9590
14	4	Householdfamilydualparent	3.75, 108, 6, 288	yes	Nissan Leaf	9590
15	4	Householdfamilydualparent	3.75, 108, 6, 288	no	Tesla model 3	6390
16	4	Householdfamilydualparent	3.75, 108, 6, 288, 6, 18	no	Hyundai Kona	9590

Tab. 4.7: Yearly consumption and production of modelled houses

House number	Baseload(kWh)	HP consumption(kWh)	PV generation (kWh)	EV consumption(kWh)
0	4800	2357	6600	3530
1	4740	1589	4200	2390
2	4640	2219	6600	1650
3	3510	2047	4500	2710
4	4550	2047	4500	1230
5	4840	2290	4500	2410
6	3500	2163	6500	1710
7	4250	2009	6500	2660
8	4740	1911	6500	3220
9	4880	1789	7200	1370
10	3350	1373	6900	168
11	2460	1608	6900	568
12	2000	1906	6900	465
13	3210	1496	6900	481
14	3700	2041	6300	2300
15	3350	1625	3400	2900
16	3910	1851	6300	1730

Evaluation

5

Chapter Objective: This chapter presents and discusses the results obtained from the simulation studies.

Chapter Contents

5.1 Introduction

This chapter shows the resulting impact of scenarios with different penetration levels of emerging technologies and different control algorithms on the neighbourhood. In the base case scenario, described in Section 5.2, the impact of emerging technologies is depicted. Afterwards, in Section 5.3, the results of the realistic scenario show the impact of different control schemes for the expected penetration levels of batteries, EVs and EMSs. The futuristic scenario, described in Section 5.4, presents the impact of different control strategies at a 100% penetration of EMSs, EVs and home batteries, whereby also the effect of a smart charging parking lot is shown.

The impact is measured in the total yearly consumption of the neighbourhood, the amount of electricity imported and exported, the self-consumption, the maximum and minimum power levels and the prices based on a dynamic pricing scheme and a fixed pricing scheme with net metering. Subsection 5.1.1 details how these measures are calculated. Furthermore, the load duration curves are plotted to illustrate how long the grid is overloaded in the simulated year. As already mentioned, the grid connection is designed for 4kW per house in this newly built neighbourhood, which is used as the threshold line for overloading the grid.

Finally in Section 5.5, the results are analyzed per household for the futuristic case to provide a clear overview of the different divisions of gains and losses for the individuals. The influence of owning a battery on both costs and self-consumption is also shown. This enables us to create insight into the differences between households and thus the social implications of smart houses.

All simulations use 15-minute intervals and the results are given for the period between 15-05-2022 and 14-05-2023 (35040 time intervals), which is the most recent data available at the time of writing. The choice to use the most recent data instead of the latest calendar year is to diminish the influence of COVID-19 and the war between Ukraine and Russia on energy prices.

5.1.1 Evaluation Metrics

As above-mentioned, different indicators are used to assess the results: the yearly consumption, import, export, self-consumption, minimum and maximum power as well as dynamic and fixed prices. These are calculated per house per measured time interval. The variables used are the energy used or produced by the baseload (E^{BL}), HPs (E^{HP}), PV-panels (E^{PV}), EVs (E^{EV}) and batteries (E^{Bat}). It should be noted that consumption gets a positive value and production a negative value, such that the PV panels always have a negative value and the battery can have both negative and positive values. The sum of these determines the energy consumption or production of a house h at each time interval t and is defined as E:

$$E_{t,h} = E_{t,h}^{BL} + E_{t,h}^{HP} + E_{t,h}^{PV} + E_{t,h}^{EV} + E_{t,h}^{Bat} \tag{5.1}$$

The evaluation metrics are determined as follows:

- **Yearly consumption**
  To determine the yearly consumption value, denoted as E^{year}, all 15-minute consumption and production values of the simulated year per device are aggregated. This results in the net meter value of the whole neighbourhood. In the futuristic scenario, this means:

  $$E^{year} = \sum_{h=1}^{H} \sum_{t=1}^{T} E_{t,h} \tag{5.2}$$

  The inner summation sums up all consumption and production for each 15-minute time interval of the year, where T is the total number of time intervals, in this case, 35040 (number of 15-minute intervals in one year). The outer summation sums all consumption and production of the different houses, where h are the houses and H is the total number of houses, in this case, 17.

- **Import & export**
  When the aggregated consumption and production of all devices in a house over one 15-minute interval is positive, that amount of electricity is imported. The imported energy is denoted as E^{imp}. When the overall consumption and production at that time interval is negative, that amount of electricity is exported. The exported energy is denoted as E^{exp}. The following equations result in the total export and import values of one household over a year:

$$E_{t,h}^{imp} = max(E_{t,h}, 0) \tag{5.3}$$

$$E_{h}^{imp} = \sum_{t=1}^{T} E_{t,h}^{imp} \tag{5.4}$$

$$E_{t,h}^{exp} = min(E_{t,h}, 0) \tag{5.5}$$

$$E_{h}^{exp} = \sum_{t=1}^{T} E_{t,h}^{exp} \tag{5.6}$$

  Where T is again the total number of 15-minute time intervals, in this case 35040. The final neighbourhood import and export is the sum of the import and export of all houses.

- **Self-consumption**
  The self-consumption, denoted by SC, is the percentage of generated solar energy that is consumed, thus not exported. It is determined by first checking whether the total aggregated value of all devices is smaller than the solar energy generated during a time interval. This can happen when a battery is also discharging. If this is the case, it means that no solar energy is being consumed and the self-consumption for that period is zero (Equation 5.7). When the total aggregated value of all devices is bigger than the generated solar energy over that 15-minute time period, the self-consumed energy, denoted by $E_{t,h}^{sc}$, is the smallest value of either the aggregated value of the devices excluding PV, or the absolute value of PV (Equation 5.8). Since not all solar energy needs to be used at that time period, the $E_{t,h}$ minus $E_{t,h}^{PV}$ decides which part of the generated PV energy is used. When all self-consumed values of a household over every time interval are known, these will be aggregated to determine the self-consumption in kWh, denoted by E_{h}^{SC}, over the year (Equation 5.9). Finally, the percentage of self-consumed energy is determined by dividing this value by the total

generated solar energy (Equation 5.10), giving the final self-consumption value in percentage of a household.

$$E_{t,h}^{SC} = \begin{cases} 0, & \text{if } E_{t,h} < E_{t,h}^{PV} \quad (5.7) \\ (min(abs(E_{t,h}^{PV}); (E_{t,h} - E_{t,h}^{PV})), & \text{otherwise} \quad (5.8) \end{cases}$$

$$E_h^{SC} = \sum_{t=1}^{T} E_{t,h}^{SC} \tag{5.9}$$

$$SC_h = \frac{E_h^{SC}}{\sum_{t=1}^{T} E_{t,h}^{PV}} * 100\% \tag{5.10}$$

Where T is again the total number of measured time intervals: 35040. As mentioned, the calculated self-consumption is given per household. For the neighbourhood SC, a similar approach is used where all devices of all houses in the neighbourhood are aggregated first. Followed by the same analysis where the h-index is omitted.

- **Costs calculations**
  There are multiple energy pricing schemes in the Netherlands at the moment. The current situation with net metering is used to calculate the energy costs using both the fixed energy tariff and the dynamic energy tariff. The dynamic tariff calculation uses the Day-ahead prices retrieved from ENTSO-E [43] over the simulated time period. However, there are also taxes that need to be paid per kWh. These values are obtained from the Dutch tax administration [44] and consist of the Renewable energy storage (ODE) tax and the electricity tax. For 2022 the ODE plus energy tax incl. VAT were €0.08142 per kWh, and for 2023 €0.15245 per kWh. All costs that did not include VAT yet are multiplied by 1.21 to obtain the including VAT prices. Note that in the net metering scheme, when the annual net meter value is below zero (meaning net production), the household will not get their taxes returned over the excess produced energy. In this case, the final costs get reduced by the final net meter consumption times the ODE plus electricity tax. The tax values used for this final calculation are the averages for 2022 and 2023.

  The costs for a household using dynamic pricing, denoted by C^{dyn}, are calculated using the aggregated consumption value (kWh) over an hourly time period times the sum of the day ahead price (P^{dyn}), ODE (P^{ODE}) and electricity tax (P^{tax}) (euro/kWh incl. VAT), as shown in Equation 5.11. In this case, T is 8760, since hourly intervals are used. These hourly consumption data are obtained from the averages of four 15-minute values.

$$C_h^{dyn} = \sum_{t=1}^{T} E_{t,h}(P_t^{dyn} + P_t^{ODE} + P_t^{tax}) \tag{5.11}$$

Fixed pricing typically uses the same kWh price for one calendar year, this price is denoted as P^{fix}. The costs are calculated including VAT using Equation 5.12.

$$C_h^{fix} = \sum_{t=1}^{T} E_{t,h}(P_t^{fix} + P_t^{ODE} + P_t^{tax}) \tag{5.12}$$

The electricity prices in 2022 and 2023 are taken from CBS [45] and are based on national average prices. This means that the fixed electricity price including VAT for up until August 2022 is €0.20687 per kWh, from September 2022 until December 2022 is €0.42245 per kWh and for 2023 €0.4 per kWh. In comparison, the average dynamic price including VAT for the simulated time period is €0.24752 per kWh.

5.2 Base Case Scenario: The Impact of Emerging Technologies

The base case scenario is performed to show the difference between a newly built neighbourhood and a traditional Dutch neighbourhood. In a traditional neighbourhood, most houses only have a baseload, and some might have PV panels on their roofs. Newly built houses need to be natural gas-free and comply with the latest Energy performance coefficient (EPC) and sustainability norms, thus they get a HP and PV panels. The implementation of a home battery and/or charging station for an EV is up to the house owners. As described in Chapter 2, studies on these emerging technologies already demonstrated that they have a significant impact on the grid load.

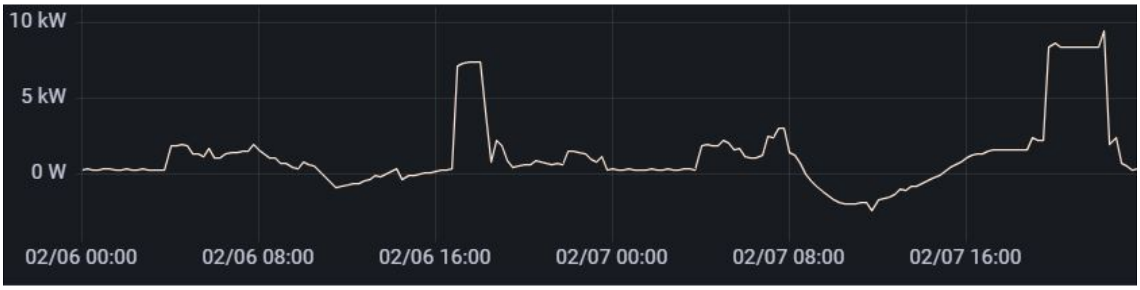
Tab. 5.1: Results of the base case scenarios

17 houses	E^{year} **(kWh)**	E^{imp} **(kWh)**	E^{exp} **(kWh)**	SC **(%)**	**Min. Power (kW)**	**Max. Power (kW)**	C^{dyn} **(€)**	C^{fix} **(€)**
Baseload	66,2	66,2			4,6	26, 7	25074	29837
Baseload, HP, and PV	-1,1	60,0	-61,1	38,9	-66,3	41,6	1611	6456
Baseload HP, PV, and EV	30,2	88,4	-58,2	41,8	-66,3	109,8	14457	20733
Baseload HP, PV and battery	-1,1	39,4	-40,6	60,2	-66,3	41,4	-671	6464
Baseload HP, PV, EV and battery	30,2	65,0	34,8	65,2	-66,3	109,4	12175	20741

In this study, multiple scenarios are used to show the impact of adding emerging technologies to the neighbourhood without the use of any control. Figure 5.1 shows the smart

(a) The baseload profile of house 5 for 2 days in winter

(b) The baseload, HP and PV aggregated profile of house 5 for 2 days in winter



(c) The baseload, HP, PV and EV aggregated profile of house 5 for 2 days in winter

(d) The baseload, HP, PV and battery aggregated profile of house 5 for 2 days in winter

Fig. 5.1: The smart meter load profiles of the different base case scenarios

meter profiles of house 5 for the different scenarios for 2 days in the winter and Table 5.1 shows the overall results of all houses together. In the first scenario (Figure 5.1a), there are no emerging technologies and thus the profile only contains the baseload. This represents a typical Dutch neighbourhood of the past. In the second scenario (Figure 5.1b), the houses have PV panels and an HP, as is the case in the newly built houses. The third scenario (Figure 5.1c) looks at the influence EVs have, assuming that all households have one EV, and the fourth scenario (Figure 5.1d) investigates the impact of a home battery without an EV. The home battery is controlled reactively, so it charges when there is a surplus of solar energy and discharges when there is demand. The last scenario examines the impact of every household owning one EV and a home battery. The load duration curve for every scenario is given in Figure 5.2.

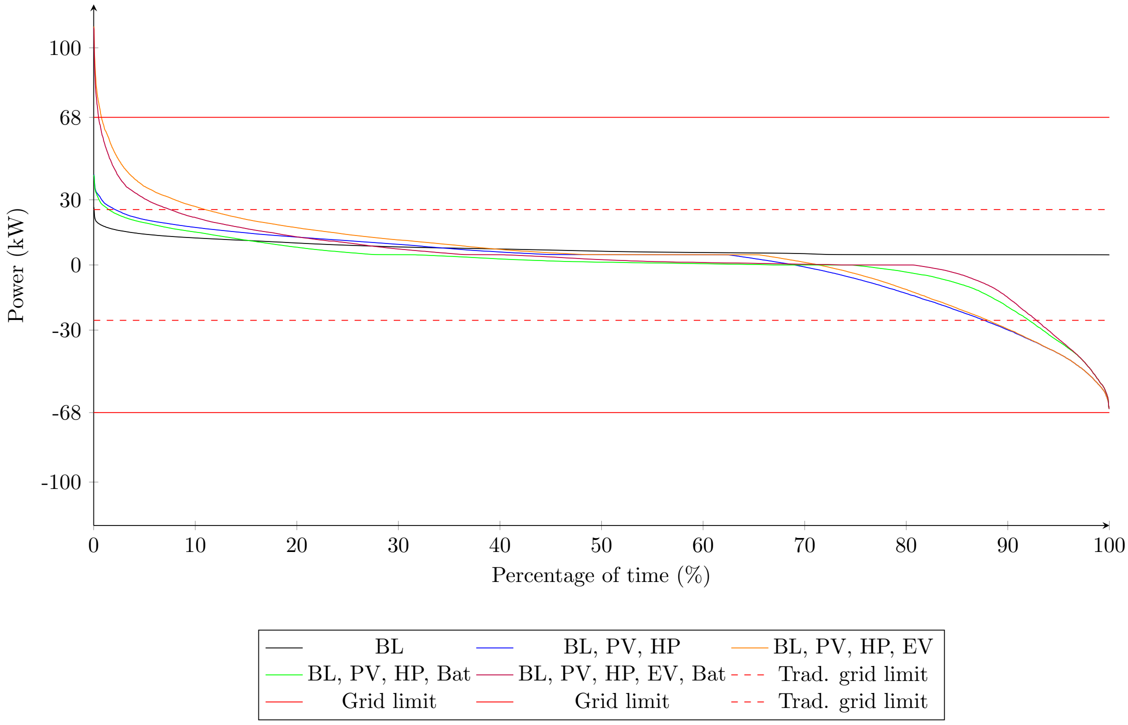


Fig. 5.2: Load duration curve of the neighbourhood for one year

The results show that the minimum and maximum power of the neighbourhood is greatly increased by the addition of emerging technologies, as is in line with the trends seen in the literature. With just the addition of HPs the maximum power increases with a factor of 1.5, and the minimum power becomes 15.4 times as big due to the addition of PV panels compared to a simulation without PV panels. It has to be mentioned that these houses have relatively many PV panels, but it is a realistic scenario since there is a financial gain for the house owners to install more PV panels than they need.

The maximum peak is further increased when the houses also own an EV, namely with a factor of 4.1 compared to the baseload scenario. The use of batteries causes the self-consumption to increase by over 20 percentage points but has little influence on the maximum and minimum power levels on the grid. This makes sense since they are controlled reactively, and cannot charge when they are full, resulting in the solar energy still being fed in during peak production periods when the battery is already full.

In the base case, the EVs are the main reason for exceeding the grid limits. The grid limit is exceeded for 38 hours with home batteries and 63 hours without home batteries. Note that here the new grid limit of 4kW is used, however, the traditional grid connections are designed for 1.5kW per household. So when comparing the results to the traditional grid limits, they are exceeded for 52 full days when only adding HP and PV to the houses and for 83 full days when also adding one EV per household (without a home battery) in the simulated year. Around 1000 hours of these are caused by the PV panels. When home batteries are used, these values would be decreased to 34 days and 53 days without and with EV respectively.

5.3 Realistic Scenario: The Impact of Different Control Algorithms

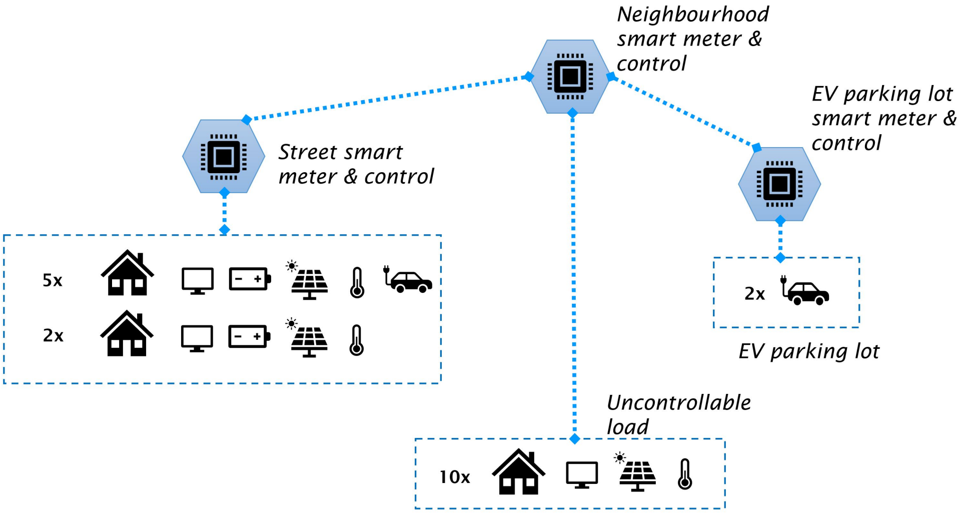


Fig. 5.3: Overview of the neighbourhood model in the realistic scenario

In the realistic scenario, we reflect the expected situation for the newly built neighbourhood. An overview of the model used for this scenario is shown in Figure 5.3. All houses have a baseload, PV panels and an HP. Houses 0, 2, 3, 6, 10, 12 and 16 also have a HEMS, battery and own one EV. Of these houses 0 and 16 do not have their own parking space, so these cars are charged at the smart charging parking lot. The results for this scenario are shown in Table 5.2. The load duration curve is given in Figure 5.4.

Tab. 5.2: Results of the realistic scenario using different control methods

17 houses and parking lot	E^{year} (kWh)	E^{imp} (kWh)	E^{exp} (kWh)	SC (%)	Min. Power (kW)	Max. Power (kW)	C^{dyn} (€)	C^{fix} (€)
Uncontrolled	10,6	60,5	-49,8	50,20%	-66,3	63,0	4701	11866
Price steering	10,7	106,2	-95,5	43,90%	-99,1	111,4	-92	11889
Profile steering	10,6	55,2	-44,6	55,40%	-52,4	34,9	3569	11852

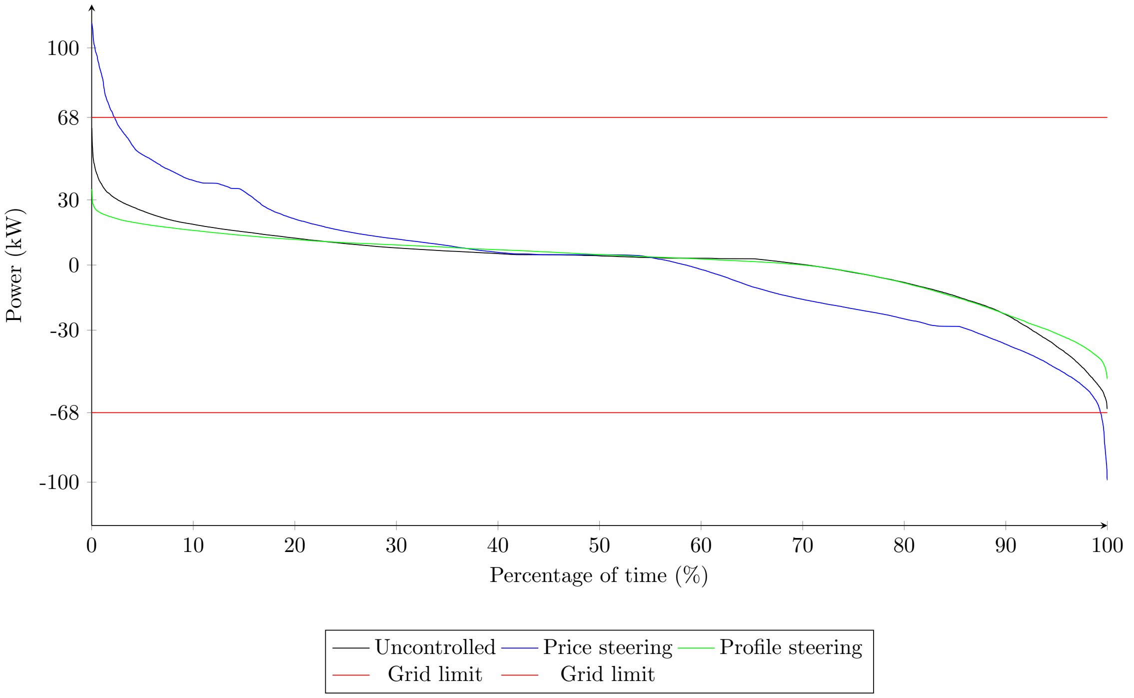


Fig. 5.4: Load duration curve of the neighbourhood for one year

As is expected with price steering, the energy costs of the household using dynamic prices are decreased by 52%, this is in line with other research mentioned in Chapter 2. Notably, even when optimizing the grid connection and self-consumption using profile steering, the energy costs are still lower than in the uncontrolled case.

It is also noteworthy that the import and export, and thus usage of the grid, is significantly higher while using price steering. This is caused by the battery charging and discharging multiple times a day to get the most profit. As the buying and selling prices are equal, the implemented price steering is not optimised for self-consumption, and thus the self-consumption is lowered by 6 percentage points compared to the uncontrolled case. In contrast, profile steering tries to keep the profile as flat as possible, increasing the self-consumption by 5 percentage points. It should be noted that in the realistic scenario, the houses that do own a HEMS and use profile steering are unaware of the behaviour of the other uncontrolled houses. If they were aware the self-consumption and grid overloading on the whole neighbourhood might be improved even further. The self-consumption for the uncontrolled case is already relatively high since the batteries are controlled reactively and thus solely used for storing and using solar energy.

The grid limits are only exceeded when price steering is used, however, the maximum and minimum peaks are increased by a factor of 1.8 and 1.5 compared to the uncontrolled case, which sums up to a total of 250 hours or 10 full days of exceeding the grid limit. This means that already if only 41% of the houses steer on price and have one EV and home battery, this can cause serious grid issues for the whole neighbourhood. On the other hand, when these houses implement profile steering, the maximum and minimum power over the grid is lowered by a factor of 1.8 and 1.3 respectively.

5.4 Futuristic Scenario: Impact of 100% Penetration of Emerging Technologies

Having seen the impact on the neighbourhood that 7 houses already have with an EMS, EV and battery, we now investigate what happens with a 100% penetration level of these devices. So the impact of the different control schemes is investigated when each household has a HEMS, EV and home battery. As not all houses can charge their EV at home, the smart charging parking lot is used to charge these cars. This parking lot might be owned by a third party that wishes to use a different control scheme than the households do, so different scenarios are simulated in case the houses and parking lot use different control strategies. The results are shown in Table 5.3 and the load duration curve per scenario is shown in Figure 5.5.

Tab. 5.3: Results of the futuristic scenario using different control methods

17 houses and parking lot	E^{year} **(kWh)**	E^{imp} **(kWh)**	E^{exp} **(kWh)**	SC	**Min. Power (kW)**	**Max. Power (kW)**	C^{dyn} **(€)**	C^{fix} **(€)**
Uncontrolled-all	30,2	65,0	-34,8	65,2%	-66,3	109,4	12175	20741
Price steering- all	30,3	200,0	-169,7	46,1%	-140,5	223,9	1250	20807
Profile steering-all	30,1	56,6	-26,5	74,7%	-35,5	31,6	9357	20696
Price steering- houses **Profile steering- parking lot**	30,2	195,4	-165,2	46,5%	-140,5	155	2841	20779
Profile steering- houses **Price steering- parking lot**	30,1	59,7	- 29,6	74,2%	-35,1	90,4	7792	20725

Impact on the grid:
As was the case with the realistic scenario, the impact on the grid increases significantly when steering on the dynamic prices compared to the uncontrolled scenario, whereas using profile steering minimizes the impact on it. This is clear when looking at Figure 5.7.

When everything is steered using dynamic prices, the maximum power exceeds the grid limit by a factor of 3.3 and the minimum power by 2. Furthermore, the duration of exceeding the grid limits is significant, as can be seen in Figure 5.5. Resulting in the limits being exceeded for 2274 hours or 95 full days. Whereas in the uncontrolled case, the limit is exceeded for only 38 hours. This is mainly caused by all batteries charging

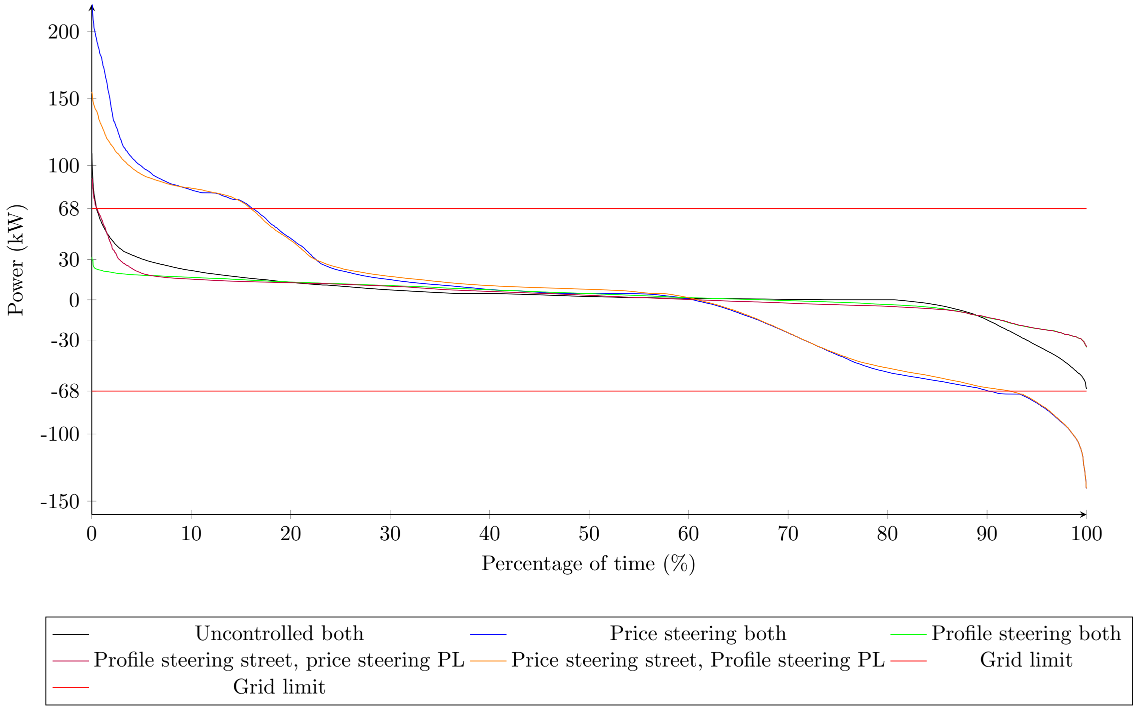


Fig. 5.5: Load duration curve of the neighbourhood in the futuristic case for one year

Fig. 5.6: The influence of batteries (yellow) and the houses' aggregated profile (red)

and discharging at maximum power at the same time. Figure 5.6 shows the profile of all batteries aggregated versus the aggregated total household profile, as can be seen, the batteries almost fully define the total profile. Most of the higher peaks of the houses' aggregated profile are caused by charging the EVs.

When all use profile steering, the maximum and minimum power are only around half of the grid limit, meaning that more houses or EVs could be added to the same connection. Noteworthy is the influence of the parking lot for EV charging, which contains 8 cars of the houses without a driveway. Dependent on the control method it can have a significant impact on the grid: When the parking lot uses profile steering and the houses use price steering, the maximum power decreases by 30% compared to the scenario in which the parking lot is also controlled using price steering. Similarly, when the parking lot is controlled by price steering and the houses by profile steering, the maximum power over the grid is increased by a factor of 2.9, resulting in the grid limit still being exceeded for 42

Fig. 5.7: neighbourhood meter using different control algorithms: Profile steering (yellow), no control (red) and price steering (blue)

hours. This shows the trend that when price steering is used by either the houses, parking lot or both, the grid overloading is significant and problematic.

Costs:
The fixed costs are very similar as expected since the overall consumption nearly does not change, interesting to note is that the dynamic costs are always lower than the fixed ones, regardless of which control method is used. The dynamic costs are 9.7 times lower when price steering is used compared to the uncontrolled case, also with profile steering the price is 1.3 times lower. The costs of the separate houses are described below in Section 5.5.

Self-consumption:
Similarly to the realistic case scenarios, the self-consumption is lowest for the price steering, namely around 46%. This is caused by the algorithm only being focused on the dynamic price profile and not on self-consumption, because selling and buying prices are the same. The self-consumption is highest for profile steering at 75%, this is also in line with the expectations since the control method tries to keep the load profile as flat as possible, meaning that the negative peak of the PV panels should be limited. Interestingly to notice is that 97% of the exported electricity happens in summer (54%) and spring (43%), while the self-consumed energy in these seasons is only 36% and 34% of all self-consumed energy respectively. This clearly shows that in winter and autumn nearly all solar energy can be self-consumed, namely 97% and 96% respectively. However, in summer and spring, only 67% and 70% of the generated energy can be consumed within the neighbourhood. A similar trend is seen in the uncontrolled scenario. In this case, the self-consumption is also relatively high with 65% thanks to the batteries charging when there is excess solar energy and discharging when there is demand. Here, in winter there is a self-consumption of 92%, whereas in summer the self-consumption is only 57%. This means that the battery size in summer is not nearly big enough to store all generated electricity, but is sufficient in winter.

5.5 Individual Households

All households have a different consumption and production of electricity as shown in Table 4.7. This results in some houses consuming, exporting and importing more electricity than others. Since the overall trends of the effect of different control algorithms are clear on a neighbourhood scale, this section shows the impact per household. This is to reveal any discrepancies between the profits and the grid impact of the households. Thus, these results show which households have the biggest impact on the grid, which have the highest profits and what the influence of having batteries and a charging station is.

Tab. 5.4: Results per house of the futuristic scenario using different control methods

House	E^{year} **(kWh)**	SC **uncntr. (%)**	SC **price (%)**	SC **prof (%)**	C^{dyn} **uncntrl (€)**	**diff** C^{dyn} **price (€)**	**diff** C^{dyn} **prof (€)**	C^{fix} **(€)**
0	635	68	45	71	201	-563	-83	735
1	2177	78	43	74	729	-341	-39	1258
2	2009	69	43	71	747	-689	-138	1399
3	3814	71	41	72	1401	-580	-142	2034
4	2179	78	44	78	726	-343	-18	1247
5	5192	79	45	78	1892	-532	-122	2646
6	919	63	43	67	323	-678	-132	895
7	-235	64	45	69	-90	-548	-72	352
8	184	66	46	71	19	-534	-69	517
9	-484	62	41	64	-88	-541	-81	214
10	-1886	48	42	59	-422	-592	-164	-163
11	-2291	43	39	57	-516	-988	-200	-286
12	-2536	41	40	56	-601	-637	-190	-358
13	-1669	48	42	60	-349	-658	-202	-89
14	2022	69	43	71	763	-730	-156	1381
15	1613	79	55	73	475	-329	-35	1001
16	-419	60	42	68	-130	-568	-106	306
Avg.	*660*	*64*	*44*	*68*	*299*	*-579*	*-115*	*770*

First, the costs per household of the futuristic case are shown in Table 5.4, so all houses have an HP, PV-panels, EV and a home battery. Next, the influence of the batteries is shown for the uncontrolled houses to see what profits these households could have when implementing an EMS in combination with a battery, as shown in Table 5.5.

When comparing the results per household to their technical specifications as described in Chapter 4, the houses with relatively few PV panels and a smaller battery (1,3,4,5,15) have a higher self-consumption in the uncontrolled case. For the price steering, we observe the lowest profits for the houses with a smaller battery (1,3,4,5,15), this is also observed when looking at the export values of these houses, which are also smaller than for the houses with the big battery, namely on average 6600 kWh versus 11700 kWh per year, respectively. However, the ratio of the battery capacity of the smaller and bigger batteries is not equal to the ratio of the export of the houses with smaller and bigger capacities. This can be explained by the influence of the PV panels since all houses with smaller batteries also have the least amount of PV panels. The elderly people in houses 10-13 have a relatively low self-consumption in both the uncontrolled and profile steering case, which can be explained by their higher export values, since they produce a lot of solar energy but are not able to consume it all.

Tab. 5.5: Results per house with or without battery in the uncontrolled scenario

House	E^{year} (kWh)	SC w/o battery (%)	SC uncntr. (%)	C^{dyn} w/o battery (€)	diff C^{dyn} uncnt with battery (€)	diff C^{dyn} price with battery (€)	C^{fix} (€)
1	2177	43	78	806	-78	-418	1258
4	2179	45	78	802	-77	-420	1247
7	-235	49	64	-4	-86	-634	352
8	184	51	66	120	-100	-634	517
9	-484	33	62	7	-95	-636	214
15	1613	48	79	568	-93	-421	1001
Avg.	*660*	*45*	*64*	*383*	-88	-527	*770*

Table 5.5 shows that having a battery greatly improves the self-consumption of the houses without control, namely by almost 20 percentage points. The energy bills for the households also go on average from having to pay €383, to earning €144 when having a battery using price steering. However, it should be noted that all these results are with net metering, without the net metering the profits from a higher self-consumption will be higher.

Tab. 5.6: Comparison of costs of the EV for the household at the public parking place versus a theoretical private parking place

EV of house	E^{EV} (kWh)	C^{PL}(€)	diff C^{fix} (€)	diff C^{dyn} (€) unc.	diff C^{dyn} price (€)
0	3405	1782	231	416	750
1	2240	1176	159	237	465
4	1205	598	76	132	246
7	2711	1426	183	414	623
8	3345	1772	234	446	738
9	1361	709	94	133	274
15	2928	1544	202	417	655
16	1756	953	136	246	407
Average	*2369*	*1245*	*164*	*305*	*520*

The costs of the charging at the smart charging parking lot, denoted by C^{PL}, for the EV owners are shown in Table 5.6. The costs of the public charging station are calculated using $1.5 * P_t^{fix}$. Suppose the houses had a private charging station, in that case, they could save in the simulated year on average €160 using a fixed contract, €305 using dynamic pricing without control and €520 using dynamic pricing with price steering. In comparison, a charging station costs around €1800, thus the break-even point is on average between 3.5 and 11 years. Note, this is even without taking into account the possible increase in self-consumption, which will further decrease energy costs in the future with the reduction of the net metering.

5.6 Summary

The results follow the trend seen in literature where the addition of emerging technologies greatly increases the demand load on the grid.

Compared to a neighbourhood without emerging technologies, the simulated neighbourhood with 17 houses shows an increase of a factor of 1.5 in the maximum peak load with the addition of HPs to the households, if EVs are also added the maximum peak is 4.1 times as big as in the baseload case. In this case, the grid limit of 4 kW is exceeded for 63 hours. Furthermore, the addition of PV panels increases the minimum peak power by a factor of 15.4. The use of batteries shows a significant increase in self-consumption, namely 20 percentage points, and a 60% decrease in hours the grid is overloaded.

The other trend seen in the results is that when price steering is used by either the houses, the parking lot or both, the grid overloading is significant and so are the profits they make. Whereas the use of profile steering decreases the peak load to significantly below the grid limits and achieves the highest self-consumption, while still lowering the energy bills for the households.

The use of EMSs using price steering, based on the dynamic pricing and including the net metering scheme in the Netherlands, results in an average of €580 decrease in costs per household per year compared to using no control. However, at the same time, the grid limits are exceeded for 2.7% of the time in the realistic scenario and 26% of the time in the futuristic scenario. The batteries mainly cause this. Whereas the use of profile steering decreases the maximum and minimum peak loads to around half of the grid limit, while still obtaining lower energy costs for the households when using dynamic pricing compared to when they use no control. Also, the highest self-consumption is achieved when profile steering is used, namely 75% in the futuristic scenario.

Note that especially batteries can both greatly improve self-consumption and decrease peak loads, but can also cause high peak loads when discharging/charging all at the same time. Furthermore, differences in profits between the households can be seen. Especially when only part of the houses owns an EMS using price steering with a battery, their impact on the grid is significantly bigger than households not using control. Furthermore, a smart charging parking lot with multiple charging stations for EVs also already has a significant impact on the grid load of the neighbourhood. The social impact of these individual differences is elaborated on in the next chapter.

Social Impact

6

Chapter Objective: This chapter discusses the societal impact of smart systems in a neighbourhood.

Chapter Contents

6.1 Introduction

The results show that the impact of smart systems and emerging technologies on the grid load and household energy costs are significant. Mainly the impact of batteries and EVs when using price steering causes serious grid capacity issues, while the household profits moneywise. Every household pays a fixed fee for the DSO service in the Netherlands, meaning that the grid operation costs are socialised. Thus, in case of costly grid reinforcements, all customers will see their fees being increased equally, regardless of for whom the grid had to be upgraded. This means that, within the current Dutch system, when one person overloads the grid, resulting in the need to strengthen the connection, the costs of this strengthening will be on everyone and not just the household causing it.

There are also situations when there is already grid congestion caused by e.g. too many PV panels or charging points installed in a certain neighbourhood, the connection for roof PV panels or a charging station of another house in that same neighbourhood can be denied until the grid congestion problem is solved, which can take a long time e.g. due to shortage of employees.

These types of issues may result in unfairness between households. In this chapter, we elaborate on the unfairness seen in the studied neighbourhood, while looking at the unequal division of physical flows and the financial accounting between the different parties involved. Specifically, the social impact of charging stations and a smart charging parking lot both owned by the community and by a third party on fairness is discussed.

6.2 Fairness

In Section 5.2 it is shown that the grid needs reinforcements when all houses have HPs, PV panels and EVs. Table 5.2 shows that when only a part of the houses use an EMS to control their EV charging and battery using dynamic prices, they already cause much higher import, export and maximum power peaks than uncontrolled houses without EVs. This results in these houses making a profit, while causing grid problems. Since they pay the same for a connection to the grid as the uncontrolled, less impactful houses, the overall connection costs increase since the grid needs reinforcement. Thus, all houses will pay more, but only a few houses benefit from it.

A similar case happens in a normal neighbourhood, where some households are able to invest in rooftop PV panels, which as a result of the net metering regulation, saves them money long term. However, since others are not able to invest, their energy bills will only get higher due to the increased grid connection costs caused by other people, who are significantly increasing the grid load. Furthermore, in the case of rooftop PV panels especially, the grid costs also increase to make up for the losses on the electricity market for all unused solar energy, since the demand cannot be properly matched to the generation moments and this energy might become worthless.

However, in line with these types of cases where some houses add more load to the grid than others due to them installing more devices, which might seem unfair, it should also be noted that there are circumstances when people will generally contribute more to the grid costs than others, simply because they live in a certain area. For example, in big cities, it is hard to place enough local renewable energy sources and most energy needs to be fed in from other places where the energy is generated. Whereas in more rural places there might be enough space for many people to own PV panels, can place wind turbines nearby and have most of their renewable energy locally generated and used. If there was a smart system in place properly dividing the energy locally between the end-users, would it be fair for these people to have lower connection costs than the people living in the city?

Another case of possible unfairness, dependent on the regulations, is caused by the difference in the possibility of having a charging station at home. Since some households do not have this opportunity, they are forced to use a (semi-) public charging station. This currently means higher prices and not being able to use their own solar energy. Since peer-to-peer trading is not yet allowed, they also cannot sell their own solar energy to the party owning the public charging station. This causes higher energy bills for households owning an EV but not having a charging station at home. Especially when net metering is abolished, their energy bills may be even higher since they have fewer means to maximise their self-consumption. The remainder of this chapter will elaborate on possible scenarios of (semi-) public smart charging in the neighbourhood and their social consequences.

6.3 Shared Smart Charging Parking lot

As shown before, the smart charging parking lot has an impact on self-consumption and costs for households. In this section, we elaborate on the different possible scenarios for the studied neighbourhood and their corresponding social implications and what the incentives for different parties could be to join such a scheme. First, the smart parking lot is owned by a third party as a business model to profit from. Secondly, the neighbourhood forms a community, which owns the parking lot.

The parking lot is owned by a third party:
In case the third party is making profits by participating in e.g. a congestion or imbalance market, they might help prevent grid overloading.

However, for the car owner, the charging costs may be higher than they would have paid at their private charging station at home. Furthermore, the solar energy generated by the households is not necessarily used within the neighbourhood. Currently, there are no incentives to do so yet, since peer-to-peer trading of solar energy to the smart parking lot is not yet allowed nor profitable yet. Furthermore, even if peer-to-peer trading is allowed the question arises whether it is actually cheaper for the smart charging parking lot owners to buy energy locally or to participate in the other larger-scale energy markets. Thus, in this situation, the unfairness question arises again since the individual households with their own charging station can charge cheaper than those without. Furthermore, is it fair that a third party causes grid problems, while the households have to bear the consequences, such as a black-out? Who would be held accountable for this and would that be fair?

Community-owned smart charging parking lot:
The households can also participate in an energy community and as a community operate and share a smart charging parking lot. There are many advantages to forming such a community. The community shares the renewable energy and decides on the prices themselves, this is usually based on the actual costs of the energy and thus non-profit. This ensures a low, fair, stable price for all members. This also encourages the participants in using as much energy locally as possible and increasing self-consumption, especially when extra (monetary) incentives are given by the DSO. When the community owns a smart charging parking lot, the same price for both private and public charging stations can be ensured, dependent on the supplier contract. Furthermore, since more people can share one charging station, the upfront investments needed are also lower for the people who otherwise would pay for a private charging station. If all charging stations are installed in one parking lot, only investing in one bigger grid connection for all EVs in the neighbourhood is possible. This could help save both community and societal costs.

The results show that the impact of the smart charging parking lot is fairly small on the self-consumption since most of the time the cars are only connected to the charging station at night. However, when the parking lot is also available for guests, or for more people from the community (outside the simulated households), the self-consumption can be increased by having more cars charge during the day. Another option in this community scenario is to introduce the concept of shared EVs [46], where people can reserve time slots in which they want to use the car, and the system makes sure the car is charged enough at that time. These cars can be connected whenever they are not used and will provide flexibility and increase self-consumption, even more so when V2G is used.

An uncertain factor of this scenario is that the exact implementation of energy communities in the regulations in the Netherlands is still unknown. However, as mentioned in Section 1.6, the EU directive 2019/944 [15] states that their member states should provide the citizen energy communities to take on any form of entity. Furthermore, it states that energy communities should be allowed to operate in the electricity market: "Citizen energy communities should not face regulatory restrictions when they apply existing or future information and communications technologies to share electricity produced using generation assets within the citizen energy community among their members or shareholders based on market principles, for example by offsetting the energy component of members or shareholders using the generation available within the community, even over the public network, provided that both metering points belong to the community." This directive forces member states, thus also the Netherlands, to provide energy communities with fair treatment, enabling framework and clear rights and obligations. They also include that households should participate voluntarily in an energy community initiative and should be able to leave when they want to.

Even though the regulations will most likely not be an issue in the future due to this EU directive, forming an energy community and using smart systems does come with its hardships [30]. For example, social acceptance plays a big role in implementing a certain optimisation method. Acceptance can be obtained by helping the participants understand the optimisation method and the results. However, the understandable algorithms might not be the fairest nor most profitable. Furthermore, either the household owners themselves or some third party, is responsible for the system running smoothly and the accounting of the costs. Furthermore, even in this situation, complete fairness does not have to be obtained, dependent on how the costs are divided between the participants and how the grid connection costs are. Will the community pay the same as for a normal connection? Furthermore, as mentioned in Section 2.4, pricing mechanisms for energy communities have already been researched and the perceived fairness of the pricing mechanism can change dependent on the members of the community.

6.4 Summary

The Dutch energy system is not designed for the speed at which the emerging technologies are being and are expected to be implemented. This results in unfairness between households, that cause grid overloading for their own profits and households that see their energy bills increase due to the manner in which the Dutch grid operation costs are divided. Furthermore, public smart charging can have a big impact on the grid load and costs of the end-users as shown in the previous chapter. Different schemes with different owners of smart charging stations are possible and each has its own consequences. In case a third party is the owner, usually the costs for the end-users are higher, but on a national level, the third party might help against grid overloading. Whereas, when the neighbourhood forms an energy community, the costs are fairly distributed and energy can be kept locally. However, forming such a community in practice is not easy due to the current regulations and participants' involvement. The regulations will probably be guided by the EU directive 2019/944 and not pose a problem in the future. The participants' understanding of the system and their definition of fairness can also greatly influence which system is being implemented and its effects on the (individual) costs and grid load. This thesis mainly looked into the fairness of the obtained results and the influence of the ownership of a shared smart parking lot, however, these are only small pieces of a very large complex system involving many parties and market mechanisms.

Conclusions and Future Work

7

Chapter Objective: In this chapter, conclusions are drawn from the presented results, to answer the research questions described in Chapter 1, after which suggestions for future work are presented.

Chapter Contents

The energy transition is causing an increase in grid overloading, electricity demand and in supply by RESs. Due to the intermittent and hard-to-predict character of renewable energy generation, it becomes increasingly harder to match the supply and demand of electricity. This results in, among others, capacity and power quality problems in the grid, that currently cannot be solved by reinforcement due to limited time, costs, labour and materials. A solution is to use the flexibility of devices to resolve peak load problems using DSM. The impact of an increase in emerging technologies and different methods to minimize this impact by using DSM found in literature are described in Chapter 2. In this work, the goal was to study the impact of individualistic-oriented incentives versus community-based incentives on the grid load, self-consumption, costs and societal consequences of a smart neighbourhood.

This chapter provides the answers to the research questions presented in Section 1.7. Finally, recommendations for future work are presented in Section 7.2.

7.1 Conclusion

From the results obtained in this study, the core research question presented in Chapter 1 can be answered:

> ***What is the impact of individualistic-oriented incentives versus community-based incentives on the grid load, self-consumption, costs and societal consequences of a smart neighbourhood?***

To answer this question, we first answer all sub-questions presented in Section 1.7 using the obtained results.

> *What is the impact of a high penetration of emerging technologies on a Dutch neighbourhood?*

The results show, in line with existing literature, that emerging technologies greatly increase the demand load on the grid when no control is used. When HPs are added to the simulated households, the peak load is increased by a factor of 1.5. When EVs are also added, the maximum peak load becomes 4.1 times bigger compared to the baseload case. The grid limit for the newly built houses is sized for 4kW per house. The aggregated grid limit of the neighbourhood when all households own an HP and EV is exceeded for 63 hours in the simulated year. The addition of PV panels does not result in exceeding the grid limits, however, it does increase the minimum peak power with a factor of 15.4, almost nearing the grid limit in case all PV panels are generating their peak power. The use of home batteries can increase the self-consumption by 20 percentage points, and decrease the grid overloading time period by 60%.

> *What is the effect of controlling the emerging technologies on self-consumption, costs and prevent grid overloading for the neighbourhood?*

The previous answer showed the effects of having emerging technologies without using control. When the individual-based control method price steering is used, the energy costs are significantly lower, whereas the self-consumption is the lowest out of all control methods. When all houses and the smart charging parking lot own an EMS and all houses own all the emerging technologies, the maximum load peak exceeds the grid limit by a factor of 3.3. Moreover, during 26% of the simulated year, the grid limit is exceeded. Even when only 7 out of the 17 houses own a battery, EV and an EMS using price steering, the grid limit is exceeded for 2.8% of the simulated year and the maximum peak exceeds the grid limit by a factor of 1.6.

The use of the community-based control method profile steering results in the highest self-consumption and lowest peak grid loads, while the costs are still 23% lower compared to the uncontrolled case when a dynamic tariff is used. The maximum load peak is only 46% of the grid limit, and the minimum load peak is only 52% of the grid limit. When only 7 houses own a battery, EV and EMS using profile steering, the maximum and minimum peak loads still stay significantly below the grid limit, namely 51% and 77% of the grid limit, respectively. Furthermore, a self-consumption of 75% is achieved, which is 10 percentage points higher than the uncontrolled scenario, in which the battery is also used for storing solar energy.

What is the effect of a smart charging parking lot in the neighbourhood?

The smart charging parking lot mainly has an impact on the grid load. The results are in line with the abovementioned findings about the effect of different control methods. When the smart charging parking lot uses price steering, it greatly increases the maximum load peaks. On the contrary, when profile steering is used, it decreases the maximum power peak significantly. The smart charging parking lot makes a difference of less than 1% in the self-consumption of the neighbourhood when it uses a different control method than the houses compared to when both use the same control method. In case only the parking lot uses profile steering, the load of the houses is unknown and therefore the smart charging parking lot cannot steer the EVs taking into account the peaks caused by the PV panels.

Are there any discrepancies on a household level between the costs, grid impact and self-consumption?

There is a significant difference between the yearly consumption, self-consumption and costs of the individual households, dependent on which control method is used. For uncontrolled, price and profile steering there is a 38, 16 and 22 percentage point difference between the lowest and highest self-consumption of a household, respectively. The grid impact difference is biggest without the use of control, but the grid impact itself is for all households biggest with price steering, where the export and import is mainly determined by the size of the home battery and the number of PV panels. The biggest cost difference between the households is seen in the uncontrolled case, whereas the difference in profits between the households compared to the uncontrolled case is greatest with price steering, with a difference of €659 between the lowest and highest cost savings. Another large cost difference is seen between charging at a private home charging station and a public charging station.

What are the social implications of different control algorithms in a smart neighbourhood?

Due to the calculations used to determine a grid connection to the houses in the Netherlands, there is unfairness between the households who cause grid problems, e.g. by using price steering for personal profits, and households who do not, but have to bear the consequences of higher connection costs due to the needed grid reinforcements. Whereas when the households in a neighbourhood work together and form an energy community, they keep the grid stable and can still lower their energy bills. In this paper, the smart charging parking lot is elaborated on to show the social implications of different control and owner scenarios. The simulation results show that smart charging parking lots can cause or help prevent grid problems dependent on the steering method used. In case a third party is the owner, usually the costs for the end-users are higher, but on a national level, the third party might help against grid overloading. Whereas, when the neighbourhood forms an energy community, the costs are fairly distributed and energy can be kept locally. However, forming such a community in practice is not easy due to the required participants' involvement and current regulations in the Netherlands.

> ***What is the impact of individualistic-oriented incentives versus community-based incentives on the grid load, self-consumption, costs and societal consequences of a smart neighbourhood?***

In short, individualistic-oriented incentives cause significant overloading of the grid, lead to a low self-consumption, and lower energy bills for the end-users. Moreover, it results in unfairness between users and non-users. On the other hand, community-based incentives keep the peak grid load to a minimum, increase self-consumption, and keep most of the energy within the community. Furthermore, it also results in lower energy bills for all users compared to a non-controlled scenario and divides the costs fairly amongst the members.

In order to minimize the use of fossil fuels as fast as possible and implement more RESs and emerging technologies, we show that it is best to use a community-based approach. The next section suggests some research topics for future works.

7.2 Recommendations for Future Work

This study has only shown a very small part of a very large complex system. Thus among others, the technological feasibility, market structures, regulations and laws and social acceptance need to be taken into account to solve the problems posed by the energy transition and the corresponding possible effects of multiple households in a neighbourhood steering on dynamic prices.
We showed that what is currently expected to be implemented in Dutch houses is not feasible for the grid. In the individualistic approach, we show that if every house steers on the same price incentives, high peaks arise at the same time when the price is low. A study on a new suitable pricing mechanism that would fit within the current electricity market structure is recommended. This pricing mechanism should take the synchronisation effects into account of all houses steering on their received pricing signals.

We also showed that a community approach is very useful in minimizing the needed grid connection, by using as much locally generated energy and dividing the demand load evenly throughout the day. However, this study has a very limited outlook on all aspects of the realistic implementation of such a community-based approach. First of all, a social study is recommended, to see what Dutch people are willing to implement, and whether they use the implemented system as supposed. Furthermore, the drivers and barriers to forming such a community should be researched, for example, what it offers to the members and how to design a community such that it is possible for people to leave and enter at will at anytime (for example when the house-owners change). Furthermore, an economic study on whether offering a community-based system has the potential of being a business model, especially for construction companies that build new neighbourhoods or organizations that offer it to existing neighbourhoods, such that not all communities need to reinvent the wheel and set everything up by themselves from scratch. This could also make it easier to implement neighbourhood-scale energy storage options and charging options, resulting in new possibilities which are hard to implement as individuals.

Another important aspect for further research is cyber-security. It should be clear how easy EMSs are to hack, what the consequences would be and how to protect the system. Moreover, this study has not taken into account exactly what happens in the cables transporting the electricity and in all different electrical phases. More knowledge on this topic could help increase the design of the grid and control methods such that no hotspots arise within the neighbourhood.

Lastly, it is recommended to perform a similar study when more data is available on real load profiles, the Dutch regulations, the flexibility households are willing to offer and new pricing mechanisms.

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