The effect of residential batteries on medium voltage substations

A socio-technical analysis of the emergence of residential batteries in the Netherlands

Pauline Verkaik

Master of Science

Sustainable Energy Technology

TU Delft

STEDIN.NET

The effect of residential batteries on medium voltage substations

A socio-technical analysis of the emergence of residential batteries in the Netherlands

by

Pauline Verkaik

To obtain the degree of Master of Science at Sustainable Energy Technology
at Delft University of Technology

To be defended on Friday October 28, 2022 at 2:00 p.m.

Student number:	4485238	
Thesis committee:	Dr.ir. R.A. (Rudi) Hakvoort	TU Delft
	Dr. P.P. (Pedro) Vergara Barrios	TU Delft
	Ir. J.H. (Jan) Warnaars	Stedin

Faculty of Electrical Engineering, Mathematics and Computer Science
Master Sustainable Energy Technology with a profile in Solar and Economics

Preface

This report was written for the completion of the master Sustainable Energy Technology at the Delft University of Technology. For the past months I have immersed myself into the world of congestion problems, electricity systems and retail regulations. This research is conducted with the help of the distribution system operator (DSO) Stedin. Insights in this company and their work has given me a broader understanding of the challenges of the electricity system and its transition.

The process of this thesis has been a challenge for me in many different ways. That is why I am very grateful for all the support I received. Thanks to my supervisor from the TU Delft, Rudi Hakvoort, for all the interesting meetings, your critical views and your leg-jokes. To Pedro Vergara Barrios, thank you for the critical reading and the useful feedback you gave. A special thanks to my supervisor from Stedin, Jan Warnaars, for your guidance during difficult times, your honesty and our really helpful discussions. I am proud to successfully finish my master thesis and look forward to contribute to the future of sustainability.

Delft, 21 October 2022

Pauline Verkaik

Abstract

This report presents an analysis of the emergence of residential batteries from a consumer's perspective and their effect on the load peak of the distribution grid. First, the future of residential batteries was evaluated in social and technical context by mapping the present situation, its trends, and its possible drivers. Three different battery control strategies were analysed: maximising self-consumption, market price arbitrage, and load peak reduction. The corresponding battery profile was determined with a rule-based approach. Second, load summation was used to simulate battery development scenarios within the distribution network, after which the effect of residential batteries was determined on a selected substation with a load peak analysis. From consumer perspective, residential batteries are driven by the phase-out of the net-metering scheme, increasing wholesale daily price spread, a decline of investment costs, or renewed tariff structures. The results showed that residential batteries become economically attractive when net-metering is abolished and the daily electricity price spread increases. The load profile results of the selected substation show a reduction of both size and number of overload hours for all control methods in case of medium and low emergence of residential batteries. In case the batteries are used to reduce individual load peaks, this reduction is largest and is smallest when batteries are used for market price arbitrage. Battery usage for self-consumption and peak reduction mainly operate during summer months when PV generation is higher. Therefore, demand load peaks in winter are not relieved as much. Although it was found that grid reinforcement is still not alleviated for the selected substation, the maximum and minimum load peak are unified leading to a reduction of required reinforcement capacity. It is found that retail price regulations strongly influence which control method will be dominant. Incentives to increase self-consumption or reduce load peaks will relieve pressure on the grid. However, critical grid congestion moments are not explicitly relieved. Therefore, further research is required to identify methods to utilise the batteries for DSO control during critical peak moments or winter seasons with low self-consumption usage.

Contents

List of Figures

List of Tables

List of Symbols

C_E Energy capacity [kWh]

C_P Power capacity [kW]

D Demand [kWh]

d Day

L Net load [kWh]

L_{av} Average daily load [kWh]

LoC Level of Charge [kWh]

P Electricity price [€/MWh]

P_{av} Average daily price [€/MWh]

P_{batt} Power battery [kW]

PV PV generation [kWh]

SoC State of Charge [%]

t Time [h]

1 Introduction

The electricity grid is heavily congested and this problem will presumably only increase as a result of the energy transition (TenneT, n.d.). Due to the increasing intermittency of energy sources and electrification of demand, electricity transportation peaks enlarge and higher grid capacity is required. However, reinforcing the grid to address this congestion is costly and time consuming. Therefore, flexible energy storage systems such as batteries have widely been proposed as an alternative way of reducing grid congestion. By using such systems, a load peak on one of the network components can be relieved on critical moments. To accelerate the adoption of such sources, multiple political parties have plead for the stimulation of battery systems and specifically for residential batteries (VVD & CU, 2022; Netbeheer Nederland & Energy Storage NL, 2021). However, there are many different aspects that may influence the emergence as well as control of residential batteries. As a result, it is still unclear what effect various stimulation policies may have on the adoption and use of batteries and consequently its potential to relieve pressure grid.

Hence, the objective of this research is to analyse the emergence and use of residential batteries from consumers perspective and their effects on load peaks on distribution grid level. Changing policies and other developments will drive the emergence of residential batteries and steer their usage. These drivers, as well as the effect the different control methods have on the grid, will be analysed for the Netherlands specific. This leads to the following main research question: *What is the effect of different residential battery use cases on the load peaks on medium voltage substations in the future?* The importance of medium voltage substations is high to distribution system operators (DSO) because of their high reinforcement costs and long construction time. Analysing the future battery effect is valuable, because policies will affect future battery emergence and because of increasing pressure on the grid by the energy transition.

This report is structured as follows: Chapter 2 provides the background to present the current problem, the residential battery context, the literature review, and its knowledge gaps. Modelling and interpretation approaches are given in Chapter 3, followed by the data and assumptions in this research in Chapter 4. Chapter 5 presents the results, which are further discussed in Chapter 6. In this chapter, the relevance of this study and a personal reflection are included. Finally, Chapter 7 states the conclusions of this work by answering the main research question.

2 Background

This chapter provides the background of grid congestion, introduces the applications of residential batteries within the Dutch electricity sector, and covers the knowledge gaps this research aims to address. In section 2.1 the grid congestion problems in the Netherlands are explained and covers multiple solutions for congestion, including the role residential batteries can have in solving it. Section 2.2 aims to map the societal context of residential batteries in the Netherlands and technology drivers will be identified. Previous research is reviewed in section 2.3, followed by section 2.4, where corresponding knowledge gaps will be identified. Finally, in section 2.5, the main research question with corresponding sub-research questions are stated.

2.1 Grid congestion

The current capacity of the electricity network is to an increasing extent insufficient, causing grid congestion. When the capacity of the grid cables, transformers and stations does not meet the current demand for transportation, grid congestion occurs. Because of renewable energy ambitions and electrification of various sectors, inevitably pressure on the grid is growing even more. In this section, first the cause of congestion and its consequences are explained. Then possible solutions are given, including the recently often proposed technology of residential battery systems.

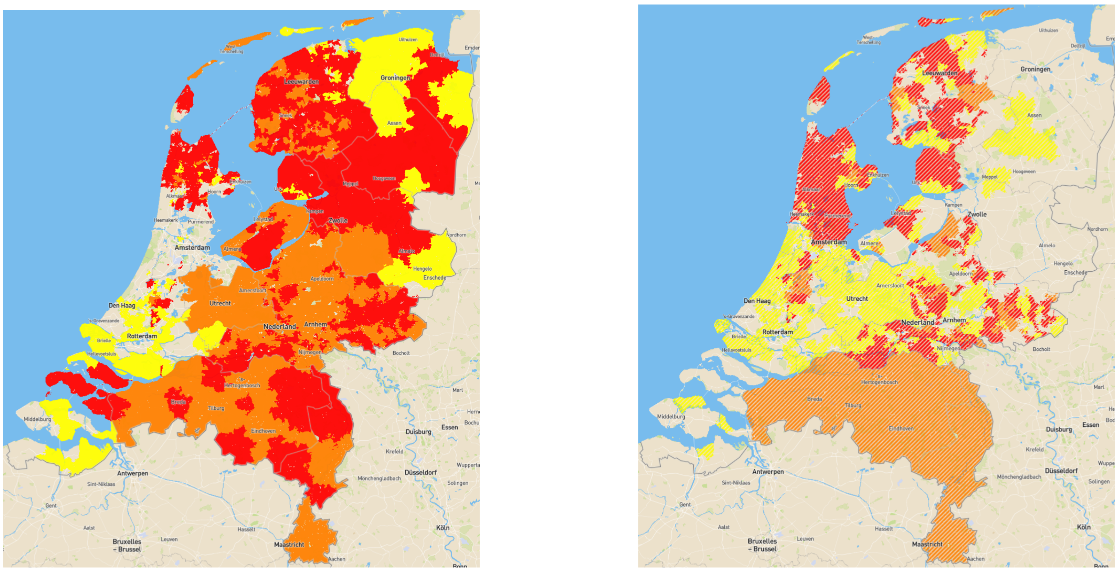
2.1.1 Capacity bottlenecks

station type power	processing time (years)	required space (m^2)	costs (€ excl. space)
EHS/HS >500 MVA	7 - 10	40,000 - 100,000	>100,000,000
HS/TS 100-300 MVA	5 - 7	15,000 – 45,000	>25,000,000
HS/MS 100-300 MVA	5 - 7	15,000 – 45,000	>25,000,000
TS/MS 25-100 MVA	2.5 - 5	2,000 – 10,000	1,500,000 – 10,000,000
MS 10-40 MVA	2.5 - 3	200 – 4,000	1,300,000 – 6,500,000
MS/LS 0.2-1 MVA	0.5 - 1	10 – 35	35,000 – 250,000

Figure 2.1: The required area, processing time and costs of building different types of stations. Source: (Netbeheer Nederland, 2019)

Pressure on the grid capacity is a growing problem because of the energy transition: an increase of renewable energy sources and electrification of energy demand lead to higher power peaks. The energy transition of the Dutch energy sector is depicted in appendix A. Due to the increasing intermittency of energy sources and electrification of demand, transportation peaks enlarge and higher grid capacity is required. Conventional power plants produce a controllable, steady energy output unlike variable renewable energy sources which are characterised by their generation peaks. During summer, generated electricity of photovoltaic (PV) peak during noon. Similarly, especially in winter when people come home from work, they simultaneously turn on their lights, heat pump and electric vehicle charger. There is an electricity transportation peak in the evening. Both events will cause grid capacity scarcity. Increasing this capacity is expensive and time consuming, as can be seen in the overview of figure 2.1, where the time, land area and costs of the build of different stations are given.

Distribution and transmission networks are designed keep functioning in case of malfunction of single components. This high reliability is due to its redundancy: most of the electricity network includes a single fault reserve without power interruption (Netbeheer Nederland, 2019; Phase to Phase, n.d.). This is indicated as 'N-1' redundancy and this means that when a component is overloaded, breaks, or in maintenance, the network does not have a breakdown. The safety capacity of a station does not include this fault reserve. In case the station load exceeds this safety capacity and the grid is not considered sufficient for new grid connections, congestion is proclaimed. Hence, exceeding the safety capacity does not immediately lead to breakdown, but the no fault reserve is remaining and power interruption is a real threat in case of another fault. In the Netherlands multiple areas are marked as congestion areas, as can be seen in figure 2.2. In these red areas a transport restriction is imposed. This means that new requests for grid connections are declined. For example, new PV parks or a new residential area cannot be connected to the grid because the capacity limit of grid components will be exceeded when new loads are connected. A more detailed description of the distribution and transmission network is given in appendix B.1.



(a) Generation (b) Demand

Figure 2.2: Congestion maps of the grid of the Netherlands. Red indicates structural congestion, which means that new generation connection requests are declined, orange indicated an advance notice at ACM (Authority Consumer and Market), yellow indicates that a distribution scarcity is near and therefore, different quote regulations are in place. No color means that there is not a distribution problem (yet). Source: (Netbeheer Nederland, 2022)

A load forecast example of 2050 on a substation can be seen in figure 2.3. The present load is shown in grey blue, indicated by 'Load 2021'. The load profiles of expected electrification technologies, renewable energy sources and new connections are added to the initial load profile. The resulting total station load is shown in the red line. The maximum safety capacity of this stations is exceeded and thus this example station is expected to be overloaded in 2050.

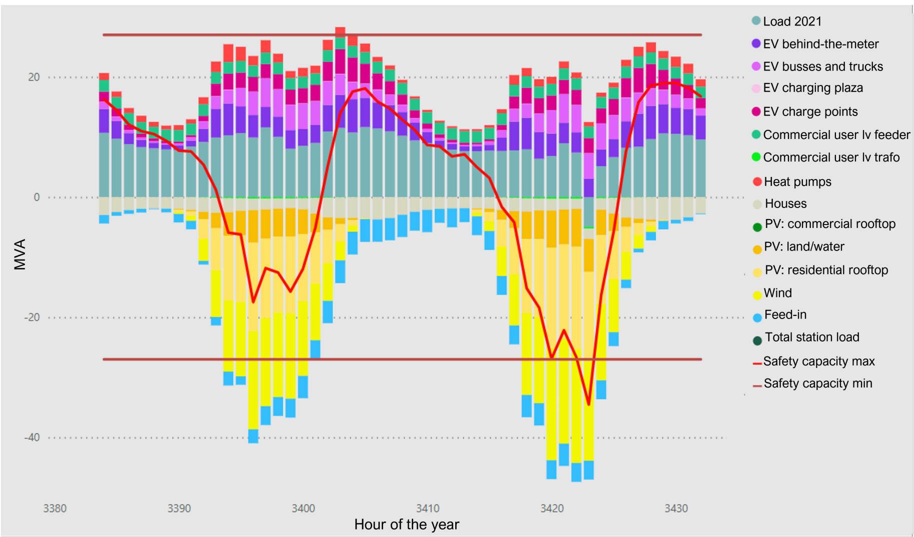


Figure 2.3: Projected load profile of 2050 on a randomly picked station of Stedin. The minimum and maximum safety cap of the station is shown and the total load on the station is marked with the red line. This exceeds the safety cap on the generation side. Source: (Stedin, 2021b)

Lately there has been a lot of discussion on how to solve the congestion problem. Grid operators have warned the government of grid capacity scarcity and plead for an overarching strategy from the government (Actieteam Netcapaciteit, 2022; Commissie Economische Zaken en Klimaat, 2022b). In February 2021, the committee of Economic Affairs and Climate had a round table discussion followed by a debate with the responsible minister for Climate and Energy Rob Jetten (Commissie Economische Zaken en Klimaat, 2022b, 2022a). A group of 14 stakeholders presented their plan for the grid transition to the Dutch Government which includes extra money for investment, rules and regulations that need revision, and called attention to the lack of technical staff (Commissie Economische Zaken en Klimaat, 2022b). The network tariffs should stimulate a better use of the present capacity. Currently, the net-metering scheme is in place for residential connections, which stimulates rooftop PV. However, net-metering does not encourage smart use of the grid by rooftop PV owners. Electricity generation peaks can be shaved by storage or by curtailment. However, the current regulations do not stimulate generation peak shaving.

2.1.2 Solutions for capacity bottlenecks

One solution for the growing pressure on the grid capacity would be to enlarge its capacity by reinforcements. Power stations can be replaced or added and the number of cables is increased or thickened. These reinforcements require a lot of labor power, have high investment costs and take up a lot of scarce land area as can be seen in figure 2.1. 80% of the processing time for the stations is preparation such as permit requests (Commissie Economische Zaken en Klimaat, 2022b). Grid operators have called for an easier legal process to speed up the construction of grid stations.

Grid reinforcement can be postponed or even prevented when the load peaks are shaved. The timing of generation and demand is out of phase and they both include high peaks. To shave the peaks or to match demand and generation in time, flexible energy sources can be used. Different methods of load peak management can be identified in figure 2.4. The present flexible capacity is still limited in the Netherlands, but the demand is growing due to the following drivers: growing share of variable energy sources, electrification of energy demand, decrease of conventional controllable generation, and congestion on the grid. There are many sources of flexibility and storage. Examples are curtailment, demand response, conversion, or batteries. Curtailment is a form of flexibility where the peak of supply is limited and 'shaved off', mostly by connecting a resistor. By conversion of electricity to a different energy carrier, it can be stored like hydrogen, gas, or heat. Demand response can either be implicit or explicit (Fonteijn et al., 2019). When it is implicit, it is activated using price signals that represent the need for adjustment of demand. Explicit demand response is when energy is traded on flexibility markets. Energy storage can perform flexibility on both the demand and the supply side by charging and discharging.

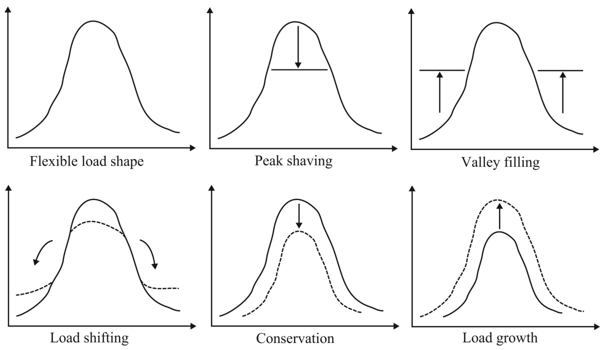


Figure 2.4: Methods of load peak management. Source: (Lund et al., 2015)

There is a lot of research and discussion about the role of storage and flexibility within the congestion problem. For example, commercial storage parties pay double taxes because for both supplying and obtaining electricity taxes are charged causing a slow emergence of the energy storage market. For these parties, grid transport costs are a relative large share of their business case. Moreover, on one side there is a lobby for residential batteries to decrease the load peaks from households from different political parties and research institutes (CE Delft, 2022; VVD & CU, 2022). At the same time, some political parties find residential batteries an expensive solution for the capacity problem and state that it is no 'silver bullet' (Commissie Economische Zaken en Klimaat, 2022a).

Figgener et al. divides the battery storage market into three parts: home, industrial, and large-scale storage systems. These are shown in figure 2.5 with their corresponding grid levels. The home storage systems are connected to the low voltage distribution network which is at 400 V, whereas the other two systems have two possible connection levels. The typical specifications of home batteries have a maximum power of 5 kW and maximum capacity of 10 kWh. Industrial storage can have similar specifications or can be as large as a few hundred kW and kWh.

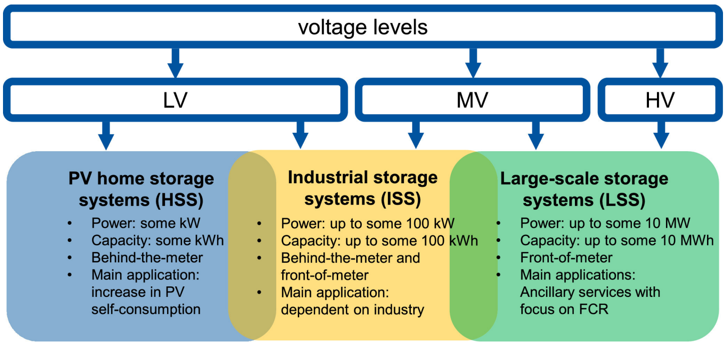


Figure 2.5: Specification of battery systems markets and their corresponding grid connection. Source: (Figgener et al., 2020)

Residential batteries

In the recent government discussions about the electricity network and its scarce transport capacity, residential batteries were repeatedly mentioned as an interesting solution (Commissie Economische Zaken en Klimaat, 2022a, 2022b). Two political parties wrote an action plan for the development of residential and community batteries and branch organisation of grid operators published a position paper in favour of subsidy for residential batteries (VVD & CU, 2022; Netbeheer Nederland & Energy Storage NL, 2021). However, the real impact of this type of flexibility is still unknown (Commissie Economische Zaken en Klimaat, 2022a).

The focus of this research will be on residential battery systems. It is yet undetermined what the Dutch policy landscape of this technology will be in the future, resulting in uncertainty for the optimal use case of the battery. The grid operators pleaded for a subsidy on residential batteries, without knowing the real impact of this type of flexibility on the grid (Netbeheer Nederland & Energy Storage NL, 2021). Also, the phase out of the net-metering scheme will change the feed-in tariff of the own generated electricity and will drive the emergence of the residential batteries.

2.2 Societal context of residential batteries

The residential electricity market is subject to various influences: net-metering and feed-in policies, extremely increasing electricity prices, growing share of residential rooftop PV, and electrification of energy demand. Pricing the residential electricity usage is regulated by energy supply companies: The residential electricity tariff paid to the energy supplier can either consist of static, double tariff, or even dynamic pricing. Next to electricity costs, the electricity bill consists of taxes, network, and metering costs. The current consumer's electricity retail market is described in more detail in appendix B.2. Recent trends within regulation and price developments will influence the residential battery market. These developments will be described in this section, followed by a description of drivers for the emergence and control strategy of residential batteries. The main trends in the residential electricity sector, the drivers for battery uptake, and their main usage to create value are depicted in figure 2.6.

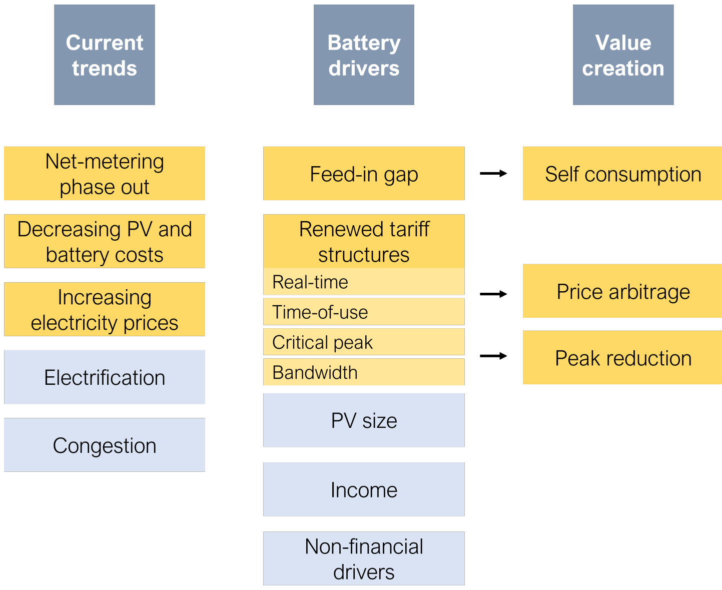


Figure 2.6: Societal context of residential batteries based on current trends, their drivers and corresponding value creation. Blue labels indicate indirect motivations for the residential battery.

2.2.1 Present regulations and price developments

The goal of the Dutch climate agreement specifically for small scale rooftop PV is 7 TWh in 2030, of which 4 TWh is already accounted for with installations operational at the end of 2020 (RVO Nederland, 2020). To stimulate small scale rooftop PV for households, net-metering is the most important motivation. The generated PV power will be cancelled one-on-one to electricity demand at another time. Net-metering does not stimulate direct use of the generated electricity. With this regulation in place, the grid virtually acts as an infinite battery for the consumer. Because of significant price reduction of PV, investing in rooftop PV is expected to become profitable without extra stimulation (Rijksoverheid, 2019). A combination of avoided demand costs and a reasonable feed-in tariff is expected to be enough stimulation (Wiebes, 2020). Therefore, to avoid over-stimulation, from the year 2025 onward the net-metering scheme will expire (Wiebes & Snel, 2019; Wiebes, 2020; Jetten, 2022a). Quantification of this phase out is depicted in table 2.1. The percentage of electricity that you can subtract from your electricity bill will steadily decrease to 0% in 2031. Yet, no binding decisions are made yet on the new policy regarding feed-in electricity beginning in 2025. In case of the net-metering policy, there is a danger for cross-subsidy. Owners of rooftop PV benefit from this scheme while the costs for increased use of the grid falls on everyone, including the low-income households not owning PV. In this case, cross-subsidy is a real threat (Esplin & Nelson, 2022).

Year	2023	2024	2025	2026	2027	2028	2029	2030	>2030
Original proposition net-metering [%]	91	82	73	64	55	46	37	28	0
Delayed proposition net-metering [%]	100	100	64	64	55	46	37	28	0

Table 2.1: Phase out of net-metering policy: Percentage of excess electricity that will be one-on-one subtracted from the electricity bill from 2023 onward. Source: (Wiebes & Snel, 2019)

The remaining stimulation for residential generation includes the tax benefit and a feed-in tariff for excess generated electricity (RVO Nederland, 2020). The Dutch government expects that residential PV soon won't need stimulation to grow because of the decline in PV cost price (Rijksoverheid, 2019). However, the price of PV has slightly increased in the past year because the Covid-19 measures affected the efficiency of the supply chain (Dutch New Energy Research, 2021). What the specific regulations will be that follow-up the net-metering scheme is still unknown. However, according to the government, the pay-back time of rooftop PV should not be affected by decrease in stimulation and should stay around 7 years (Rijksoverheid, 2019). Nowadays, when as a small consumer produces more electricity than consumed they get a feed-in tariff, which is a lot lower than they would pay for electricity. The ACM has not set a minimum feed-in tariff, although the tariff must be 'reasonable'. The consumers association (Consumentenbond) pleads for a minimum feed-in tariff of 70% of the basic electricity tariff (Donat, 2022). Two large electricity suppliers recently changed their feed-in tariff in opposite trends. Vattenfall increased their feed-in tariff from 7 to 16.8 eurocent per kWh. On the contrary, Eneco drastically reduced the tariff from 56.5 to 9 euro cent per kWh. A lower feed-in tariff, which is a policy impact, will drive the battery uptake (Esplin & Nelson, 2022).

Dynamic electricity pricing encourages efficient grid usage. Then, it is profitable to minimise electricity demand during price peaks, which normally occur in the evening and in the morning and shift the demand to lower pricing moments around noon and at night. A residential battery can make profit by shifting energy consumption over the day or by maximising self-consumption (Stultiens, 2021).

The electricity prices are escalating since the end of 2021. At the beginning this was caused by the release of Covid-19 measures, increasing the demand for energy and a cold winter. Then the Russian invasion in Ukraine caused an extreme rise in gas prices, highly influencing the electricity price. The wholesale day-ahead electricity prices roughly increased from about 50-100 €/MWh to 300-600 €/MWh. The prices highly fluctuate and the price spread during the day has increased as well. The retail prices have followed this rise, and directly influence the interests of civilisation on electricity usage. Suddenly, electricity and gas are not self-evident and renewables and self-sufficiency speak more to mind. Because of the rising daily price spread and the scarcity of grid capacity, there is a high demand for flexibility in energy sources and demand. There are multiple parties that plead for a stimulation of battery systems and specifically for residential batteries (VVD & CU, 2022; Netbeheer Nederland & Energy Storage NL, 2021).

Because of the current policies in the Netherlands, it is not yet financially feasible to use home batteries for your own electricity generation and consumption. In the Netherlands, there is no incentive for consumers to directly self-consume their PV generation nowadays, because of the net-metering policy. There is no subsidy available for residential batteries and the network tariff is unrelated to the capacity peak of consumers, so the stimulation of reducing electricity peaks is lacking. Therefore, currently the number of residential batteries in the Netherlands is negligibly small. The electricity price regulations are different in Germany and Belgium are residential batteries are emerging in these neighbouring countries. In Germany a high feed-in gap, and in Belgium an altered capacity tariff, drives battery uptake. Their residential battery emergence is explained in more detail in appendix C. In 2021, about 1,350 households in the Netherlands owned a residential battery to match their PV generation to their electricity demand (Janssen & Jansen, 2022). The average capacity of these batteries amounts 4 kWh. There is not yet any steering in the usage and purchase of a residential battery by the government. The Dutch grid operators plead that next to a preferably accelerated phase out of the net-metering scheme, a subsidy for decentralised storage systems is necessary to provide enough space in the network for the increasing share of renewable energy sources (Netbeheer Nederland & Energy Storage NL, 2021).

2.2.2 Drivers for uptake: policies and value creation

There are multiple motivations to purchase a residential battery. A household's income as well as the size of the rooftop PV installation are positive drivers for uptake (Alipour, Irannezhad, Stewart, & Sahin, 2022; Best, Li, Trück, & Truong, 2021). The household independent factors are cost price, the feed-in tariff, electricity market prices, and the net-metering (Afman, 2021). Financial drivers are only partly responsible for the decision to purchase a battery. Non-financial drivers are self-sufficiency, energy independence, and technological interest. These non-economic factors are not always in line with political incentives (Esplin & Nelson, 2022). As an example the uptake of PV in Germany is given by Esplin and Nelson, where the high feed-in tariffs did not immediately lead to a high deployment, only until the social opinion had shifted. Besides, a new technology entails uncertainty for customers regarding benefits and potential customers lack information. Residential battery users are characterised as innovators (Alipour et al., 2022). Especially with a high investment cost, the new technology will only be adopted by early innovators according to the 'diffusion of innovations' theory. These innovators act as an example and information source to others, following diffusion of the technology. Another example of a non-financial motivation is given for using smart charging of an electric vehicle: 'deriving a broader interest in and more joy from using smart home technology' (Henriksen, Throndsen, Ryghaug, & Skjølsvold, 2021). This is stated for electric vehicle flexibility and this idea can be extended on battery systems.

The deployment of residential batteries is difficult to govern, however how the batteries are controlled is easier to regulate (Fett, Fraunholz, & Keles, 2021). Three policies that would stimulate the residential battery are PV self-consumption feed-in tariff bonus, a reward when the batteries discharge when the grid needs it most, and dynamic electricity prices (Zakeri, Cross, Dodds, & Gissey, 2021). Zakeri, Cross, et al. conclude that PV stimulating policies should be replaced with electricity self-consumption policies. Possible stimulations for peak power reduction are tariff structures or a connection bandwidth tariff (Tresoor, 2022). When the tariff would better correlate with the use of the grid, an efficient use would be stimulated. Examples of this renewed tariff structure are time-of-use, critical peak pricing, or real time pricing (Fonteijn et al., 2019). With the time-of-use tariff the price of electricity would be higher in peak periods and lower in off-peak periods. The critical peak pricing could be added to a regular fixed tariff or the time-of-use pricing and would imply a higher tariff during load peak and is thus location specific. Real-time pricing would be based on wholesale prices of the electricity market.

Figure 2.7 shows the economic value for generators, grid operators and end consumers of batteries direct and indirect applications. Arbitrage is a transaction with the objective to profit from price differences. For energy generators batteries can be used to smooth the renewable energy sources and make sure that these are integrated. For the distribution system operator (DSO) it can delay the investment in higher capacity cables and transformers or function as a reserve capacity. For end-consumers it can be economically beneficial to have the flexibility of batteries, or by self-consumption the utilisation of existing assets and the power quality can be increased. In the Netherlands the electricity reliability is already high. Therefore, in this research, residential batteries are only controlled for the increase in self-consumption and end-consumer arbitrage. The self-consumption control method is implemented in two manners: for maximisation of self-consumption and for household's load peak reduction.

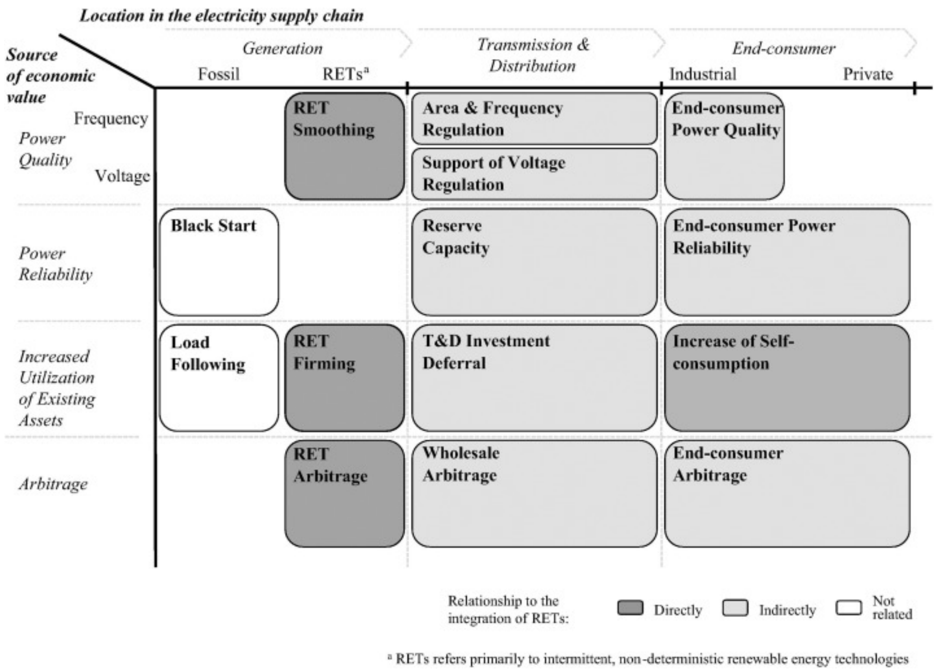


Figure 2.7: Economic value of batteries for multiple locations in the electricity chain. Source: (Battke & Schmidt, 2015)

Maximising self-consumption

When electricity generated by PV is used for on-site electricity consumption this is called self-consumption. By maximising self-consumption by means of a battery, the excess generated PV electricity is stored in the battery instead of delivered to the grid. The battery matches the electricity demand and production over time. Especially in the Dutch cold climate, the PV generation is not related to the consumption, that usually has an evening power peak when there is no PV (Klingler, Schreiber, & Louwen, 2019). The business case for self-consumption is based on the price gap between the electricity retail price and the feed-in tariff of excess PV. Because of the current net-metering scheme in the Netherlands, this price gap is zero. When the feed-in tariff is lower than retail electricity prices, maximising self-consumption would be beneficial.

Market participation

Households cannot participate in wholesale electricity markets because of their small size. A description of electricity markets can be found in appendix B.3. System operators set requirements for parties that participate in the electricity market or offer balancing services (Zakeri, Gissey, Dodds, & Subkhankulova, 2021). For example, in the Netherlands the minimum power bid in the balancing market is 1 MW. Therefore, this market would not be accessible for smaller residential batteries which have a typical size of a few kilowatts. For those sized batteries to participate in the market, a set of storage units can be aggregated and controlled by an aggregator. However, the emergence of aggregators is slow (Eid, Codani, Chen, Perez, & Hakvoort, 2015). Eid et al. state that for the integration of flexibility in the grid, aggregators are important. The given causes for the slow emergence are: "minimum bidding values, bid duration and strong penalties for non-supplied services". Afman states that until 2030, the FCR (Frequency Containment Reserve) balancing market will be the dominant market for aggregated residential batteries. However, this will decrease in value with up to 70%. Thereafter the day-ahead market will be mainly used as income source. It should be noted that the analysis is performed before the market prices and fluctuations increased the second half of 2021.

In the Netherlands, more and more energy suppliers provide dynamic real time prices. These retail prices are based on the day-ahead wholesale market prices. In that way, participation of market prices can be done by households themselves (Stultiens, 2022b). By the dynamic pricing, smart usage of electricity is stimulated. When prices are high, electricity demand should be decreased and the other way around when prices are low or even negative, feeding in generated electricity should be delayed. Because of the assumption that residential batteries installation will be emerging mostly after 2030, in this research day-ahead electricity prices are taken as the electricity market to work on.

Load peak reduction

By load shifting during the daily generation and demand peaks, the residential battery can be used to shave load peaks. The battery would also be used to increase self-consumption, however with consideration of reduction of connection capacity. The difference between individual load peak reduction and congestion prevention is the load the battery control is based on. An individual household can use a battery to reduce their load peaks and limit connection capacity. The battery is not necessarily used on critical moments of DSO's congestion. Quantification of the added value of the peak reduction method is based on several benefits it brings (Faruqui, Harris, & Hledik, 2010). These factors are the redundant of peak power capacity, the costs of avoided energy usage, and the reduced transport capacity. The DSO only benefits from reduced load peak when station load would otherwise be exceeding the safety capacity and cause congestion. Only on these critical moments, the DSO directly benefits from the peak reduction and is even willing to pay for the possible peak reduction. Appendix B.3.3 elaborates on the market working of congestion prevention.

2.3 Literature review

The effect of residential batteries on the grid capacity and the profitability and usage of this type of battery has been researched multiple times in the past years. Table 2.2 shows different researches with their focus point, method, related conclusion, and most important research gap.

Both Barzegkar-Ntovom et al.; Bagalini, Zhao, Wang, and Desideri analyse what the profitability of battery systems is when maximising self-consumption. Barzegkar-Ntovom uses the Levelised Cost of Use (LCOU) to access the profitability and assumes constant electricity prices and a policy that does not have compensations for excess PV generation in the grid. It concludes that battery prices are currently too high to be profitable. Bagalini et al. uses real data of a Chinese PV-battery system to access the profitability. The same conclusion as Barzegkar-Ntovom et al. is drawn, partly because of the low electricity prices and PV subsidies. A combined battery system will be profitable when the electricity prices double, the export tariff halves and the investment costs of batteries decrease significantly. In both studies, the grid impact of DSOs is not assessed. Nyholm, Goop, Odenberger, and Johnsson analyse the self-consumption rate when combining PV with batteries on the basis of real data from Swedish residents. In this paper, the grid impact is disregarded. The paper of Camilo, Castro, Almeida, and Pires found that a PV system with a battery system positively affects the low-voltage grid impact, when batteries are used for maximum self-consumption. Only two typical days in summer and winter are used to analyse the grid impact. Additionally, in Portugal, where this research is based on, the winter and summer differences are smaller than in the Netherlands.

Alnaser et al. research the impact of increased self-consumption policies on the distribution grid. In their paper it is stated that most studies do not take the implications on distribution networks into account. This research uses two different use-cases for batteries: the user-led and the DSO-led strategy. The user-led strategy first determines PV and battery sizes by minimising the installation costs whilst achieving maximum self-consumption. The battery may be fully charged before the critical time periods (before noon), because the interests of DSOs are not taken into account. In the DSO-led strategy, generated PV power is only used to charge the battery when the excess energy reaches a certain threshold. The main conclusions are that when the charging strategy is user-led, the small-sized batteries will be fully charged before the critical periods. This study only analysed a time span of one single day. Additionally, this study does not take the economics of the different control methods into account, as well as the future projection of the substation load nor the market based price arbitrage.

Seydali Seyf Abad, Ma, Marzooghi, and Ahmadyar perform a probabilistic analysis of the effects of batteries on the minimum PV hosting capacity of the grid. For both the self-consumption and varying tariff the grid load peaks decreases only when the battery is still charging during the critical period which is between 12 and 13h. The effects on the load peak of both flat and Time-of-Use tariffs is the same so the type of network tariff is unrelated. In this research only one day is taken into account.

Schopfer, Tiefenbeck, and Staake determine the strong dependency of the specific load profile of a household on the profitability of a PV - battery combination. Also, the profitability of integrating residential batteries is strongly dependent on its price developments. In von Appen, Braslavsky, Ward, and Braun the profitability of battery systems in Australia and Germany is assessed. In Austria, PV combined with batteries will be feasible in the near future. In Germany however, currently just rooftop PV is more profitable. PV generation peak reduction can be significant when using batteries, but this depends on the control strategy.

In Sani Hassan, Cipcigan, and Jenkins an optimisation use for a battery system under both wholesale prices and double tariff is formulated. The results show that when wholesale prices are low or negative, the battery charges using the grid. When PV generation is maximum, the battery uses this energy to charge. Also, when optimally sizing the battery in favour of revenue, the capacity of the battery would be 3 kWh.

Source	**Use case**	**Measured effects**	**Method**	**Related conclusion**	**Gap**
(Camilo et al., 2016)	SC	Voltage, active power and losses	Power summation	SC promising solution	Profitability, real data
(Barzegkar-Ntovom et al., 2020)	SC	profitability	LCOU	not profitable currently	specific policy used and no DSO
(Nyholm et al., 2016)	SC	optimal sizing PV and B	MILP	Optimal relative sizing	No electricity markets and DSO effects
(Bagalini et al., 2019)	SC	Profitability	Pilot data	decrease in load peaks, not economic feasible	Used large battery, no DSO and VT
(Seydali Seyf Abad et al., 2022)	VT and SC	grid impact of B	Probabilistic and MILP	Impact improves more in cost minimisation then SC	Only one day, no electricity market prices
(Alnaser et al., 2021)	SC, CM	SC, OS	MILP and Monte-Carlo	SC will not relieve grid impact, DSO control strategy will	Influence of electricity markets
(Cerna, 2022)	CM with B and DR	optimal residential usage scheme	MILP	optimal DR reduces energy consumption costs	No electricity markets and DR is used
(von Appen et al., 2015)	maximal profit and CM	impact pricing schemes and grid integration	MILP	peak reduction possible depends on control strategy	No real data and no scenarios
(Schopfer et al., 2018)	maximal profit	costs of PV and B for positive net present value	Data and machine learning	profile influences profitability maximal price level of battery	different scenarios, no DSO
(Sani Hassan et al., 2017)	VT	MP	MILP	Optimalisation wholesale charging strategy found	No effects DSO

Table 2.2: Overview and comparison of the related research. The abbreviations in the table are: self-consumption (SC), congestion management (CM), levelised cost of use (LCOU), battery (B), mixed-integer linear programming (MILP), variable tariff (VT).

2.4 Knowledge gap

Based on the previously described context and literature of residential batteries, multiple knowledge gaps are defined below:

- From the societal context follows that grid congestion and intermittency of the growing renewable energy sources become a larger problem for the system. With policy makers the question rises whether residential batteries will help by solving these problems, and thus whether they should be stimulated. Their corresponding effect on the distribution system is not determined.
- As soon as batteries have a positive business case they will emerge. The most profitable residential battery control method in the future is uncertain for the Netherlands because of the altering policy landscape. It is unknown what the consequences of various ways of battery control are on the distribution grid and whether they will help to solve the congestion problem.
- Comparable research fails to combine the effect on the level of a real distribution grid with the potential control methods of the batteries.
- In this research, specifically the Dutch electricity retail market and its related policies are considered. Their context is changing fast.

This research performs a scenario analysis of the future of residential batteries. The battery profiles are modelled from consumer perspective. Because of uncertainty of the policy landscape, different control options of the battery are evaluated. Their corresponding business cases are calculated. With a load profile summation model the batteries are integrated in the distribution grid. Their load effects on the distribution grid can be determined, specifically on the medium voltage substation. This research aims to compare consumers' battery control methods based on their profitability and load effects. The battery and station load profiles are computed over a time span of one whole year. Since the emergence of residential batteries will take place in the future, the effect of batteries on the future distribution grid load will be considered and part of the real Stedin network hierarchy is included. By integrating the expected amount of residential batteries in the future system, the real impact can be evaluated.

2.5 Research questions

The phase out of net-metering will likely be a stimulation for the emerge of residential batteries and at the same time the DSOs face an increasing pressure on the grid due to electrification and variable energy sources. The Dutch market of residential battery systems is still niche and lacks regulations and policies. There are several options for the control strategies for residential batteries. What the ideal use case of residential batteries will be in the future Dutch electricity system will depend highly on the development of policies and regulations. What these batteries will change in the load on the electricity grid is highly dependent on the control strategy and unknown for the future network. Therefor, the main research question is:

What is the effect of different residential battery use cases on the load peak on medium voltage substations in the future?

This question roughly consists of two parts: different use cases of residential batteries and the effect on the peak load in distribution medium voltage substations. In this research question, medium voltage substations are chosen to represent the distribution grid, since the amount of connections is high enough to assume individual load peaks are averaged out. The importance of these substations is high to DSOs because of the high reinforcement costs and long time to construct. 2050 is an important milestone in the current climate agreement, because the CO2 emissions must be reduced by 95% compared to the year 1990. In this research, the years 2030, 2040 and 2050 are chosen to represent the future to analyse the developments of the grid. Currently, the amount of residential batteries is still small and the net-metering policy, which is a suppressing measure for the emerge of batteries, is only planned to be phased-out by 2031.

In order to answer the main question, five sub questions have to be answered first. The sub-questions are given and their corresponding research approach is explained.

1. How is the load on a medium voltage substation expected to change until 2050?
To define the context of the problems of the grid and in order to analyse the changes on the capacity of a substation, the present situation of capacity profiles and daily and yearly load profiles on the station should be known. The model that analyses the expected load impact on the network for Stedin area, SETIAM, must be understand. The inputs and parameters must be identified and simulations of the network should be understood.

2. What will drive the emergence of residential batteries and their usage?
To model the resulting residential battery load, the different control strategies must be identified. There are multiple control strategies and each have specific advantages depending on the policy landscape and battery specifications. To identify the control strategies, first the context of the owner of the battery must be analysed. The consideration of buying a battery is analysed based on literature. Also, the factors that determine why a specific use case is chosen are mapped. Consequently, the use cases itself are defined.

3. What is the expected development of residential batteries in the Netherlands?
To assess the effect of residential batteries, the future of these batteries must be mapped. The approach to this answer is both social and technical. A literature research will be performed on battery prognoses based on policies, forecasts and specifications.

4. What is the load profile and corresponding profitability of a residential battery per control method?
To determine the resulting load profile of a battery, the control strategies defined in the previous sub-question must be modelled. The input parameters are defined by the expected future scenarios of residential batteries. The most suitable modelling method must follow from the second research step. Additionally, the profitability of residential batteries is determined per control method in order to compare them.

5. Will residential batteries relieve load peaks of the selected distribution station?
The next step is to simulate the battery scenarios in the distribution network. For this step the Setiam model is used. Different scenarios for the batteries are both the previous defined use cases and the created capacity scenarios. The batteries must be distributed over the Stedin network, with the input parameters from the expected future distribution of sub-questions 2 and 3.

By reflecting on this research, recommendations can be given by answering the following question:

6. What regulations can improve the integration of residential batteries in the electricity network?
The approach of this phase is reflecting on the possible policies that lead to certain use cases and the effects these use cases have. The possible market policies and there consequences on battery usage are researched. With the overall desired effects, recommendations will be given.

3 Methodology

Three different control options of residential batteries are analysed from consumers' perspective and their effect on the distribution grid will be evaluated. First, in section 3.1, rule-based approaches to determine the individual household battery profiles are described. Then the economic valuation from consumers' perspective is explained in section 3.2. Finally, in section 3.3, the load profile summation method is described to determine the future yearly load on a medium voltage substation, and how the batteries will affect this load.

3.1 Determination of single battery profile

Batteries can be used to maximise self-consumption, for load peak shaving, or for market price arbitrage. With this latter control method, the battery is used for price arbitrage based on day-ahead market prices. This control is denoted by market participation, however the battery power is not directly used for bidding on the market. Most battery users indicate to use their storage for more than one application (Janssen & Jansen, 2022). In this research however, one single application method is assumed at the time, in order to compare the effects of each of them. This will be discussed further in Chapter 6.

The corresponding power output of residential batteries in the different control strategies will be determined with a rule-based approach. This method has been used before in comparable studies, and is thus considered fitting for this research (Seydali Seyf Abad et al., 2022; Zhang, Lundblad, Campana, Benavente, & Yan, 2017; Olaszi & Ladanyi, 2017). In the next sections the calculation of the battery output is described by means of a flowchart per control strategy. In order to determine the battery power output of all three use cases, the parameters, input variables, and output are defined below. In the next Chapter 4, the input data and parameter values are specified.

The following parameters are used in the calculation.

- Time t in hours starts at 0 and ends after one year at $t = 8760$ h. This time frame is chosen to fit in the station load model accordingly.
- Day d is defined to calculate the average value of that day starting at 0:00h and ending at 24:00h
- Energy capacity of the battery C_E in kWh, chosen as most commonly used battery size
- Power capacity of the battery C_P in kW
- Initial Level of charge LoC in kWh at $t = 0$ h
- Grid load threshold TH_{min} and TH_{max} in kWh which determine the grid capacity limit relative to the average daily load
- Electricity price threshold P_{TH} €$/MWh$ which identifies when the price peak is high enough to initiate (dis)charging of the battery

The following variables are input for the calculation.

- Demand load D per hour of one household in kWh for one year
- Rooftop PV generation PV per hour in kWh for one year
- Average load L_{av} in kWh of the current day (24 hours)
- Dutch day-ahead electricity prices in €$/MWh$ for every hour
- Average day-ahead electricity prices P_{av} in €$/MWh$ of the current day (24 hours)

The following variables calculated using the previous described input and defined parameters.

- Battery power P_{batt} in kW for one year
- Battery's level of charge LoC in kWh for every hour in one year

3.1.1 Self-consumption

Because of the time-based mismatch of demand for electricity and rooftop PV generation, the generated electricity cannot be used directly to satisfy demand. Excess PV generation during the day is fed back into the grid and excess demand is satisfied from the grid. A battery can be used to match this load demand to the PV generation of a household. The battery is charged with excess PV power and discharged when demand exceeds this generation.

In figure 3.1 the flowchart of determining the battery power profile is shown. At the start the initial time value $t[h]$ and the initial Level of Charge $LoC[kWh]$ are set to zero. The demand D and PV both in $[kWh]$ in hour t are read. When generation exceeds D and the LoC of the battery is still below its energy capacity $C_E[kWh]$, the battery is charged. The charging power of the battery is limited by its power capacity $C_P[kW]$. Within one hour, the battery can charge the excess PV power with the limit of this maximum C_P. The battery is charged until the C_E is reached. When D is greater than the PV generations and thus net demand, the battery will discharge if the LoC is non-zero. This discharge is limited by the C_P. The battery will discharge to satisfy the net demand until the LoC reaches zero. The power of the battery $P_{batt}[kW]$ at time t is determined by the change in charge of the battery. This iterative calculation of P_{batt} is executed until all hours of the year are covered. The output is the battery power profile over one year of one single household.

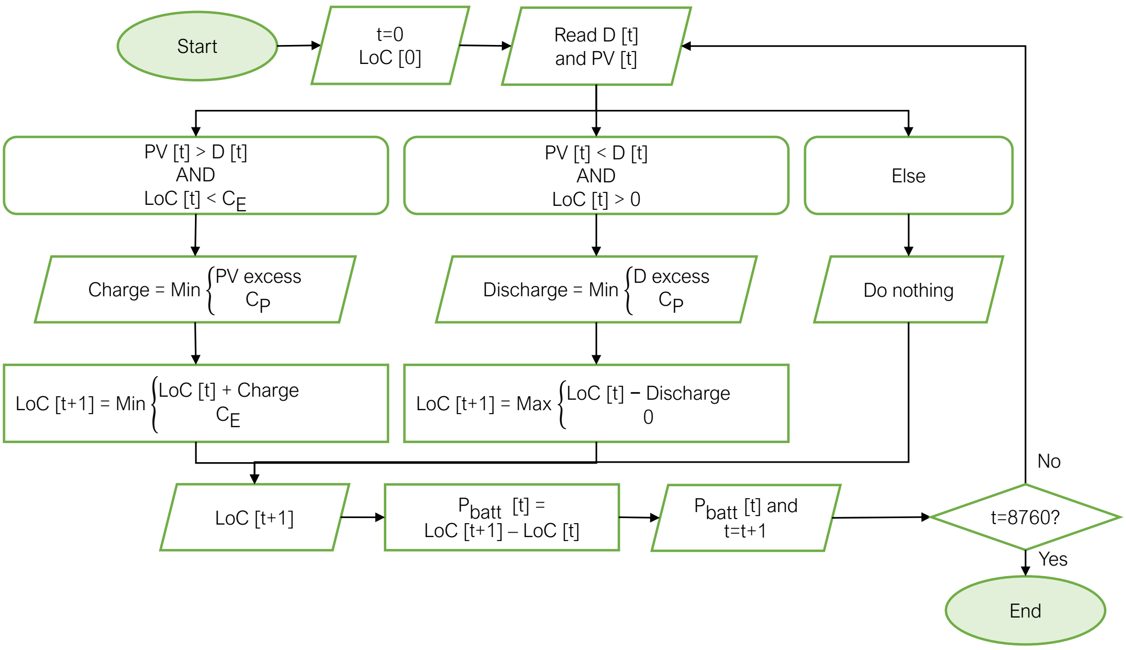


Figure 3.1: Flowchart of battery profile construction in self-consumption control.

3.1.2 Power peak reduction

Battery storage can be used to reduce grid power peaks by absorbing the peaks in both demand and generation in the battery. The self-consumption rate should not be compromised in this use case with respect to the previously described maximising self-consumption method (Moshövel et al., 2015). However, maximisation of self-consumption often leads to a fully charged battery before the PV generation peak in the afternoon, which still results in a grid load peak (Moshövel et al., 2015). Therefore, the self-consumption method won't relieve stress on the grid. When charging the battery would be better spread out during the PV excess, the power peak can be reduced.

In figure 3.2, the flowchart to construct the battery power over one year is shown. The total load on the grid is calculated by subtracting the PV generation from the demand load. Then the average daily load L_{av} is calculated over 24 hours. This would imply a perfect forecast of the electricity consumption and demand the day before. Around the L_{av} a threshold limit is set by TH_{min} and TH_{max}. When the power exceeds this limit, it is defined as a peak and the battery will charge or discharge. The power of this peak relative to the threshold limit is the amount of (dis)charge, only when this does not exceed the power capacity. The battery is (dis)charged until it reaches its energy capacity limit. From the difference in battery charge, the battery output power is calculated. This process is iterated over all hours of the year.

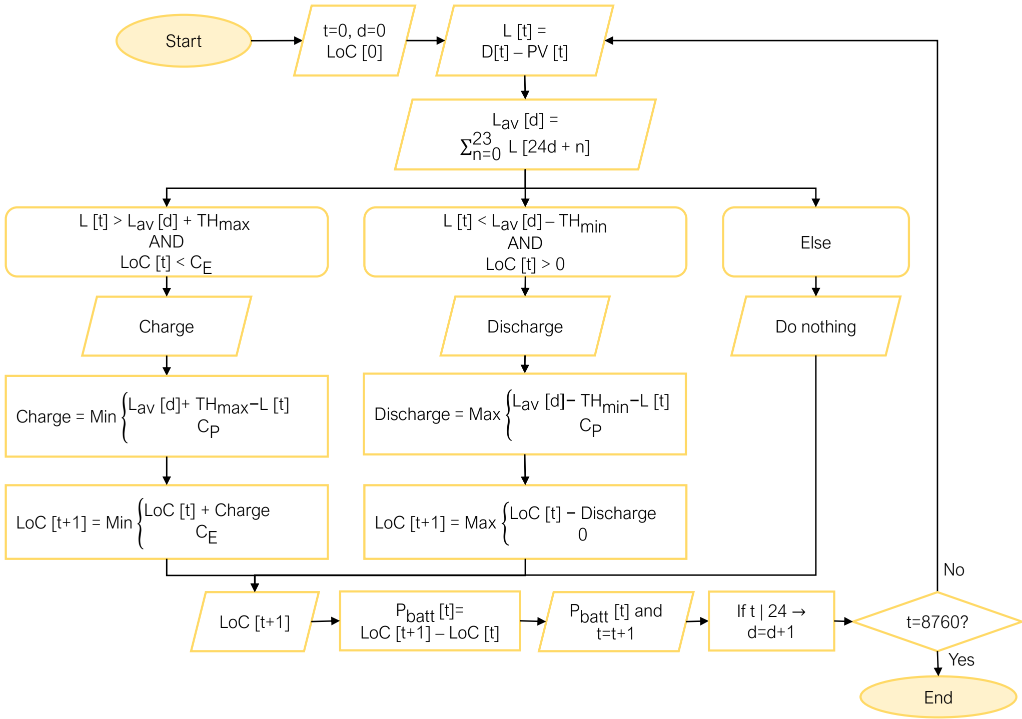


Figure 3.2: Flowchart of battery profile construction in peak reduction control.

The grid load threshold is based on the daily average instead of a fixed grid limit during the year to make sure that for both generation peaks and demand peaks there is still battery capacity left. The threshold limit around this average load value should be large enough to ensure high self-consumption and grid relieve, yet low enough to ensure the battery is able to cover the peak before it is fully (dis)charged. In this research perfect forecast is assumed over the average total load of the day ahead. Although the moments of demand or PV peaks are uncertain and daily changes can happen, this assumption is justified since it is an averaged value.

3.1.3 Market price arbitrage

The business case for price-based battery control is based on the difference in price when charging and discharging: price arbitrage. This is stimulated for dynamic electricity price contracts. The control of the battery is unrelated to the current demand load because it is only based on electricity prices. Figure 3.3 shows the flowchart to construct the battery power profile over one year. The battery will be discharged in order to sell the electricity when the price is high and cheap electricity will be used to charge the battery again. The battery will discharge when the electricity price exceeds a certain price limit. This limit is defined as the average price of that day plus a certain threshold. The battery will discharge at its power capacity until it is empty. The same method is applied for charging when the price falls below the average price minus the price threshold. The battery is then charged until it reached full capacity. The updated LoC is calculated and from that change the battery power is recovered. When all hours of the year are calculated, the iterative process is ended.

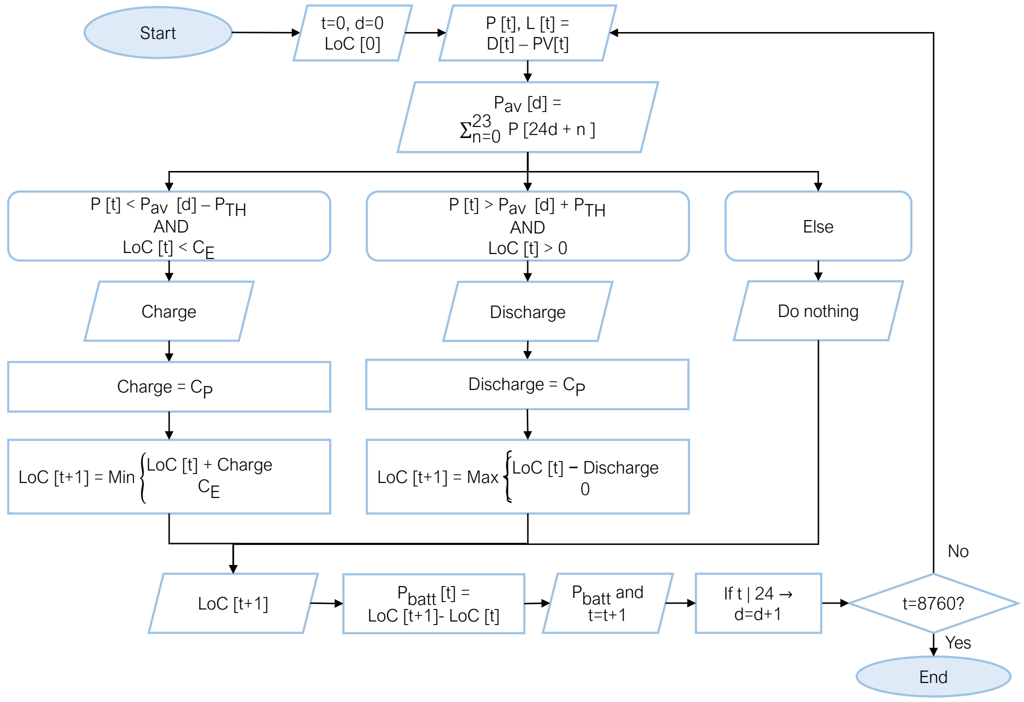


Figure 3.3: Flowchart of battery profile construction in market participation control.

Thresholds are defined around the daily average value to identify the daily price peaks to make sure that the battery is only controlled when the price peaks are significant and to reduce the amount of charging cycles of the battery. The threshold value represents the willingness to use the battery even though a charging cycle decreases its lifetime. For this calculation the daily average market price is required. The day-ahead market auction takes place, as the name would imply, at noon the day ahead. Therefore, the average price for the current day is a known parameter when a household is charged with market prices by their electricity supplier. This study does not take into account the influence the batteries have on the market prices.

3.2 Residential economic drivers

The revenues per control strategy can be calculated for various pricing mechanisms. Self-consumption can be stimulated with a price gap between electricity's retail price and feed-in price. In this study, the net-metering scheme is neglected for calculation of the business case for residential batteries. When this scheme is still in place, there is no incentive to increase self-consumption, because the grid basically acts as an economic unlimited battery. When there is a gap between the retail electricity price and the feed-in tariff, the so-called feed-in gap, it is profitable to consume your own generated electricity instead of feeding into the grid and buy grid electricity again. The self-consumption rate is defined as the directly and indirectly self-consumed PV generated electricity divided by the total PV generated electricity (Han, Garrison, & Hug, 2022). Price arbitrage using a battery is possible when small connections can be charged with day-ahead prices or when the battery is controlled by an aggregator who can participate on the market. In the Netherlands already a few energy suppliers use hourly variable electricity prices. Peak reduction can be stimulated with capacity tariffs. To determine the profitability of residential batteries for individual households, the pay-back period is determined. The pay-back period is defined as the investment costs divided by the annual revenue.

3.3 Effects of residential batteries on the distribution grid

In this research, a simulation of the battery implementation will be performed in the distribution network of Stedin using load profile summation. The battery emergence will be implemented in a scenario-based manner: the different use cases each form an individual scenario together with the overall number of batteries. These batteries will be virtually distributed over the distribution network and their load effect on connected grid components is determined. The model SETIAM will be used, which is described in appendix D. Stedin uses this model to simulate the increasing load on the distribution grid to oversee necessary grid investments.

First, the batteries are distributed over the residential connections of Stedin area. The method distribution of the batteries equal for all the scenarios and control cases. They are randomly distributed over the houses with installed PV and categorised as 'residential'. The chance only depends on PV and not on income and other technologies like electric vehicles and heat pumps because when controlling for maximising self-consumption, PV is crucial. All connections are then randomly ordered and assigned a battery until the number of batteries from the battery scenario for the Stedin area is reached.
Second, the battery load profiles of all households with a battery are individually determined. The battery profile highly depends on annual electricity consumption, size of PV installation, consumption of a heat pump, and the ownership of an electric vehicle. Then, all these battery load profiles connected to the selected station are added, by yearly load summation. For every battery scenario and battery control method, the effect of the batteries on the station load is determined for the years 2030, 2040 and 2050. A single medium voltage substation is selected as a representative of the distribution network.

The effects on the grid are analysed by assessing load pressure on the substation during the whole year with respect to their capacity limit. With this comparison, congestion prediction can be performed to assess the need for investment on particular substations. To assess the effect of implementation of residential batteries in the network, the load peaks on the substation can be compared to the initial profiles. The battery power output for each control strategy is assessed individually to identify their disadvantages or benefits.

4 Data

This chapter describes the assumptions, required input variables and constants for the research methodology in more detail. First, general assumptions in the scope of this research are given in section 4.1. In order to determine the residential battery profile, the electricity consumption and PV generation must be defined. In section 4.2, the yearly residential electricity demand and PV generation profiles are described and the day-ahead market prices of 2021 are given, which is input for the price arbitrage. Section 4.3 presents various specifications of residential batteries to identify the used battery parameters for this research, and trends of electricity prices and battery costs are described. The different battery control strategies that are included in this research are named in section 4.4 and the emergence scenarios are created. At last, section 4.5 provides the future station load profiles without the connection of residential batteries.

4.1 General assumptions

All battery profiles are determined using a rule-based approach, based on standardised load profiles or 2021 market prices. The market prices of 2021 do not one-on-one correspond perfectly to the yearly loads on the station. Assumed is that the market prices are not influenced by the batteries and are known day-ahead. Demand response and multi-application of the battery are neglected. Only one control method at the same time is evaluated to be able to compare the different battery control methods. Also, no other flexibility sources are taken into account for the station load. The station load is determined by load flow summation. Therefore, grid frequency and voltage fluctuations are not considered as well as lower grid components.

4.2 Annual residential load and price profiles

For the electricity demand profile of a household the standardised load profile of NEDU is used (van Langen, van Tol, Quak, Sinke, & van Bruggen, 2021). This yearly demand profile is then multiplied by the annual electricity consumption to form the demand profile. For calculations for single households the average annual electricity consumption of 3300 kWh is assumed. The used PV generation profile is supplied by grid operator Liander and is a general PV profile unrelated to a particular year. The size of the rooftop PV installation is taken as 3.3 kWp, which in the Netherlands approximately corresponds to the annual demand of 3300 kWh. The resulting yearly load profiles of demand and PV generation are shown in figure 4.1, and the daily profiles are shown in figure 4.2 where two days in January and July are shown. The demand of electricity increases at the end of the afternoon until the evening. A smaller increase is noticed during the morning hours. Both during the day around noon and during the night, the demand is lowest. During the year, electricity consumption is significantly higher during winter months. The generation of rooftop PV is significantly higher during summer and fluctuates on a daily basis. In January, the PV generation does barely exceed the electricity demand at its peak moment.

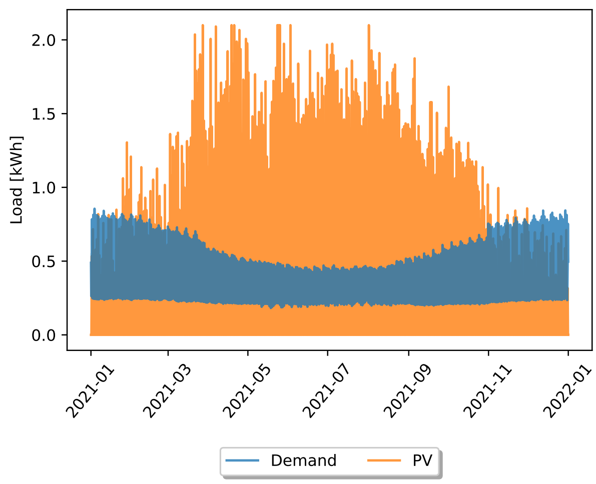
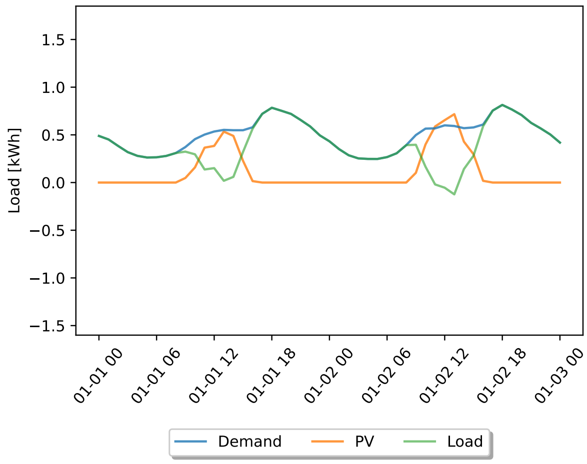
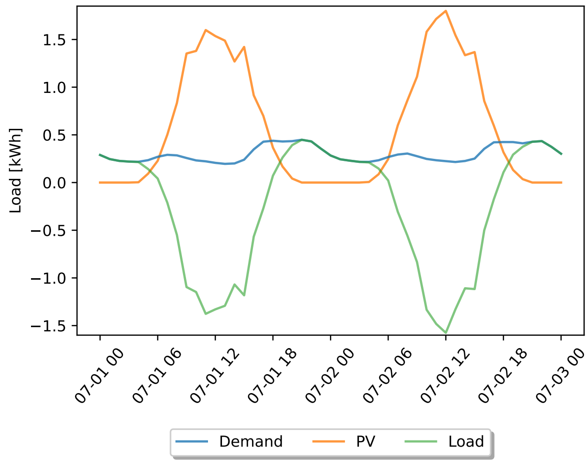


Figure 4.1: Yearly residential demand and PV generation profiles.



(a) Two days in January

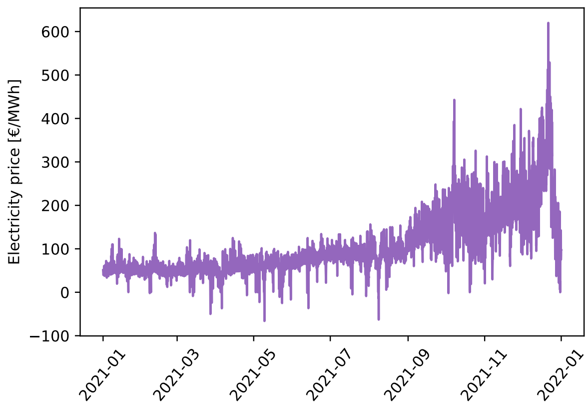


(b) Two days in July

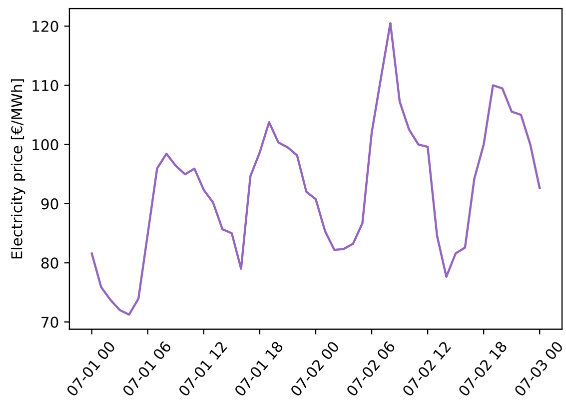
Figure 4.2: The averaged hourly load profiles of households demand and rooftop PV generation for two days. The electricity demand and generation are summed for the total connection load indicated in green.

For the calculation of the overall battery profile over the station load, the specific annual electricity consumption, PV size, heat pump and electric vehicle of the individual houses are all inputs for the battery profile. For each individual connection of Stedin the annual electricity consumption is known in kWh. Each connection is categorised by a type of NEDU profile. The size of the PV installation is individually projected by Stedin using parameters as neighbour's PV installation, rooftop size and energy consumption. The potentially present heat pump profile is based on the size of the heat pump, the outside temperature and the previous annual gas consumption. The possibility of an electric vehicle is also included in determination of the electricity consumption per household.

In this research, only the day-ahead wholesale electricity prices are taken into account. An aggregator can be involved to control the battery in favour of the owners in order to participate in the day-ahead market. However, there are new energy suppliers that supply electricity for hourly dynamic prices, which are based on the day-ahead prices. With those suppliers you wouldn't need an aggregator. The market prices of 2021 are taken and the yearly profile can be seen in figure 4.3a. A steep increase can be seen at the end of 2021. This is caused by many factors, including growing electricity demand because the ending of corona measures and the uncertainty of gas supply because of the Ukrainian war. Daily price fluctuations can be seen in figure 4.3b, which shows two days in July. Mid day the prices are low because of PV generation and lower electricity demand. At the beginning of the evening when everyone gets home, the electricity demand increases and thus the market prices.



(a) Year 2021



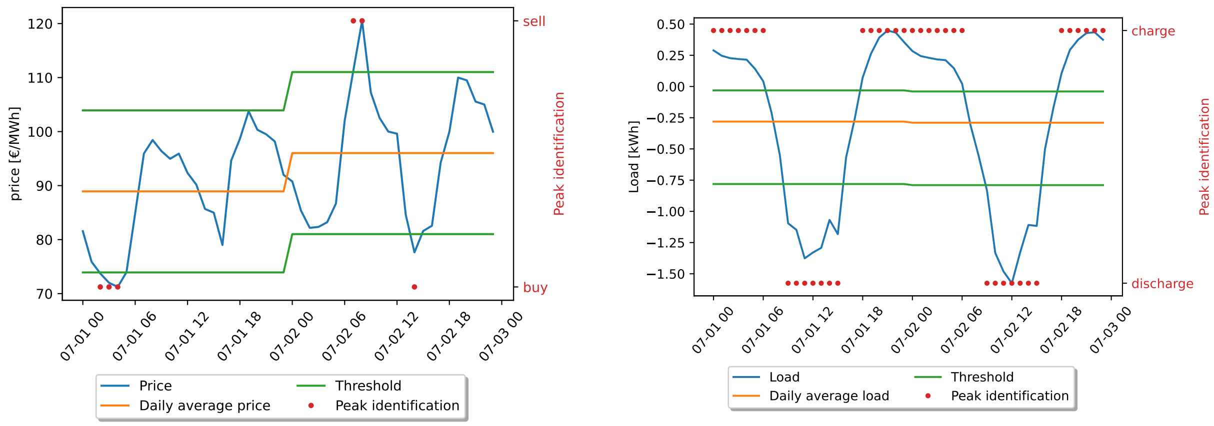
(b) Two days in July

Figure 4.3: The day-ahead electricity price profile of 2021 of the whole year and zoomed-in over 2 days in July. The prices increase towards the end of the year and the spread during the day increased as well.

As well as the wholesale electricity market prices, the retail consumer prices are rapidly changing as well. The prices differ per energy supplier, however as an average an electricity price of €0.24/kWh in 2021 and €0.67/kWh in 2022 is assumed and a feed-in tariff of €0.07/kWh in 2021 and €0.17/kWh in 2022.

When the battery is used for price arbitrage, it is controlled based on a threshold relative to the average day-ahead market price. The price threshold is set at 20 €/MWh. This should be related to the willingness to pay for this one cycle. Now, this threshold of 20 €/MWh is chosen to keep the frequency of battery charging cycles around once a day. Price peak identification using this method of two days in July can be seen in figure 4.4a.

When the battery is controlled to reduce load peaks, the peak of PV generation or demand is reduced to a threshold. This threshold is defined as the daily average load plus or minus a certain threshold. In order to do this, there must be a perfect forecast. In reality this would be an estimation based on the daily demand and estimated PV generation. In this research the load threshold is set on 50% of the average daily load. This means that when the load peak exceeds +50% or -50% of daily average, the battery will charge/discharge to shave this peak. The identification of load peaks based on the average load in combination with a threshold, can be observed in figure 4.4b.



(a) Price peak identification

(b) Load peak identification

Figure 4.4: (a) When the electricity price exceeds the threshold limits electricity is bought or sold (b) Load peaks are identified and the peak is reduced by (dis)charging until the threshold load value.

4.3 Battery parameters

4.3.1 Present

The most common types of home batteries are lithium-ion and lead-acid (Gysel, 2021). The first one is the upcoming type and is driving lead-acid, the second most common battery type, out of the market because of its great price decline and technological improvements. Although the latter one is cheaper than lithium-ion batteries, the depth of discharge is only half of the total capacity and has a shorter lifetime (Han et al., 2022). Recently, the main battery technology is lithium-ion (Li-ion) and most of the big brands like Tesla, LG and Samsung merely use lithium-ion batteries. The Dutch residential battery start-up company sells a iron-phosphate battery. Specifications of some residential batteries are given in table 4.1. Most battery producers give a warranty of usually 10 years. For Lithium iron phosphate the cycle life is around 6000 cycles and for lithium-ion batteries it is typically between 4,000 and 8,000 cycles. For lead acid batteries this is around 800 - 1,000 cycles. A lifetime of 15 years is assumed. For simplicity, charging or discharging power losses are neglected. At present, residential batteries cost between €600 - €1,000 per kWh (Stultiens, 2022a). For a residential battery of size 3kW/6kWh this would be €3,600-€6,000

Brand	Usable energy (kWh)	Continuous power (kW)	Round trip efficiency (%)	Price indication (€)
Tesla powerwall	13.5	5	90	9,000
LG Chem	9.3	5	94.5	7,000
Generac	9	3.4	96.5	8,800
sonnen eco	5	3	86	6,000
Charged Sessy	5	2	unknown	3,250
- This study -	6	2	neglected	4,500

Table 4.1: Comparison of specifications of various residential batteries. Specifications chosen in this study are included.

As a common, averaged residential battery size, 6 kWh is chosen. There are bigger ones like the Tesla's powerwall, however in the Netherlands there is limited PV production in comparison with other countries and when used related with own electricity consumption 6 kWh is plenty, especially in the summer. An equal battery size is chosen for all battery control methods. Usually, the maximum power capacity is around half of the energy capacity meaning that it can (dis)charge fully in two hours. However, using this maximum power output is decreasing the lifetime of a battery significantly. Therefore, a power capacity of 2 kW is chosen. The initial SoC is set at 0 %. A battery is not necessarily always completing a charging cycle from fully charged to fully empty. It is defined that a battery completes a single charging cycle when the summed discharged power equals the battery's capacity. The degradation of the batteries during their lifetime is not taken into account, however, with the use of thresholds the number of cycles is limited to slow down the degradation process.

4.3.2 Future

The main parameters that affect the profitability of residential batteries are future electricity prices, technology costs, potential subsidies and facing-out of net-metering (Klingler et al., 2019; Afman, 2021). To estimate the future electricity prices, the future share of renewable energy sources and the electricity demand is accessed. The Dutch wholesale electricity prices will rise in the following years according to Klingler et al.. The estimated values are given in table 4.2. However, the electricity prices have increased enormously during 2020. The average wholesale electricity price of 2021 already was 103 €/MWh. Although, these estimated future prices do show the expected market trend of rising electricity prices.

Year	2020	2030	2040	2050
Mean wholesale prices [€/MWh]	38.8	79.2	101.3	108.1

Table 4.2: Estimated increasing wholesale electricity prices in the Netherlands for the years 2020, 2030, 2040 and 2050 in €/MWh. Source: (Klingler et al., 2019)

Battery prices have fallen enormously in the past years, mainly due to the upcoming electric vehicle industry. This decline is expected to continue in the coming years, as can be seen in figure 4.5 and in table 4.3. The costs of batteries in the future is estimated by Klingler et al. using the so called 'experience curve', which is based on the historic correlation of double cumulative production leading to a decline of production price by an established percentage. The production costs decrease because of scale benefits and technical learning. The decrease in cost by every doubled cumulative production is called the learning rate. The price of residential batteries has declined from 2000 €/kWh in 2012 to 1600 €/kWh in 2016 (Klingler et al., 2019). A learning rate of 12.5% is determined, however it is noted that the small number of data points could result in an inconsistent learning rate over the years. In (Han et al., 2022) the costs of residential batteries are taken as a constant value of 295-459 €/kWh + 249-388 €/kW in the year 2020. According to Kairies et al., in 2018 the prices declined with more than 50% with respect to 2013.

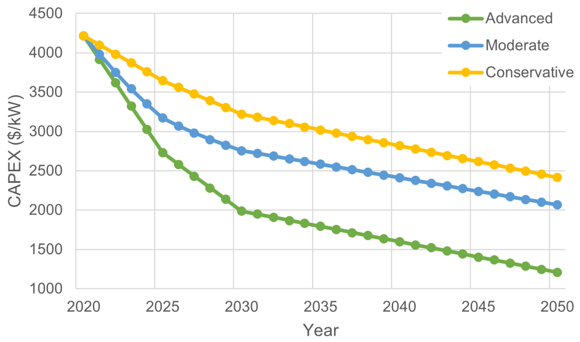


Figure 4.5: The predicted battery price of a 5 kW/20 kWh residential battery for three different scenarios. Source: (NREL, 2021)

Year	Investment costs			Operation costs	
	€/kWh	€/kW	€/3kW|6kWh	€/kWh	€/kW
2020	377	319	3,219	1.41	4.7
2025	233	197	1,989	0.87	2.91
2030	158	133	1,347	0.59	1.97
2035	123	104	1,050	0.46	1.54
2040	110	93	939	0.41	1.37
2045	103	87	879	0.38	1.28
2050	96	81	819	0.36	1.2

Table 4.3: The expected development of battery prices divided in costs for both energy and power and for both investment costs and operation costs. Source: (Han et al., 2022). The expected investment prices are translated for a 3kW/6kWh battery.

4.4 Residential battery scenarios and control methods

Battery control method For each individual house that has been assigned a residential battery, the battery profile is determined based on the three different control methods: self-consumption, market participation and peak reduction.

Battery adaptation scenarios The development of residential batteries in the Netherlands depends on multiple factors. The policy landscape is crucial as well as the technological innovations and investment costs. Multiple parties and stakeholders created capacity projections for residential batteries in the Netherlands. Klingler et al. estimates the market diffusion of residential batteries using the 'diffusion of innovation' theory. There is assumed that the battery increases self-consumption and the excess PV electricity can be sold on the wholesale market. They expect that in 2050 the battery prices have fallen to 364 €/kWh and 90% of the households owning a PV installation, has combined this with a residential battery. In the Netherlands, this would imply a battery capacity trend as described in table 4.4a. A comparable study has been done by DSO Liander for their area (Afman, 2021). They performed a study on residential battery business cases to develop possible scenarios. The estimated adaptation of residential batteries in these scenarios can be seen in table 4.4b.

Year	Capacity [MWh]	Number of 6 kWh batteries [x mln]
2020	0	0
2030	2,000	0.33
2040	6,392	1.07
2050	5,329	0.89

(a) Adoption scenario by Klinger

Year	Total installed power [GW]			Number of 2 kW batteries [x mln]		
	Low	Medium	High	Low	Medium	High
2020	0	0	0	0.00	0.00	0.00
2030	0	0.4	2	0.00	0.20	1.00
2040	0.6	2.7	5.8	0.30	1.35	2.90
2050	1.2	3.9	7.3	0.60	1.95	3.65

(b) Adoption scenario by Liander

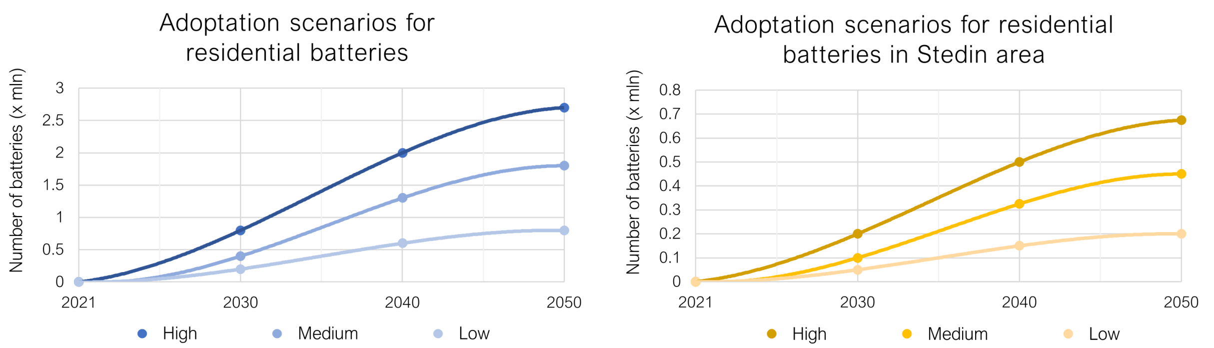
Table 4.4: The expected emergence of residential batteries in the Netherlands for the years 2020, 2030, 2040 and 2050 and the corresponding amount of 2kW/6kWh batteries (a) in capacity (MWh) source: (Klingler et al., 2019) and (b) in battery power (GW). Source: (Afman, 2021)

From the Energy Transition Model for the II3050 (Integral Infrastructure outlook 2030-2050) for the scenario of 'National Guiding', on which the grid operators scenario 'National Ambition' (ND) is based, the amount of residential batteries is estimated at 3,5 million in 2050 with a capacity of 5 kW each. The scenarios of Netbeheer Nederland are based on the scenarios of (den Ouden et al., 2020) and the expectations for battery storage and flexibility is shown in table 4.5.

	Regional guidance	National guidance	European CO_2 guidance	International guidance
Residential batteries	++	+	+	+
Community batteries	+	++	0	0
Large-scale battery storage	0	+	++	+
Expected battery storage (GW)	6	17	4	1

Table 4.5: Focus on type of battery system per energy scenario. Source: (den Ouden et al., 2020)

Based on all these estimations, scenarios are created and projected on Stedin area specific. The scenarios are divided in 'high', 'medium' and 'low' expected emergence of residential batteries and can be found in figure 4.6 and table 4.6. The minimum and maximum values of the previously described projections are taken into account. The future scenario for rooftop PV is also considered in the maximum number of residential batteries, assuming that the number of batteries does not exceed the number of rooftop PV installations (Klingler et al., 2019). Therefore, the maximum number of residential batteries of the Liander scenario and of II3050 would exceed this amount and a maximum of 2.7 million batteries is simulated. Extremely low emergence of residential batteries would not affect the distribution grid load and are neglected. The simulated emergence scenarios show a S-curve which is common for the growth of innovations. In 2021 the Netherlands has around 8 million households of which roughly 2 million are within Stedin's service area (CBS, 2021). Hence, the national scenario is divided by 4 obtain the Stedin level scenario. The number of batteries is cumulative per year starting in the initial year which is set as 2021.



(a) (b)

Figure 4.6: Scenarios for the amount of batteries installed until 2050.

	x mln	2030	2040	2050
Totaal	Low	0.20	0.60	0.80
	Medium	0.40	1.30	1.80
	High	0.80	2.00	2.70
Stedin	Low	0.05	0.15	0.20
	Medium	0.10	0.33	0.45
	High	0.20	0.50	0.68

Table 4.6: Scenario for the amount of adopted batteries for the years 2030, 2040 and 2050. The year 2021 is in all cases set to 0.

4.5 Base station load in years 2021, 2030, 2040 and 2050

To determine the load on substations in the future, the load changed by the connected technologies is added to the present, initial station load. In the top left corner of figure 4.7, the measured station load of 2021 of the selected substation can be found. In the following years, this station load will change due to the following technology changes, subdivided in four categories: generation, houses, mobility and growth. First, generation of electricity is changing because of upcoming wind and PV. Conventional electricity generation was not connected to the distribution medium voltage substations. On the contrary, decentralised renewable energy generation is connected to the lower voltage network. This is causing a changing load of the medium voltage substation in the future. Additionally, the load of connected houses change because of electrification of heating, new and demolished houses and the installation of residential batteries. The electrification of mobility will also impact the station load by increase in electric vehicles and their infrastructure. Lastly, an overall electricity demand growth of industry, agriculture and utilities is taken into account. For a more in depth overview of the changes in the electricity sector, see appendix A.

Figure 4.7 shows the predicted annual station load in the years 2030, 2040 and 2050. As can be seen in the initial year of 2021, the station load over the year is amply sufficient for the safety capacity on 27 MWh, indicated by the red lines. By 2030, both demand and generation increases during the year. This is causing load peaks on the station and therefore on particular moments the safety capacity of the station is not sufficient anymore: the station is overloaded on the electricity demand side. The increasing generation does not lead to overload yet. This is different in 2040, where the increase in generation leads to overload on both the demand and generation side. In the year 2050 this overload is only growing. On this substation, the consequences of the energy transition are clearly visible and increasing. Per substation (Stedin operates 177 substations), the load will be affected differently and thus possible overload on either sides will be unique. Dominance of generation or demand overload differs per station.

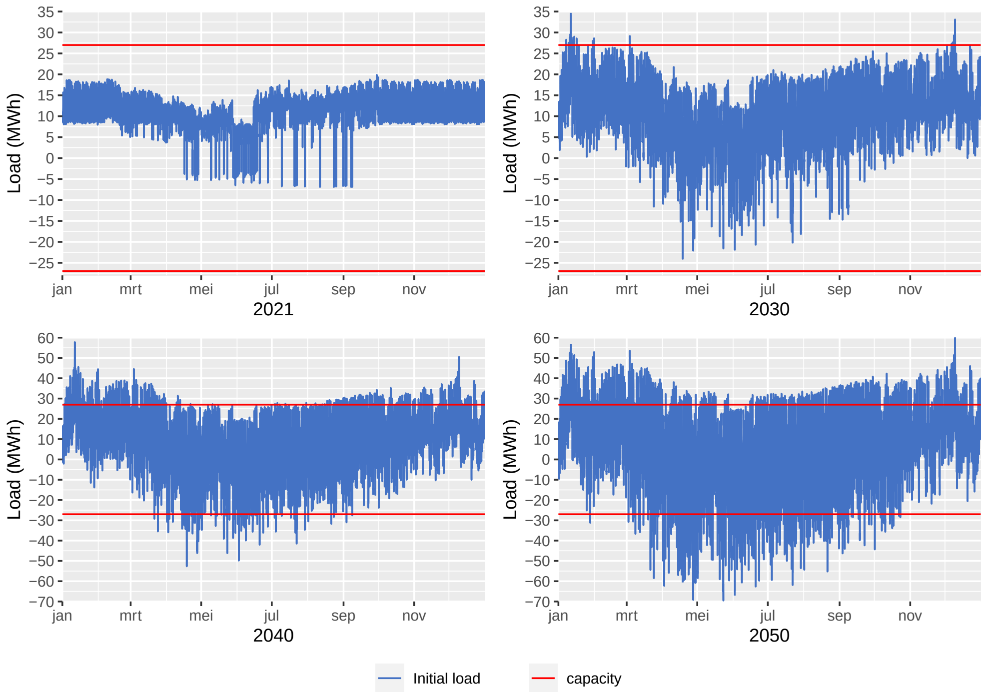


Figure 4.7: Residual load of the selected substation without residential batteries in 2021, 2030, 2040 and 2050. Source: (Stedin, 2021b)

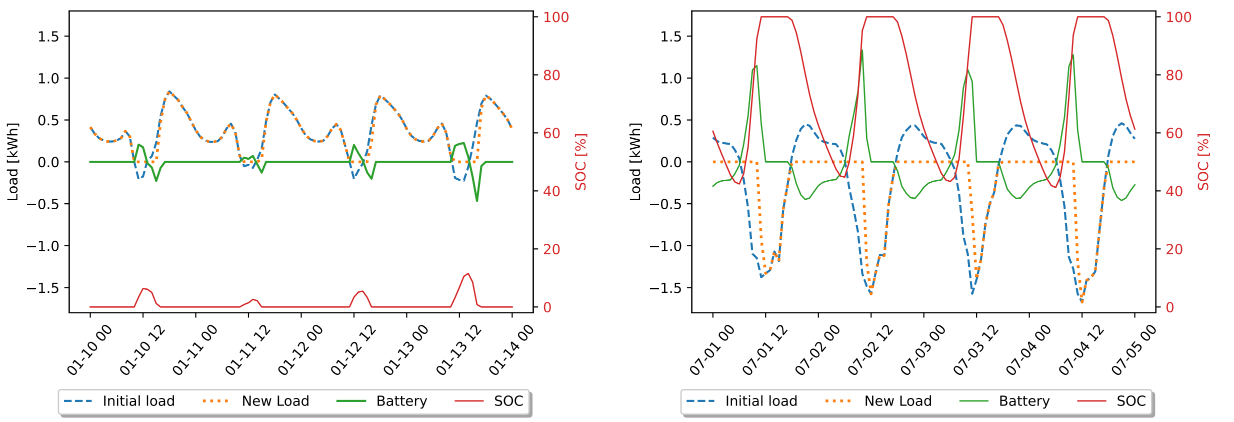
5 Results

In this chapter, the results of this research are presented and the main findings are described. The results for the individual consumers' battery profiles are presented in section 5.1. The business case for a residential battery when controlled for maximising self-consumption and market price arbitrage are given in section 5.2. The resulting station load profiles with the residential batteries effects are presented in section 5.3, together with the results of the peak analysis. At the end, in section 5.4, the selected substation will be put in context with the other substations.

5.1 Household's battery profiles

The load profile of three residential battery control methods: maximising self-consumption, load peak reduction and price arbitrage by market participation are constructed using the flowcharts in figures 3.1, 3.2 and 3.3. The resulting battery profiles and their effect on the residential grid load of a few days are shown in figures 5.1, 5.2 and 5.3, for the battery in self-consumption, peak reduction, and price arbitrage control mode respectively. The load is given in hourly power and so has the unit kWh. A positive battery load indicates battery charging and vice versa.

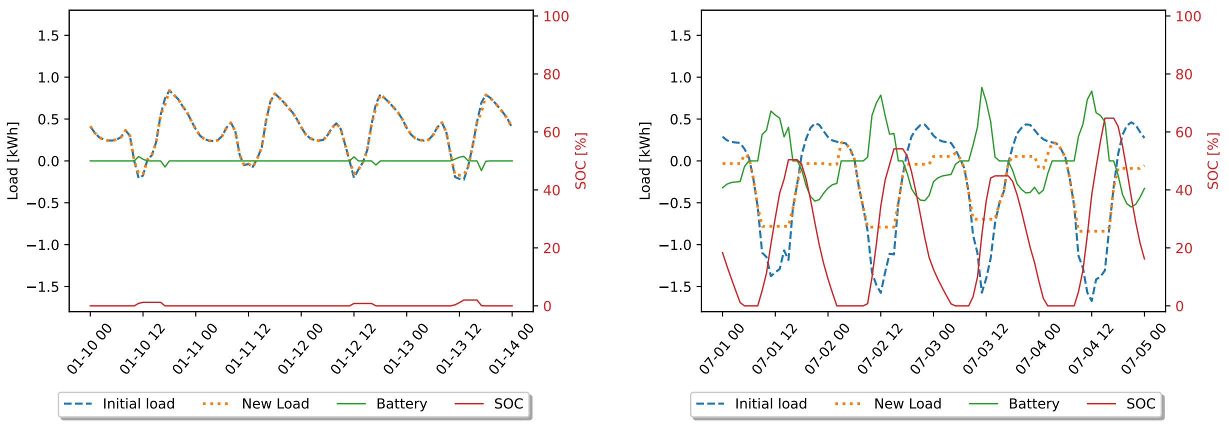
When the residential battery is in self-consumption control mode, excess PV generation is used to charge the battery and net consumption is used to discharge the battery. The objective is to increase the amount of self-consumed electricity and reduce the amount of electricity that is fed into the grid. The timing of peaks, or pricing are not considered. In figure 5.1b, can be seen that in case of net generation, the battery starts charging and around noon the battery is fully charged. The excess generation is then fed into the grid. The battery can be fully charged before the generation peak. As a result, it does not necessarily reduces grid load peaks. The electricity consumption is in this case fully covered by discharging the battery and is thus equal to zero. During winter, the generation does barely exceed electricity demand and thus the battery cannot be charged to significantly reduce total load, as can be seen in figure 5.1a.



(a) January (b) July

Figure 5.1: Output of battery power when used for maximising self-consumption with the resulting grid load and the SoC of the battery of 4 days in January and July.

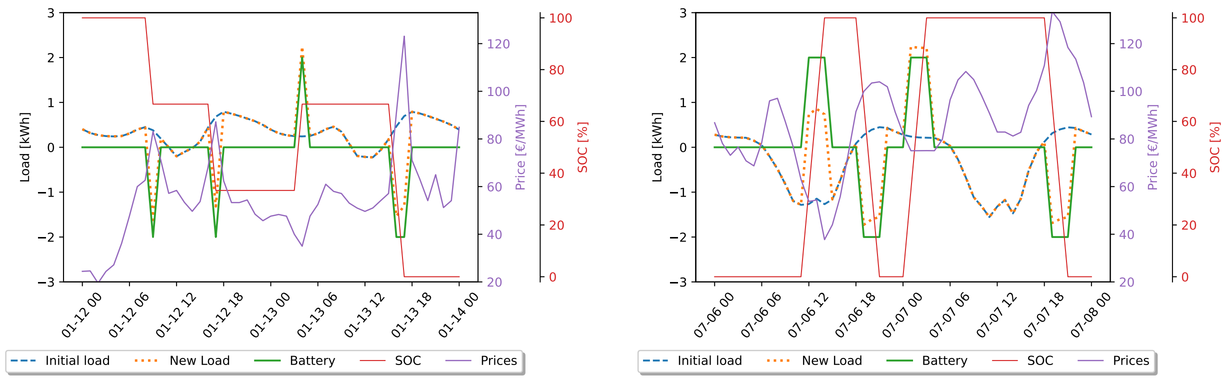
In peak reduction control mode, PV generation is more gradually used to charge the battery and thus is not fully charged before load peaks. The battery only starts (dis)charging when load exceeds a certain threshold which is related to the average daily load. The new load in figure 5.2 shows a more gradual battery charging profile. However, because this battery control is not daily optimised, the self-consumption rate is not optimal: it can be seen that the battery is not charged enough to cover the daily consumption, while not yet fully charged. Also, during the winter, the PV generation peaks are smaller, the chosen threshold does not cause the battery to charge during the day in order to cover demand peaks.



(a) January (b) July

Figure 5.2: Output of battery power when used for load peak reduction with the resulting grid load and the SoC of the battery of 4 days in January and July.

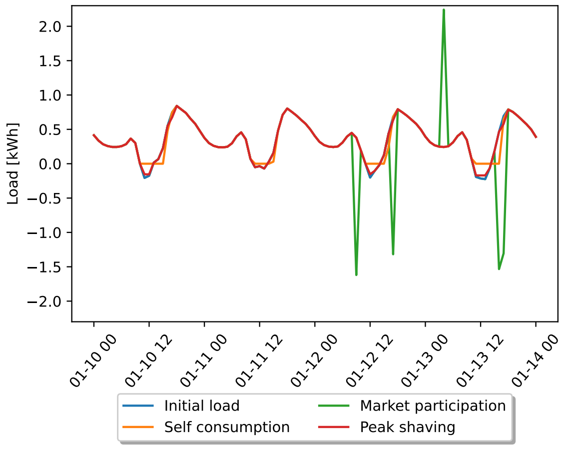
The control of the battery when based on the day-ahead wholesale electricity prices is shown in figure 5.3. The day-ahead electricity prices are shown in purple. During a price peak the battery is charged until the price drops again or when fully charged. The new total load shows an increase in fed-in electricity. When the price is low the battery charges and the grid load increases. As can be seen, the price profile relates to the load profile. Normally around noon the prices drop and in the morning and evening, when the load is normally higher, the prices are higher. However, the battery does not consistently reduce grid load peaks on the right moment. The battery control is not significantly different for winter and summer days in these graphs.



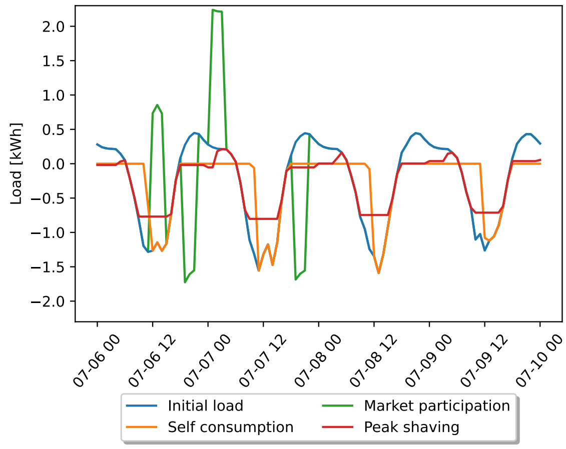
(a) January (b) July

Figure 5.3: Output of battery power when used for price arbitrage with the resulting grid load, the SoC of the battery and the market prices of 2 days in January and July.

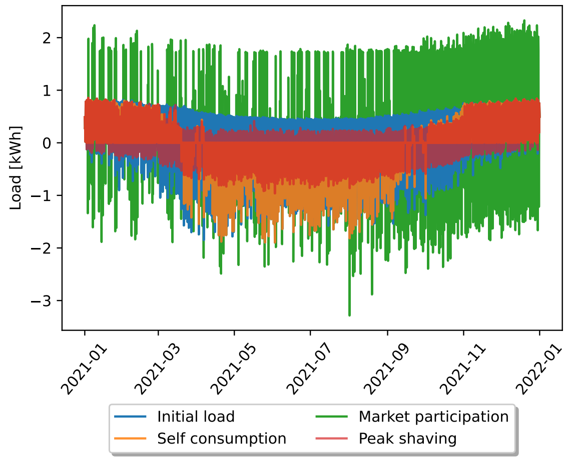
The resulting annual grid load of a single household is determined by adding the annual battery profile to the initial load. An annual electricity consumption of 3,300 kWh is assumed, which is an average household consumption. A PV installation of 3.3 kWp is assumed and no heat pump or electric vehicle are present in this example. These technologies are regarded in the load profiles connected to the substation. The initial annual electricity consumption of an average household is shown in blue in figure 5.4c, which is the PV generation added to the electricity consumption, both shown in figure 4.1. In this figure the resulting electricity load for the three control methods are presented as the blue line. Figures 5.4a and 5.4b show the household load profiles over 4 days in both January and July, in which the effect of the battery on the load on a daily basis can be seen. During winter, when PV generation is significantly lower than in summer, the battery is charged less for self-consumption and peak reduction, and thus the effects on the residential load are smaller.



(a) 4 days in January



(b) 4 days in July



(c) Yearly

Figure 5.4: Net grid output load of household without a battery and owning a battery using for self-consumption, in market participation and by reducing load peaks.

The number of charging cycles per control method is determined by dividing the cumulative discharged power with the battery size. The results can be found in table 5.1. The number of charging cycles in self-consumption mode is lowest although the battery is used everyday, since the maximum capacity is rarely used on a single day. The number of charging cycles when acting on the market is highly dependent on the price threshold and is in this case still less than when the battery is used to reduce load peaks. In this latter case, considering the charging cycles it can be seen that the battery is used more intense than for self-consumption.

Control method	Number of charging cycles
Self-consumption	186
Peak reduction	254
Market participation	228

Table 5.1: Number of charging cycles per control method per year

As can be seen in figure 5.4c for the self-consumption control method, during winter months the electricity feed-in is zero and during summer months, the energy consumption can mostly be covered by the battery. The battery charges during PV generation and discharges during net demand. The demand peaks are not significantly reduced in winter, because the battery does not contain enough PV energy to cover the day. In summer however, the battery is fully charged during the day and thus cannot capture all PV generation. The feed-in peaks during summer are not significantly reduced. This can be seen in figure 5.4b where the feed-in peaks remain and there is no electricity consumption left. The peak reduction control method works on a comparable basis as in self-consumption method, although it charges more gradually. Therefore, the summer feed-in peaks are reduced more significant, however peaks are similar during winter. These winter demand peaks are not optimally captured because of the fixed peak threshold that is used to identify load peaks for the whole year. The household load is irrelevant for the battery when it is controlled based on the day-ahead market. The battery charges 2 kW during low pricing and discharges 2 kW during high pricing. The battery can create its own feed-in and consumption peaks which is in this case a high share of the household load profile.

Figure 5.5 shows the change in electricity grid consumption and feed-in of a household after installing a battery for maximising self-consumption. The annual electricity consumption of a household is assumed at 3,300 kWh and the PV installation of 3.3 kWp corresponds in the used model to an average annual production of 3,282 kWh. Because of mismatch in timing of demand and generation, without the use of the battery the grid feed-in is 2,080 kWh annually and the net grid demand is 2,098 kWh. By installation of the battery, the grid feed-in reduces to 1,181 kWh and thus the net grid demand is 1,202 kWh per year. Initially the self-consumption rate without the use of battery is 0.37. This is increased to 0.64 with the use of the battery.

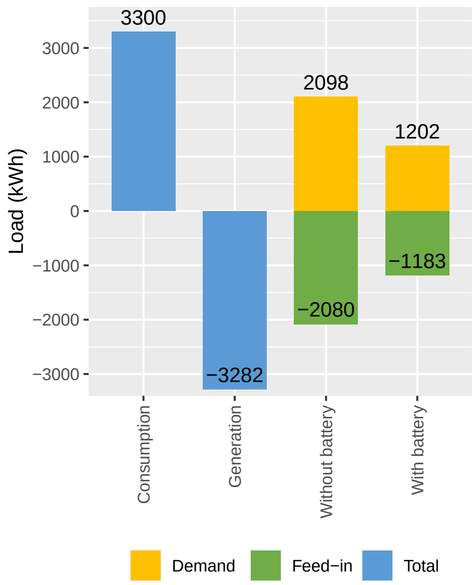


Figure 5.5: Annual electricity consumption and generation of a single average household. Cumulative net grid demand and feed-in with and without the use of a residential battery in self-consumption mode.

5.2 Household's profitability of residential batteries

The revenue of the battery is determined per control method. For the self-consumption and market participation control, the calculation of the revenue can be found in tables 5.2 and 5.3. For the control method of individual peak reduction, the feed-in reduction and thus its business case is similar to maximising self-consumption. The business case for the peak reduction method is not specifically evaluated in this report, because of similarity of self-consumption and no concrete indications exist of the price incentive of possible peak reduction stimulation. The revenue for consumers using a residential battery is based on the annual electricity consumption of 3,300 kWh, a PV installation of 3.3 kWp, no heat pump and no electric vehicle. Because of the fast changing electricity prices, the revenue is calculated based on both 2021 and 2022. For the business case of maximising self-consumption, net-metering is neglected and a feed-in tariff is assumed for the excess generated electricity.

Year	Electricity price (/kWh)	Feed-in tariff (/kWh)	Battery profit
2021	€ 0.24	€ 0.07	€ 152
2022	€ 0.67	€ 0.17	€ 449

Table 5.2: Revenue of a residential battery by increasing the self-consumption rate. For the years 2021 and 2022 the average electricity prices are taken, where the net-metering scheme is neglected. The costs of overall electricity consumption are given under base load. Without the use of a battery, 2,080 kWh of the 3,282 kWh generated is directly consumed.

Year	Charging costs	Discharging revenue	Battery profit
2021	€ 151	€ 258	€ 108
2022*	*indicated daily price spread of €0.2/kWh		€ 438

Table 5.3: Revenue of residential battery from market price arbitrage. The costs of residential electricity demand for 2021 day-ahead market prices and corresponding battery revenue. Because of rising market prices, an indication of battery revenue is given for 2022.

The average retail electricity price in 2021 was €0.24/kWh and so far this has increased to €0.67/kWh in 2022. The feed-in tariff for excess PV electricity on average has increased from €0.07 in 2021 to €0.17/kWh in 2022. The feed-in gap in combination with the changed grid consumption as seen in figure 5.5 leads to an annual battery revenue of €152 in 2021 and €448 in 2022.

When the battery charges and discharges based on 2021 market prices, charging the battery would cost €151 and discharging would gain €258 over one year. This leads to a (rounded) battery revenue of €108 in one year. In table 5.3, an indication of battery profit for 2022 market prices is included. The electricity prices are on the rise since the end of 2021, including an larger price variation during the day. The daily electricity price spread in 2022 is estimated on €200/MWh. A higher daily price spread leads to a higher profit per charging cycle of a battery. At the start of 2021, this daily price spread was in order of magnitude €40/MWh, and this increased to the order of magnitude of €300/MWh at the end of 2021. For a 6 kWh sized battery, a daily price spread of €200/MWh will yield €1.20 per charging cycle, resulting in an annual revenue of €438.

The pay-back time of the investment is determined to quantify the profitability of the residential battery. The payback time is influenced by a large number of variables that is uncertain. The variables investment price and feed-in gab or price spread are considered and included in table 5.4. Current values and their trends are discussed in chapter 4. Investment prices for a residential battery are between €6,000 and €3,000 for a 3kW/6kWh battery. Prices are expected to decrease because of scale-up and innovation in the coming years as described in the Data section 4.3. Recently, the feed-in gap or wholesale price spread is rapidly increasing. The revenue that a battery is able to capture is based on these price differences. It can be observed in table 5.4 that all 2022 prices indicate a pay-back period shorter than the battery lifetime of 15 years. On the contrary, the business case for a residential battery is negative for 2021 electricity prices in all covered cases. The trends of decreasing investment costs and higher price gaps show a positive impact on the payback time.

Investment price	Feed-in gap	Net battery revenue	Pay-back time
€ 6,000	€ 0.10	€ 90	67 year
	€ 0.20	€ 179	33.5 year
	€ 0.30	€ 269	22.4 year
	€ 0.40	€ 359	16.8 year
	€ 0.50	€ 448	13.4 year
	€ 0.60	€ 538	11.2 year
	€ 0.70	€ 628	9.6 year
€ 4,500	€ 0.10	€ 90	50.2 year
	€ 0.20	€ 179	25.1 year
	€ 0.30	€ 269	16.8 year
	€ 0.40	€ 359	12.6 year
	€ 0.50	€ 448	10.1 year
	€ 0.60	€ 538	8.4 year
	€ 0.70	€ 628	7.2 year
€ 3,000	€ 0.10	€ 90	33.5 year
	€ 0.20	€ 179	16.8 year
	€ 0.30	€ 269	11.2 year
	€ 0.40	€ 359	8.4 year
	€ 0.50	€ 448	6.7 year
	€ 0.60	€ 538	5.6 year
	€ 0.70	€ 628	4.8 year

(a) self-consumption

Investment price	Wholesale price spread	Net battery revenue	Pay-back time
€ 6,000	€ 0.04	€ 88	68.5 year
	€ 0.08	€ 175	34.3 year
	€ 0.16	€ 350	17.2 year
	€ 0.20	€ 438	13.7 year
	€ 0.30	€ 657	9.2 year
	€ 0.40	€ 876	6.9 year
	€ 0.50	€ 1,095	5.5 year
€ 4,500	€ 0.04	€ 88	51.4 year
	€ 0.08	€ 175	25.7 year
	€ 0.16	€ 350	12.9 year
	€ 0.20	€ 438	10.3 year
	€ 0.30	€ 657	6.9 year
	€ 0.40	€ 876	5.2 year
	€ 0.50	€ 1,095	4.2 year
€ 3,000	€ 0.04	€ 88	34.3 year
	€ 0.08	€ 175	17.2 year
	€ 0.16	€ 350	8.6 year
	€ 0.20	€ 438	6.9 year
	€ 0.30	€ 657	4.6 year
	€ 0.40	€ 876	3.5 year
	€ 0.50	€ 1,095	2.8 year

(b) market participation

Table 5.4: The influence of the investment price and the feed-in gap or wholesale price spread on the battery revenue and pay-back time. Yellow and blue respectively indicate the electricity price of 2021 and 2022. Green indicates when the pay-back time is shorter than the average battery lifetime of 15 years. For market-participation a single charging cycle per day is assumed.

5.3 Results for substation load

The overall battery load profile on the selected substation is added to its base load to find the resulting annual load in combination with batteries. Figure 5.6 shows all load profiles of 2030. The initial station load is indicated by blue, the battery load acting on the station in black, leading to a total load depicted as 'Result' in orange. Only for the 'High' battery scenario for the year 2030, the results are shown here because of the better visibility. All results can be found in appendix E in figures E.3, E.4 and E.5.

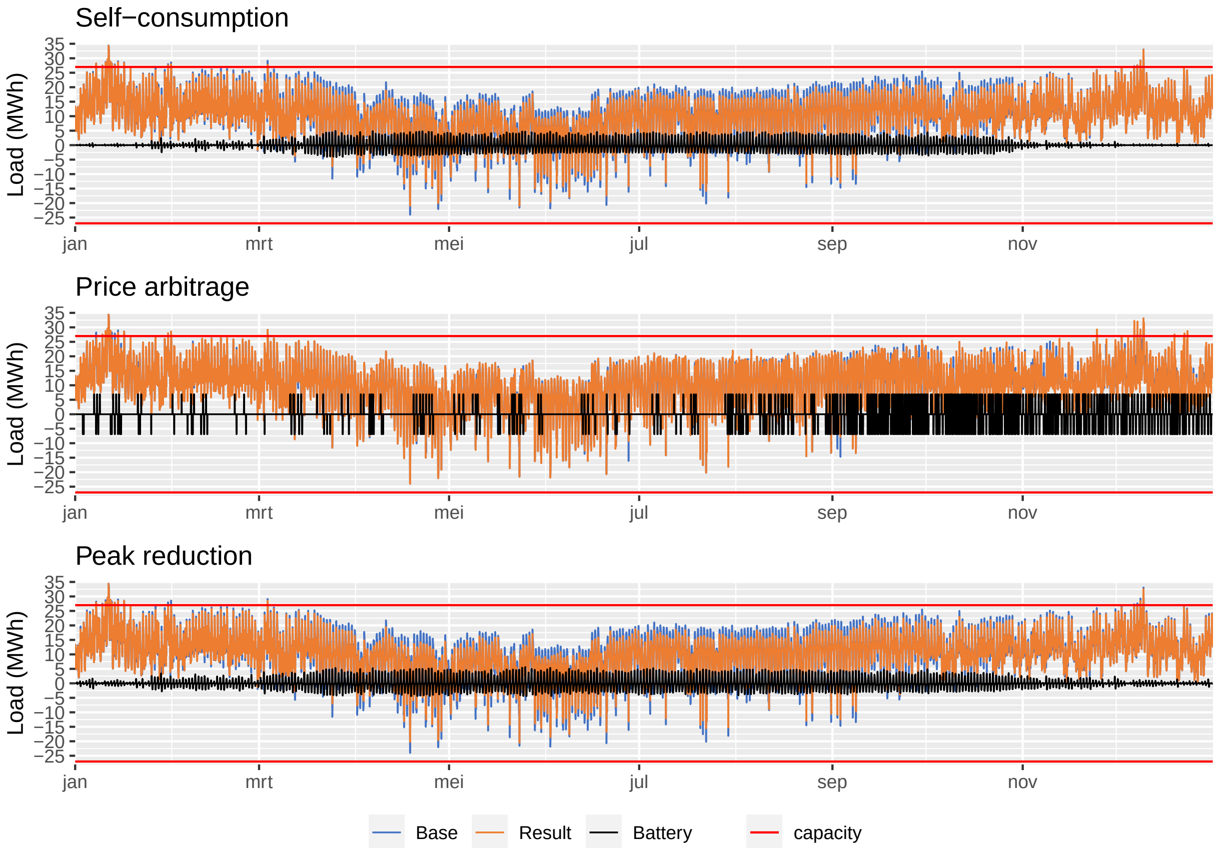
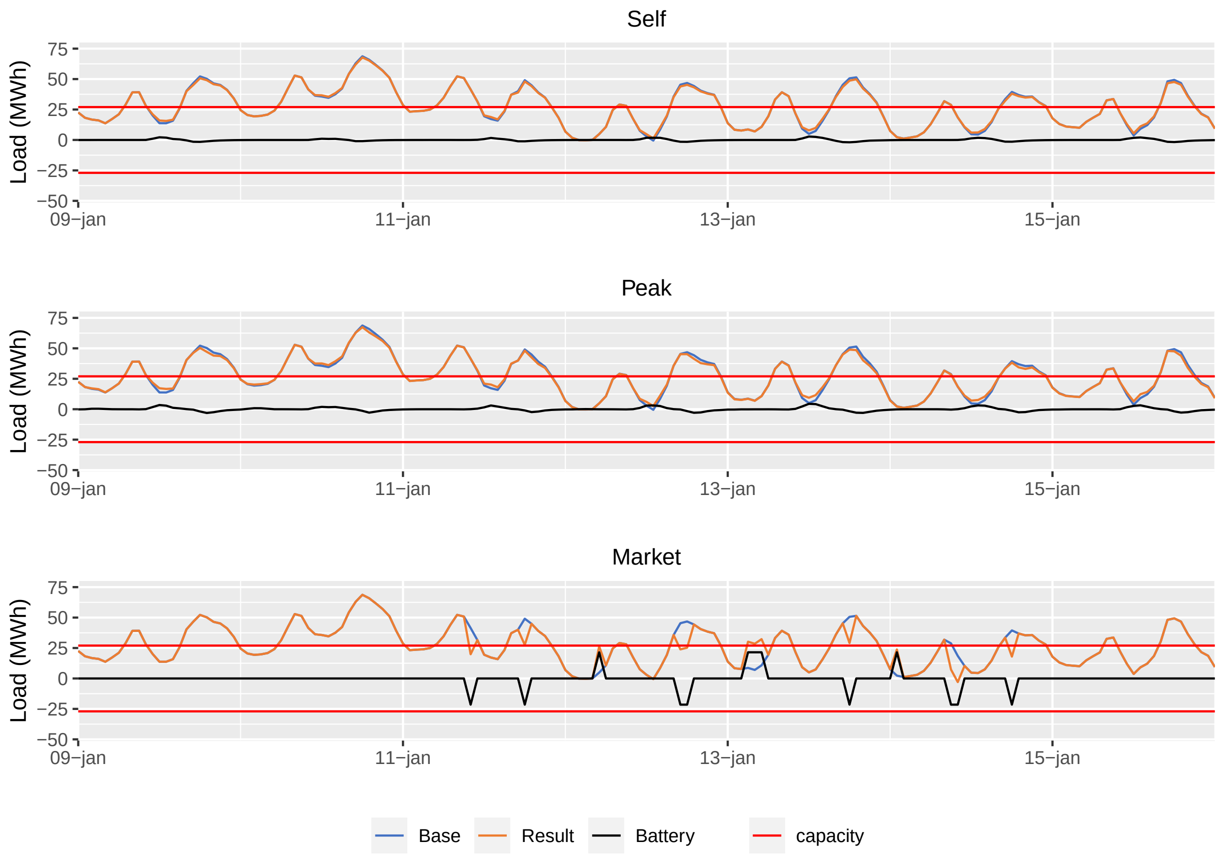


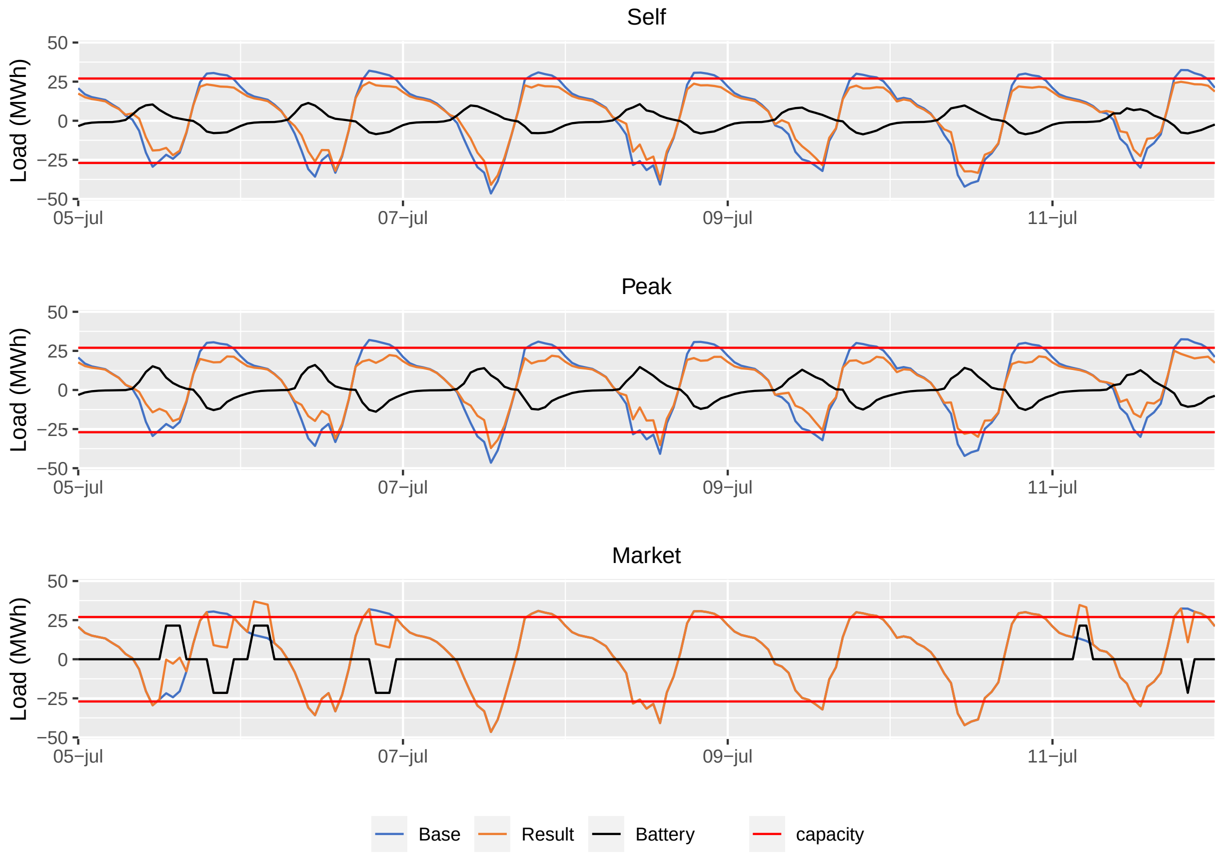
Figure 5.6: Resulting station load in high scenario for 2030. From top to bottom represent battery control self-consumption, market participation and peak reduction. Blue indicated the initial station load without residential batteries and orange depicts the resulting load when batteries are added. Black represents the battery load. The safety capacity of this station is equal to 27 MWh.

When load peaks on the substation are relieved by the use of batteries, a blue line is observed in the graphs of figure 5.6. When the resulting station load peaks coincide with the initial load peaks, the batteries did not relieve load. With batteries in market participation mode, the base load is not well visible since the resulting load is mostly higher than before batteries.

In figures 5.7a and 5.7b, results are zoomed in over one week in January and July, where the daily effect of the batteries are more visible. The load profiles of the batteries in self-consumption or in peak reduction control are comparable. Although, with peak reduction the battery shows higher charging power profiles during the day. Batteries are not fully charged before the end of the day because the battery only works at times of load peaks. Additionally, the battery can be used to seize consumption peaks by feeding electricity into the grid. Therefore, the battery has more capacity left at the beginning of the generation peak and can capture both peaks. With self-consumption, battery power is never used to feed in the grid or vice versa, grid electricity is not used to charge the battery. Therefor, only the excess generation and demand of the particular household is (partly) covered, and there is not compensated for the load peaks of other connections. Looking at the weekly load when batteries act on the day-ahead market, the grid can both be relieved during peak moments or the batteries can cause its own load peaks.



(a) Week in January



(b) Week in July

Figure 5.7: Weekly profile of station load in summer 2050 with different control methods in the high battery adaption scenario.

The base station loads are individually shown in figure 4.7. In year 2021, the station load does not exceed the safety capacity and thus there is no congestion on this station. From 2030 forward there is overload observed. In 2030, demand peaks cause overload in 43 hours during winter months. On the generation side, the load does not exceed the station capacity. In 2040 and 2050 the station load grows continuously. In 2040, the overload by demand peaks is increasing during winter. Also even during summer months, the station load exceeds the capacity limits multiple times.

The self-consumption mode results on the top of figure 5.6 show a significant decrease in demand load during the summer months, however the winter demand peaks are not seized. All resulting load profiles of all years and battery scenarios can be found in appendix E. As can be seen by the black line, the residential battery power in self-consumption control is significantly lower during winter months. During the winter there is little excess PV generation. The battery won't be fully charged during the day and thus cannot cover the winter consumption peaks. During the summer months net PV generation exceeds net consumption. Consumption can be covered with the load in the battery, however the PV generation can not be captured and the battery is fully charged before the end of the day. Therefore, the residential batteries are not able to seize station's generation load peaks.

When the batteries are controlled to reduce residential load peaks, most peaks on the substation are reduced. However, the maximum station load peaks are not fully captured by the batteries. The batteries are only controlled based on the load profile of the household and reduce their individual generation and consumption peaks. However, other type of connections caused their own load peaks on the station and those are not covered by the residential batteries. Those load peaks are not covered by the residential batteries because they are controlled based on the load profile of the individual house, instead of the station load profile.

When the battery is controlled based on the wholesale market prices, all batteries are controlled equal and thus charge and discharge on the same moments. The blue indicated base load is almost not observed, because of the overlapping resulting load. In this high battery scenario, the summed battery power can create its own peaks and has significant power over the resulting station load.

When the station load exceeds the safety capacity, there is overload and components of the substation could fail. The overload of the station is shown in graph 5.8 in hours and the total size of all overload hours can be found in the appendix E in figure E.6. However, the station's capacity is based on the maximum and minimum load the station must carry. Therefore, in case of overload the station must be reinforced. Only when congestion is managed in case of delayed reinforcement, the reduction of overload is beneficial. Congestion management will correspond to DSO's costs of around €200/MWh according to the ACM grid code. In the high battery adaption scenario, residential batteries are able to halve the overload hours in 2040 and 2050. When only considering the year 2030, notable for batteries in market participation is the reduction of overload hours in the low and medium adaption scenarios, whereas in the case of high adaption, the amount of overload increases. A high amount of batteries have their own impact to create station overload peaks. In the low scenario, the market control method even reduces overload more than peak reduction control.

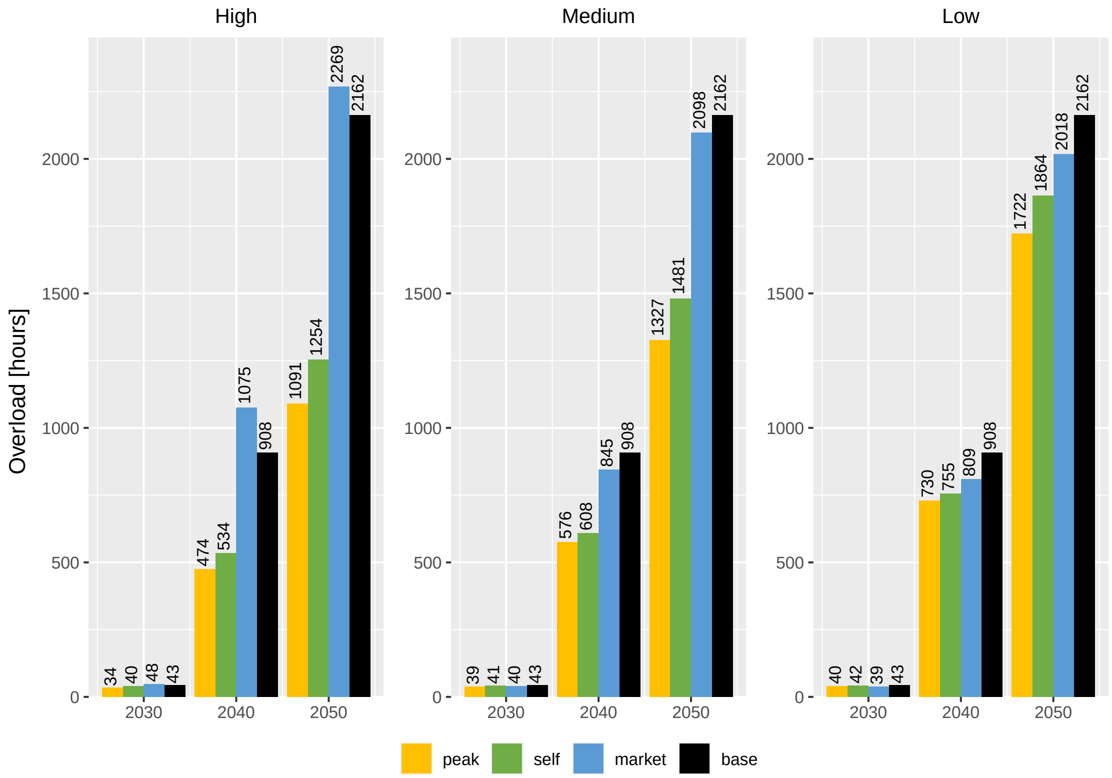


Figure 5.8: Change in annual overload hours of the selected station with the emergence of residential batteries in different controls and scenarios

The maximum and minimum station load per year for the high scenario are given in figure 5.9 and the values of all battery scenarios are given in table E.1. For this station the safety capacity is 27 MWh, and is equal for both the demand and generation side. The load peak is maximum on 11 January at 18:00 and the minimal load occurred on 18 April at 12:00. The maximum and minimum values increase over the years and for the initial load in 2050, the generation peak is at 80 MW, which will thus be the station's capacity. With the batteries, the maximum value won't decrease significant, however this minimum values can be reduced to 68 MW in 2050. This value is similar to the maximum station load peak.

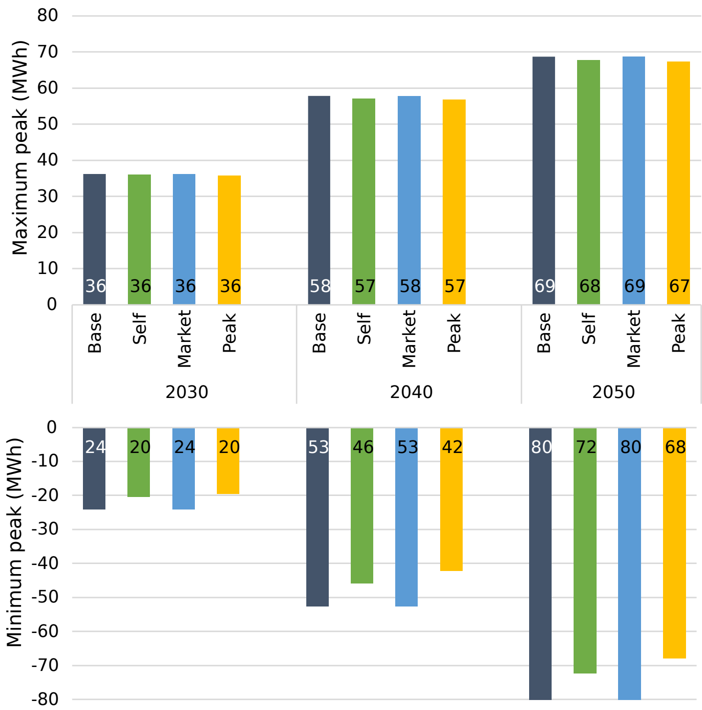


Figure 5.9: Change in the annual maximum and minimum station load peak in high scenario.

In the previous analysis, the size of load peaks on the station is considered without identifying the causes and load contributors. The contribution of different technologies and connections to the load on the selected station at peak hours is shown in figure 5.10 of the year 2030. Regarding the maximum load peak, heat pumps are the main contributor to the station load. Almost 19 MWh is caused by the increase of this technology. Decentralised generation, PV and wind, are both equal to zero at the moment. During the minimum load peak, the growth in decentralised generation leads to a large decrease of station load. Both wind and PV (of large-scale consumers, commercial, and residential) affect the station load with almost -23 MWh.

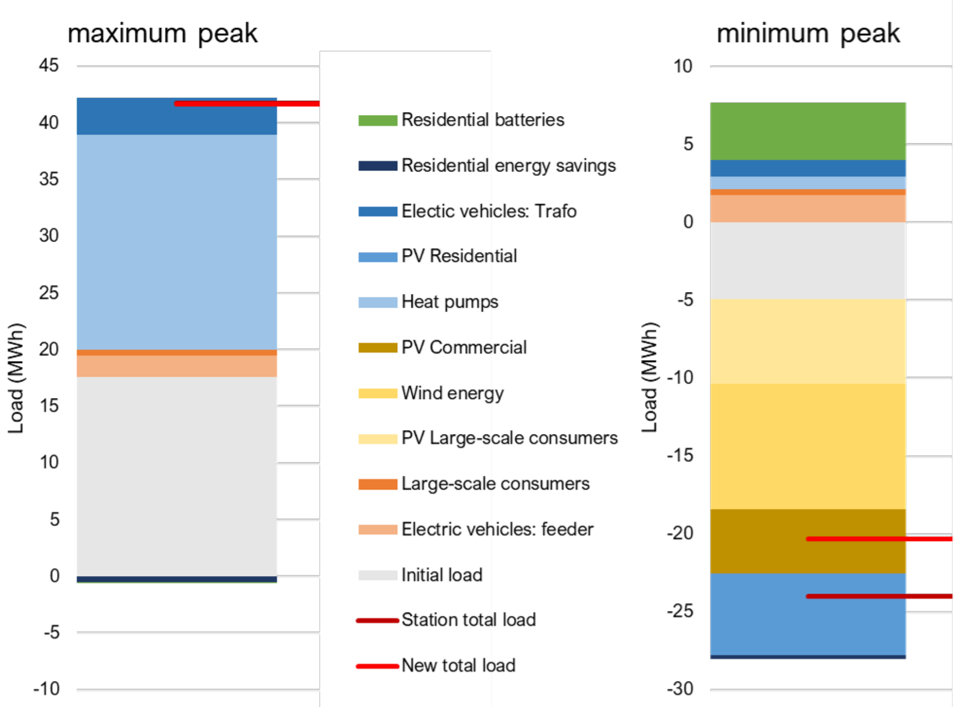


Figure 5.10: Contributors of load on the selected station during the maximum and minimum peak hour in 2030. The summed station load before emergence of residential batteries is depicted as 'station total load' and with residential batteries the station load is indicated with 'new total load'. The residential battery contribution in these figures is based on the maximising self-consumption control method.

Electricity load from residential connections include the expected residential energy savings and residential PV, which both act a negative station load, and transformer connected electric vehicles and heat pumps, which act as a positive station load. The residential battery load will operate in both directions. In figure 5.10, the residential battery load is shown when operating in self-consumption mode. During the maximum station load peak, they only relieve less than -0.1 MWh load on the station. Nearly 25% of decentralised generation during minimum peak hour is caused by residential PV. Residential batteries can significantly relieve the station load with 3.7 MWh. It can be observed that during the maximum peak the residential batteries are barely used to relieve the station peak, whereas during the minimum peak the residential batteries do significantly relieve station load.

5.4 Generalisation impact residential load on all substations

The impact of residential load the total station load will be different for the selected substation and the remaining stations of Stedin. In this section the selected substation will be brought in perspective of all substations. In figure 5.11, the selected substation is related to the rest of Stedin's substations based on proportion of residential connections and their share of rooftop PV.

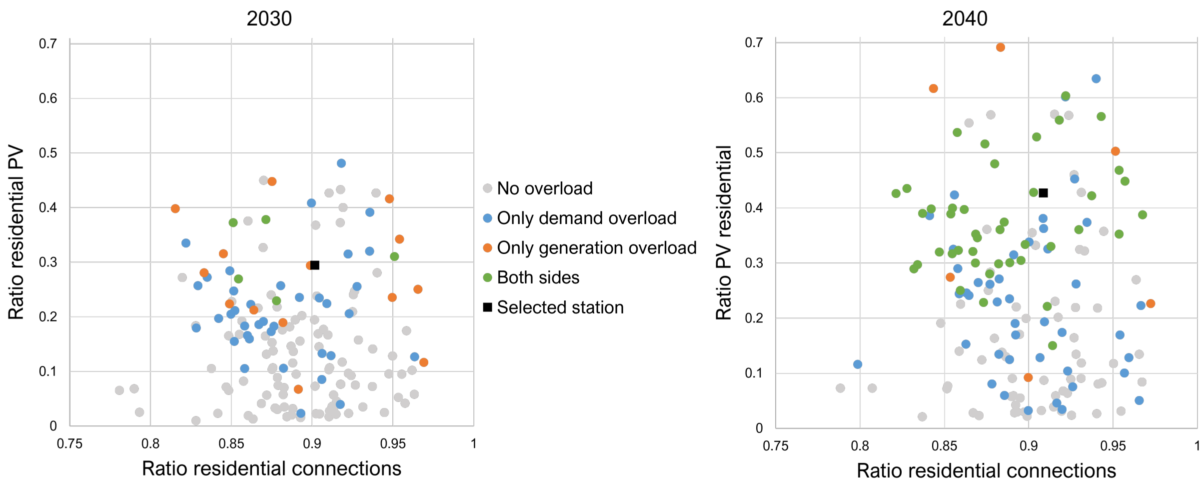


Figure 5.11: The ratio of residential connection versus rooftop PV for Stedin's stations, indicated which are expected to be overloaded by either excess demand or generation load, or both. The selected substation is marked in black.

Stedin manages 177 substations of which 157 have more than 500 residential connections. In the scenario it is calculated that without any changes to the grid in 2030, 57 of those 157 substations are expected to be overloaded by either excess demand or generation load. Both graphs of figure 5.11 show that most stations without overload, marked with grey, have a low share of rooftop PV. The right graph indicates the expected overload in 2040. This graph makes clear that most stations with a high share of rooftop PV, are expected to overload by excess generation, indicated with orange and green. The selected substation has a significant share of residential rooftop PV compared to the other stations.

Residential rooftop PV is an important driver for residential batteries. The stations with a high rate of rooftop PV, located at the top right of the graphs, have the highest potential for residential batteries. Table 5.5 shows the values of the connections of the selected substation relative to the mean values of all Stedin's substations. The selected station clearly shows a larger rate of residential connections and the share of residential rooftop PV is almost twice as large as average.

	2030	2040
Number of stations	177	
Number of stations with #residential > 500	157	
Mean station capacity	29.9	
Stations overloaded		
Only demand	38	43
Only generation	14	6
Both sides	5	43
Total	57	92
Mean per station		
# connections	11,822	12,725
# residential connections	13,280	14,183
# residential PV	1,799	2,856
Ratio residential connections	0.81	0.82
Ratio residential PV	0.16	0.24
Selected station		
Station capacity	27	
# connections	20,500	22,100
# residential connections	18,482	20,082
# residential PV	5,445	8,577
Ratio residential connections	0.90	0.91
Ratio residential PV	0.29	0.43

Table 5.5: Information of Stedin's substations, their overload and the selected substation specific.

6 Discussion

In this chapter the results of Chapter 5 are analysed and the technical results are combined with their corresponding regulations. First, in section 6.1, the results of this research will be interpreted by means of answering the previously stated research subquestions. These questions are specified by consumer's, DSO's, and policy-makers' perspective. The main research question will be covered in the next chapter. In section 6.2, the research will be tested on its representation of reality and assumptions will be discussed. Finally, in section 6.3, the research will be reflected upon. Here, future work will be suggested based on limitations, the relevance of this study will be discussed, and my personal reflection will be given.

6.1 Interpretation of the results: answering research subquestions

1. How is the load on a medium voltage substation expected to change until 2050?

The load on a medium voltage substation is currently determined by required transportation of electricity, which is caused by local deviations in generation and demand. The energy transition will affect both generation and demand load sizes and profiles, as well as their location. First, electricity generation will shift from centralised fossil fuel-based to decentralised renewable energy sources. On the one hand, this will change the generation profile daily and yearly due to fluctuating generation peaks and seasonal differences. On the other hand, decentralisation leads to more electricity feeding on lower grid levels. This will cause increasing load pressure on the lower voltage grid. Second, the demand for electricity changes due to electrification of the energy sector. Heating sources will shift from natural gas to heat pumps, energy sources for mobility will shift from fossil fuel-based to electric, and industry will electrify their processes. Heat pumps will mainly increase electricity demand during colder months. In case the station load exceeds its safety capacity, the grid is not considered sufficient for new grid connections and congestion is proclaimed. In the Netherlands, in more and more stations the safety capacity limit is reached and areas are marked as congested. It is expected that grid congestion will be a growing problem in the future.

DSOs must predict which substation will be overloaded to plan their grid reinforcements ahead. In order to do this, they map the expected changes of different technologies in the energy systems. The corresponding load profiles of the different electrical technologies will add up to estimate the future station load. If a substation is expected to be overloaded, the station will be reinforced. This process of reinforcement takes up many years, land area, and has high costs.

Consumer's perspective

2. What will drive the emergence of residential batteries and their usage?

Recent price developments will influence the residential battery market. Electricity prices have increased rapidly since the end of 2021, and with them the daily price spread. At the same time, battery and rooftop PV costs are decreasing. Due to electrification of heating and mobility, the demand for electricity increases. Residential batteries are repeatedly mentioned in discussions about grid capacity scarcity as a potential solution. All these current trends positively influence residential battery development.

The deployment of residential batteries is difficult to govern, however how the batteries are controlled is easier to regulate. The main usage of residential batteries will be determined by the residential electricity pricing regulations. Possible regulations are their influence on battery usage are explained. Currently, the regulation of net-metering suppresses the interests for residential batteries. There is no stimulation to self-consume PV generated electricity or shift consumption over the day. Net-metering will phase out starting in the year 2025. A feed-in tariff will remain for excess generated electricity. A price gap between demand and feed-in tariff will stimulate electricity self-consumption, which can be maximised by means of a residential battery. Dynamic retail electricity prices are based on wholesale electricity prices and would enable price arbitrage for households: profit from price differences during the day. Peak tariff structures or a connection bandwidth tariff, which are not in place yet, would stimulate an efficient grid usage. Residential batteries can shift load away from peak moments to reduce load peaks. So positive drivers for residential batteries include an electricity feed-in gap and renewed retail tariff structures.

3. What is the expected development of residential batteries in the Netherlands?

The recent trends of decreasing battery costs, increasing daily electricity price spread, and net-metering phase-out indicate growing drivers for residential batteries. Additionally, the political and societal discussions around the use of residential batteries may positively influence its growth. These findings suggest that the uptake of residential batteries is likely to increase in the Netherlands.

The development of residential batteries depends on multiple factors as mentioned in the previous research question. Because of the uncertain policy landscape of residential batteries, it is not yet certain which control strategy will be dominant in the Netherlands. Likewise, the development of residential battery capacity in the future in unsure. Therefore, in this research three emergence scenarios for the Netherlands are designed. These scenarios are based on previous research, the projections of number of rooftop PV, and the common innovation growth curve. The resulting development scenarios can be found in figure 4.6.

4. What is the load profile and corresponding profitability of a residential battery per control method?

In this research, residential batteries are charged based on three different control methods: maximising self-consumption, own load peak reduction, and using price arbitrage on day-ahead market prices. The results of the battery output can be found in section 5.1. When the battery is used to maximise self-consumption it will be charged by excess PV generation until fully charged. Battery power will be used to cover electricity demand. During winter, because of the small amount of PV generation, the battery can only cover a certain part of the daily demand. During summer, when there is a higher net generation than net consumption, the battery is fully charged before the end of the day. As a result, generation peaks can remain. The self-consumption rate can be almost doubled by using a battery to maximise self-consumption. However, as long as the net-metering scheme is fully in place, residential batteries are not attractive for self-consumption usage. In peak reduction battery mode, the excess generation is used more gradually to charge the battery, leading to a significant decrease in generation load peaks. However, when only considering load peak reduction, the self-consumption rate is undervalued. When the batteries are used for price arbitrage on market prices, the battery starts charging when the prices exceed a certain threshold and discharges when prices are low. The battery profile is unrelated to the residential electricity consumption load profile and is mostly used at the end of the year, when the market price spread is higher. The battery can create its own supply and demand peaks.

The profitability and payback time for both maximising self-consumption and price arbitrage is determined, which can be found in section 5.2. Load peak reduction is not included here, because there are no specified indications of the value of possible renewed tariff structures, which would stimulate this type of battery control. For the profitability of increased self-consumption, the net-metering policy is neglected and a feed-in gap is considered. Results show that residential batteries will become more economically attractive as the daily electricity price spread grows. In this context, daily electricity price spread includes both the net-metering abolition resulting in a feed-in gap, and the daily variation of market prices. With current electricity prices, the payback time of residential batteries is shorter than its technical lifetime. However, prices change and fluctuate heavily, and battery investment costs decrease, which both affect the calculated payback time. Hence, while this work does not claim to give a realistic business case for residential batteries, the results particularly indicate that the price developments positively influence their emergence.

DSO's perspective

5. Will residential batteries relieve load peaks of the selected distribution station?

For this research one medium voltage substation is selected on which the effect of residential battery load profiles is determined. This substation will be overloaded on the demand side starting in 2024, due to the increase of winter demand load. This is mainly caused by increasing demand of heat pumps. After 2030, extra generation will cause overload on its supply side.

For all three emergence scenarios and control methods, overload of the substation's safety capacity is not prevented by residential batteries. However, for the medium and low emergence scenarios, both the number and size of overload hours are reduced, which can be seen in figure 5.8. This reduction is largest when the batteries are used to reduce individual load peaks, and smallest when used for price arbitrage. In case of high emergence, market price arbitrage can cause more and higher load peaks on the selected substation.

The maximum peak of the selected substation is not affected by the emergence of residential batteries. The batteries mainly affect generation load during summer. The peak reduction mode, as well as the self-consumption mode, do relieve the minimum station load peak as can be seen in figure 5.9. Specifically for this selected substation this leads to unification of required demand and generation capacity of the station. Additionally, the batteries provide a reduction of base grid usage. However, when grid capacity is plentiful, the DSO does not benefit from these load reductions.

At first, the selected substation is overloaded on the demand side to a higher extent than generation. However, in 2050, load peaks on the generation side are expected to transcend maximum load demand peaks and thus generation overload will become more dominant. Residential batteries in both self-consumption and peak reduction mode mainly act during summer, when generation is high. Because of this, the generation load peaks are further relieved. Some of Stedin's substations have a higher share of residential PV than this selected substation has, and are dominantly overloaded on generation side. These substations can be found at the top of figure 5.11. On these substations, residential batteries might play a bigger role in overload reduction.

Policy-makers' perspective

6. What regulations can improve the integration of residential batteries in the electricity network?

Currently, there is no steering in residential battery usage. The results of this research indicate that each control method affects the station load differently. As long as there are not too many batteries, there are no adverse effects on the selected substation's load for all chosen control methods. The number and size of overload hours declines for the medium and low emergence scenarios. The peak reduction and maximising self-consumption battery control relieves peaks further than the case of price arbitrage. Therefore, motivations to increase self-consumption or reduce power peaks for households would reduce pressure on the grid. Replacing the net-metering scheme with a feed-in gap would stimulate self-consumption. Peak reduction can be stimulated by bandwidth or peak tariff structures. However, it should be noted that suppressing full battery charging or discharging by capacity bandwidth pricing would be unfavourable in case residential batteries could be aggregated for congestion management.

Without the obligation for energy suppliers to apply net-metering to rooftop PV owners, electricity market prices would be translated to both corresponding retail and feed-in tariffs. As a result, electricity market prices and retail prices would correlate with each other. In this case, a comparable revenue can be expected, provided that retail pricing is not regulated. This means that regulating the feed-in tariff of consumers will affect the usage of residential batteries, since it uncouples the wholesale prices and retail prices.

The load profile of batteries shows a lower usage during winter months for both self-consumption and peak reduction methods. At the same time, during these months the selected substation has a higher congestion problem by demand overload. Therefore, the question arises whether residential batteries can be controlled particularly in favour of the DSO at times of low usage by households. Given the emergence of residential batteries, there is a potential for the DSOs to use them in favour of their congestion problems. The unused capacity of residential batteries could act simultaneously in favour of congestion relief on critical peak moments. Hence, this would make it interesting for the DSO to acquire some degree of power over residential batteries.

6.2 Validation of the results

This section will discuss to what extend the results of this research represent reality. Also, their uncertainties will be pointed out. First, the model for station profiles is discussed, then important assumptions are covered including battery parameters, and at last the control methods of the batteries is discussed.

The model that is used to calculate load on the substation in the future is SETIAM, which is created by Stedin internally. The load profile of 2021, the first year, is measured data. Therefore, these load profiles can be considered to be valid. The changes on the load profiles are based on scenarios of different electrical technologies. National scenarios are created in collaboration of all grid operators. The scenarios are then projected on Stedin area. This scenario won't 100% match future reality, as scenarios are estimations. However, the scenarios are based on governmental steering, recent developments and past market trends. Therefore, the trends of future technology developments are properly captured. Next, future technologies like rooftop PV, heat pumps and PV parks are distributed over Stedin area. This distribution is based on connection requests, municipality plans, neighbourhood or house specific data, like building year. Based on the scenario, low voltage connections like houses get assigned certain technologies, for example rooftop PV or a heat pump. However, this method of technology distribution does not claim to actually predict the future for every specific connection. This uncertainty is justified because the load profiles are summed over a larger area for higher voltage components in the model. This means that all changes to individual connections are added up and therefore, the specific location does not influence the overall station load. That is why the effects on medium voltage substations better represent the reality than lower voltage components.

In this research many assumptions have been made. General assumptions have been discussed in chapter 4. In this research only single-application of the battery is used. In reality, when regulations for PV stimulation or retail pricing changes, electricity demand is likely to change a little as well by demand response, smart usage of a heat pump, or smart charging of an electric vehicle. However, in this research this is not taken into account in order to be able to compare the different battery strategies. Regarding the business case of residential batteries, only an average value of annual electricity demand and PV size is considered. Additionally, no heat pump or electric vehicle is included in the calculations. These values are chosen for comparison of the different control methods. Compared to the studied chosen values, the profitability of a residential battery will change with a different electricity demand. Besides, the profitability of the batteries highly depends on investment price and feed-in gap or wholesale daily price spread. The uncertainties of these parameters is captured by including their influence on the payback time. Because of the uncertainties and chosen parameters, this study does not claim to give a realistic business case, though it indicates that the price developments positively influences their profitability. Furthermore, a fixed battery capacity and power size are chosen in this study. However, in reality there are many different capacity and power values of residential batteries possible. Because the emergence is still low and the control method is yet uncertain, no indications of the actual development of sizes are present. In this study, a fixed value of batteries is chosen to represent the average battery size. Another battery value will change the profitability per control strategy differently. However, this is neglected in this study and would be interesting for future research.

The three control schemes which are used to determine the battery profiles will be discussed one by one. All three control schemes are based on a rule-based approach. First, for a battery in self-consumption mode, a rule-based approach stays close to the truth. To be able to maximise self-consumption and minimise grid usage the battery must be charged or discharged directly with excess demand or generation. By fully charging the battery when there is excess generation, gradual grid capacity usage is not taken into account. In contrast, battery usage for peak reduction is a bit more complicated than that. Smart charging could apply load peak shaving to keep load within a certain bandwidth. However, in this study a rule-based approach in chosen to make sure simulation time is within acceptable limits. Modelling the optimisation of individual peak shaving for every connection would be time consuming. Therefore, a threshold based on a percentage of the average daily load is chosen to identify the load peaks. A daily altering threshold makes sure the battery still has capacity left to shave the load peaks. So it will discharge before the actual demand peak in winter or charge before the actual generation peak in summer. Although this is not claimed to be the most ideal method for individual load peak shaving, it does show the potential of batteries for a more efficient way to use the capacity of the grid. Because this method is not optimal, the business case of individual households by peak reduction is not included in this research. In case of a perfect forecast of both electricity consumption and generation, the battery can be optimised to both maximise self-consumption and bandwidth limitations. Finally, in this research the price arbitrage battery control is not optimised and thus does not perfectly charge or discharge at peak moments. It is only charged when the price exceeds a certain threshold. Therefore, smart control is not taken into account: the battery can be full or empty before the maximum price peak and the charging timing is not perfect. Especially because the prices are highly variable during the year, the price threshold is not optimal for the whole year. The electricity market prices drastically increase towards the end of the year leading to an increasing usage of the battery. Despite these shortcomings, the battery profiles for this control method depict the consequences of all batteries acting simultaneously and their power over this station load.

6.3 Research reflection

In this section, the whole research and process will be reflected upon. First, suggestions for future work will be discussed based on some limitations of this work. Then the relevance of this work is given for both academic and social sectors. To conclude the reflection, a brief personal view on this study and my process will be given.

6.3.1 Limitations and future work

There are numerous limitations to this research, some of which are highlighted in this section as recommendations for future work. First, while this research focuses on single application usage, the economic value of residential batteries is assumed to be underestimated. Using the battery for various applications at once is neglected for this research to be able to compare the various use cases. Additionally, price arbitrage on other markets than day-ahead is not analysed, and the effect of various retail tariff schemes or feed-in regulations on battery usage is not taken into account. Furthermore, the rule-based approach to determine the battery outputs does not lead to the optimal control for both price arbitrage and peak reduction. Future research should include more battery control methods to better describe the economic feasibility of batteries. Also, in this research a fixed battery size of 6 kWh with 2 kW continuous power capacity is chosen in this research for all control methods in all houses. The size of the battery influences the revenue per control. For market control, the revenue scales linearly with battery size, whereas the self-consumption rate is less affected by battery size.

Second, changing feed-in regulations and tariff schemes can influence electricity consumption. When a battery is used for maximising self-consumption control, it shifts electricity from excess generation to excess consumption. This is theoretically equal to perfect demand response. If a household would be able to shift their electricity consumption to moments of PV generation, a battery would be redundant. In case of changing retail pricing, especially feed-in and net-metering, changing consumption behaviour would be beneficial. In this research, demand response or smart home appliances are neglected. Future work could analyse demand elasticity in case of increasing electricity prices and changing tariff schemes. Especially with the currently fast changing electricity retail prices, demand elasticity can be studied in more detail.

Third, this research does not cover the influence the DSO can have on residential batteries. The DSO influence has two aspects. The first includes the maximum effect, which occurs when batteries are optimally used to relieve substation load peaks. It would be interesting to quantify this effect on the distribution grid. An option could be to analyse aggregated batteries that 'work for the DSO' and react when the station has load peaks or to the use of the batteries during winter months when they are used less by the consumers themselves for self-consumption. The second aspect includes the question of how the DSO would access the batteries. This requires to identify methods that analyse how to make use of the residential batteries in case of lower individual usage. Methods to activate and steer batteries, as well as multiple regulations for DSO access or price motivations can be examined.

6.3.2 Academic and societal relevance

Addition to academic knowledge

This study focused on specifically the Dutch retail market and its regulations. Since the Dutch regulation landscape is changing and its future is uncertain, this study acts as a new starting point for a future study on residential batteries in the Netherlands. With the coming debate for changing the electricity law to abolish net-metering, a lot will change in the coming years.

This study combines the profitability for consumers and their effect on the distribution grid congestion. When considering the consumer's perspective first, the effect is determined for a passive DSO. This study can help them to prepare for the future of residential batteries. Additionally, this study shows that in case of high emergence of residential batteries, there is a potential the DSO might be able to bend towards their benefit.

Societal impact

In the Dutch government, the question arises whether residential batteries would help solving grid congestion problems. A few political parties already have pleaded for residential battery stimulation. Additionally, phase out of net-metering will cause a feed-in gap which is a stimulation for battery usage. In short, residential batteries are on the political agenda and thus their impact on the distribution grid must be identified. From this study it is clear that the usage of the battery impacts the station load peaks and therefore, steering battery control is important. Regulations concerning retail market prices and tariff structures will influence the drivers and profitability of residential batteries. In short, this study acts as a tool to emphasise the importance of steering the usage of residential batteries and not merely stimulate their emergence.

For DSOs this study indicates how and why residential batteries will emerge in the Netherlands and what their load impact on the distribution grid will be. In case the DSO must perform congestion management, this study identifies the unused potential of batteries in favour of the grid especially during winter peaks. In case the DSO wants to take advantage, it must play an active role in load peak reduction, since the residential batteries do not automatically relieve critical station load peaks to their full potential.

6.3.3 Personal reflection

What would I have done differently if I could start over? First of all, I would have included more pricing schemes to test the effect they have on residential battery usage and thus on the distribution grid. Then, I would have computed the individual battery profiles in a different, more optimal way. This would give more insight in the household situation within those pricing schemes. Secondly, I would want to try to give more insights of the effect on the whole distribution network instead of on one case substation. The effect could be seen in a broader perspective and for different situations of the substation.

This final step in obtaining my master degree has not been an easy task for me. Yet, looking back I have learned a lot. Before I started this project, I wrote down a few things I was hoping to learn. I recently found this list again and I am happy to see that almost all of them can be crossed off. 'Learn what I like and what I don't' and 'learn about my own skills and get confident about them' were the first and probably the most important two lessons of a master thesis. Get to know your weaknesses and strengths can be confronting, though very valuable. 'Understand the electricity distribution system' and 'understand why or how congestion is caused' are the next two items about subjects I initially knew nothing about. This project has helped me to see the complexity electricity system, and even though I realise there is still a lot to learn I appreciate the insights Stedin gave me in the reality. Next to that, this socio-technical study taught me that technical analytics is more of interest to me than societal literature analytics. After my applied physics bachelor, I made a shift to a broader, more social study of sustainable energy technology, because I missed the application of technologies in society. That is also one of the reasons I wanted to to my master thesis at a company, to apply knowledge in society and relate them to regulations. However, after this research, I start to appreciate technical analytics a little bit more again.

7 Conclusions

This report presents an analysis of the development of residential batteries from a consumer's perspective and their effect on the electricity distribution grid. The main research question was posed to find the effect of different residential battery use cases on the load peak on medium voltage substations up to 2050. To do so, the social context of residential batteries was studied. It was found that recent trends of decreasing battery costs, growing electricity price spread, and net-metering phase-out lead to growing drivers for residential batteries. Three battery control methods were considered: maximising self-consumption, market price arbitrage, and load peak reduction and their corresponding load profile, which was determined with a rule-based approach. Additionally, the emergence of residential batteries in the Netherlands was projected by three development scenarios. Then, the annual load on the medium voltage substation was calculated by power profile summation. A peak analysis was performed to evaluate the effect of the residential batteries on the load peak.

7.1 Main research question

The research question of this study is formulated as follows: *What is the effect of different residential battery use cases on the load peaks on medium voltage substations in the future?*

From the consumer's perspective, the emergence of residential batteries is uncertain and difficult to govern, however, the battery control is easier to regulate. The dominant battery control method is determined by retail electricity pricing regulations. A feed-in price gap will stimulate maximising self-consumption, and a more efficient grid usage and load peak reduction are stimulated by different tariff structures or a bandwidth connection tariff. Dynamic hourly electricity prices would enable residential batteries to perform price arbitrage: discharge the battery during peak prices and charge when prices are low. The results show that residential batteries will become economically attractive as a result of abolition of net-metering, the growing daily electricity price spread and feed-in gap, and decreasing battery cost. These developments positively influence their emergence. There is uncertainty regarding tariff schemes and feed-in tariff, and these retail price regulations will strongly influence which control method will be dominant.

From DSO's perspective, how the residential batteries affect the load peaks on the selected substation is different per battery control method and the extent of their development in the Netherlands. The results show that for a medium and low emergence of residential batteries the size and numbers of overload hours is reduced for all three control methods. The effect on the overload is largest when the batteries are used for individual peak reduction. However, in all cases overload is not prevented on the selected substation and thus grid reinforcement is still inevitable. In fact, in case of high emergence the batteries can even cause an increase in load peaks when simultaneously used for price arbitrage.

The selected substation first overloads at the demand side, mainly due to the growth of heat pumps. After 2040, the minimum generation load peak exceeds the maximum demand load peak on this station. Towards 2050, the residential batteries used for self-consumption or peak reduction are able to unify the maximum and minimum peak leading to a smaller required capacity of reinforcement for this substation. Batteries used for self-consumption or peak reduction are mainly used during summer months because the battery is mainly charged by rooftop PV generation. Therefore, the generation peaks on the selected substation are significantly more reduced than the demand winter peaks. In case a medium voltage substation mainly overloads on the generation side, there might be a higher relief of load peaks by residential batteries, and even a possible reinforcement prevention. Especially when these generation overloaded substations have a high share of residential rooftop PV which has a high potential for residential battery emergence, load peak relief has more potential value.

7.2 Recommendations

The peak reduction and maximising self-consumption battery control relieves station load peaks further than the case of price arbitrage. Therefore, incentives to increase self-consumption or reduce power peaks for households would reduce pressure on the grid. Self-consumption can be stimulated by replacing the net-metering scheme with a feed-in gap, peak reduction can be stimulated by a connection bandwidth tariff or peak tariff structures. However, it should be noted that suppressing full battery charging or discharging by capacity bandwidth pricing would be unfavourable in case residential batteries could be aggregated for congestion management on critical peak moments. Because of the lower usage of residential batteries during winter, the DSO might be able to use the excess battery capacity in their favour. The impact the DSO can have on battery control, as well as battery aggregation are not included in this study and thus more research is required on this topic.

Because of the Dutch ambitions for renewable energy sources and specifically rooftop PV, the stimulation for more efficient grid usage and stimulation of residential batteries should not hinder rooftop PV installation. Abolition of net-metering or renewed tariff structures can have a positive influence on the development of residential batteries, whereas reduce the advantages of rooftop PV installation. An example of this effect can be seen in Germany. After an increasing feed-in gap, the emergence of residential batteries increased significantly. However, there was not enough additional stimulation for rooftop PV which resulted in a decrease of new PV installations in Germany. The Dutch government should be cautious for this effect and prevent this negative residential PV development. Moreover, electricity retail regulation will steer the usage of residential batteries. By regulating the feed-in tariff of consumers the wholesale market prices and retail prices will be decoupled: When the electricity retail prices are based on the wholesale electricity prices by retail companies, the feed-in gap will correspond to the wholesale electricity price spread. This will cause the profitability of residential batteries by either self-consumption or price arbitrage to be comparable. Regulating the retail prices or feed-in tariff will steer the usage of residential batteries to one of these two control methods.

References

ACM. (2017, 5). *Incentive regulation of the gas and electricity networks in the netherlands.*

Actieteam Netcapaciteit. (2022, 1). *Samen sneller het net op.* Online. Retrieved from https://www.netbeheernederland.nl/_upload/Files/Samen_sneller_het_net_op_-_Actieteam_Netcapaciteit_28_01_2022_240.pdf

Afman, M. (2021, 5). *Opslag bij kleinverbruikers met zon-pv* (Tech. Rep.). Liander.

Alipour, M., Irannezhad, E., Stewart, R. A., & Sahin, O. (2022, May). Exploring residential solar PV and battery energy storage adoption motivations and barriers in a mature PV market. *Renew. Energy*, *190*, 684–698.

Alnaser, S. W., Althaher, S. Z., Long, C., Zhou, Y., Wu, J., & Hamdan, R. (2021, December). Transition towards solar photovoltaic Self-Consumption policies with batteries: From the perspective of distribution networks. *Appl. Energy*, *304*(117859), 117859.

Bagalini, V., Zhao, B. Y., Wang, R. Z., & Desideri, U. (2019, October). Solar PV-battery-electric grid-based energy system for residential applications: System configuration and viability. *Research (Wash D C)*, *2019*, 3838603.

Barzegkar-Ntovom, G. A., Chatzigeorgiou, N. G., Nousdilis, A. I., Vomva, S. A., Kryonidis, G. C., Kontis, E. O., ... Papagiannis, G. K. (2020, June). Assessing the viability of battery energy storage systems coupled with photovoltaics under a pure self-consumption scheme. *Renew. Energy*, *152*, 1302–1309.

Battke, B., & Schmidt, T. S. (2015, October). Cost-efficient demand-pull policies for multi-purpose technologies – the case of stationary electricity storage. *Appl. Energy*, *155*, 334–348.

Best, R., Li, H., Trück, S., & Truong, C. (2021, April). Actual uptake of home batteries: The key roles of capital and policy. *Energy Policy*, *151*(112186), 112186.

Brunner, C., Deac, G., Braun, S., & Zöphel, C. (2020, April). The future need for flexibility and the impact of fluctuating renewable power generation. *Renew. Energy*, *149*, 1314–1324.

Camilo, F. M., Castro, R., Almeida, M. E., & Pires, V. F. (2016, May). Self-consumption and storage as a way to facilitate the integration of renewable energy in low voltage distribution networks. *IET Gener. Transm. Distrib.*, *10*(7), 1741–1748.

CBS. (2021). *Huishoudens nu.* Online. Retrieved from https://www.cbs.nl/nl-nl/visualisaties/dashboard-bevolking/woonsituatie/huishoudens-nu (Accessed on:26.4.22)

CE Delft. (2022, 3). *beleidsmaatregelen voor vol stroomnet.* Consult. Retrieved from https://solarmagazine.nl/nieuws-zonne-energie/i26778/ce-delft-presenteert-beleidsmaatregelen-voor-vol-stroomnet-van-nieuwe-subsidie-thuisbatterij-tot-producententarief

Cerna, F. V. (2022, January). A hybrid PV scheme as support to relieve congestion in the domestic supply network. *Int. j. electr. power energy syst.*, *134*(107413), 107413.

Commissie Economische Zaken en Klimaat. (2022a, 2). *Commissiedebat: Elektriciteitsnet, energie-infrastructuur & res.* Committee meeting. Retrieved from https://www.tweedekamer.nl/debat_en_vergadering/commissievergaderingen/details?id=2022A01223

Commissie Economische Zaken en Klimaat. (2022b, 2). *Rondetafelgesprek elektriciteitsnet (digitaal).* Committee meeting. Retrieved from https://www.tweedekamer.nl/debat_en_vergadering/commissievergaderingen/details?id=2021A08418

den Ouden, B., Kerkhoven, J., Warnaars, J., Terwel, R., Coenen, M., Verboon, T., ... Koot, A. (2020). *Klimaatneutrale energiescenario's 2050* (Tech. Rep.). Berenschot and Kalavasta. Retrieved from https://www.berenschot.nl/media/hl4dygfq/rapport_klimaatneutrale_energiescenario_s_2050_2.pdf

De Vries, L., Correljé, A., & Knops, H. (2012). Electricity market design and policy choices. *Delft University of Technology*.

Donat, J. (2022, 8). *Consumentenbond wil snel nieuw minimum terugleververgoeding voor zonnestroom.* Online. Retrieved from https://www.consumentenbond.nl/energie-vergelijken/

consumentenbond-wil-minimum-terugleververgoeding-voor-zonnestroom (Accessed on: 10.10.22)

Dutch New Energy Research. (2021). *Nationaal solar trendrapport.* Retrieved from https://www.solarsolutions.nl/trendrapport/

easyEnergy. (2022). *Energietarieven.* Retrieved from https://www.easyenergy.com/nl/energietarieven (Accessed on: 17.02.2022)

EBN. (2021). *Energie in cijfers 2022.* Online. Retrieved from https://www.energieinnederland.nl/wp-content/uploads/2022/01/14253-EBN-Infographic-2022_A4-final_ENGELS.pdf

Eid, C., Codani, P., Chen, Y., Perez, Y., & Hakvoort, R. (2015). *Aggregation of demand side flexibility in a smart grid: A review for european market design.* doi: 10.1109/EEM.2015.7216712

EPEX. (2021). *Market results.* Retrieved from https://www.epexspot.com/en/market-data (Accessed on: 23.12.2021)

Esplin, R., & Nelson, T. (2022, March). Redirecting solar feed in tariffs to residential battery storage: Would it be worth it? *Econ. Anal. Policy*, *73*, 373–389.

Faruqui, A., Harris, D., & Hledik, R. (2010, October). Unlocking the €53 billion savings from smart meters in the EU: How increasing the adoption of dynamic tariffs could make or break the EU's smart grid investment. *Energy Policy*, *38*(10), 6222–6231.

Fett, D., Fraunholz, C., & Keles, D. (2021, November). Diffusion and system impact of residential battery storage under different regulatory settings. *Energy Policy*, *158*(112543), 112543.

Figgener, J., Stenzel, P., Kairies, K. P., Linßen, J., Haberschusz, D., Wessels, O., . . . Sauer, D. U. (2020, 6). The development of stationary battery storage systems in germany – a market review. *Journal of Energy Storage*, *29*. doi: 10.1016/j.est.2019.101153

Fonteijn, R., Amstel, M., Nguyen, P., Morren, J., Maarten Bonnema, G., & Slootweg, H. (2019, July). Evaluating flexibility values for congestion management in distribution networks within dutch pilots. *J. Eng. (Stevenage)*, *2019*(18), 5158–5162.

Frank energie. (2022). *Voordeliger dan vast en variable.* Retrieved from https://www.frankenergie.nl/goedkoop (Accessed on: 17.02.2022)

Gysel, P. (2021). *Hoe werkt een thuisbatterij?* Retrieved from https://blog.eneco.be/thuisbatterij/hoe-werkt-een-thuisbatterij/ (Accessed on: 16.12.2021)

Hage, J. (2020). *Hoe zit mijn energierekening in elkaar?* (Tech. Rep.). Consumentenbond. Retrieved from https://www.consumentenbond.nl/energie-vergelijken/energierekening (Accessed on: 17.02.2022)

Han, X., Garrison, J., & Hug, G. (2022, 4). Techno-economic analysis of pv-battery systems in switzerland. *Renewable and Sustainable Energy Reviews*, *158*, 112028. doi: 10.1016/J.RSER.2021.112028

Henriksen, I. M., Throndsen, W., Ryghaug, M., & Skjølsvold, T. M. (2021, December). Electric vehicle charging and end-user motivation for flexibility: a case study from norway. *Energy Sustain. Soc.*, *11*(1).

Janssen, G., & Jansen, D. (2022). *Nationaal smart storage trendrapport 2022* (Tech. Rep.). DNE research. Retrieved from https://www.smartstorage.nl/trendrapport/

Jetten, R. (2022a, 7). *Nota van wijziging - wijziging van de elektriciteitswet 1998 en de wet belastingen op milieugrondslag ter uitvoering van de afbouw van de salderingsregeling voor kleinverbruikers* (Tech. Rep.). Klimaat en Energie. Retrieved from https://www.rijksoverheid.nl/documenten/regelingen/2022/07/01/wijziging-van-de-elektriciteitswet-1998-en-de-wet-belastingen-op-milieugrondslag

Jetten, R. (2022b, 2). *Periodieke update over de schaarse transportcapaciteit op het elektriciteitsnet* (Tech. Rep.). Directoraat-generaal Klimaat en Energie. Retrieved from https://www.parlementairemonitor.nl/9353000/1/j9vvij5epmj1ey0/vlqbqm94y7z3

Kairies, K. P., Figgener, J., Haberschusz, D., Wessels, O., Tepe, B., & Sauer, D. U. (2019, 6). Market and technology development of pv home storage systems in germany. *Journal of Energy Storage*, *23*, 416-424. doi: 10.1016/j.est.2019.02.023

Khomami, H. P., Fonteijn, R., & Geelen, D. (2020, October). Flexibility market design for congestion management in smart distribution grids: The dutch demonstration of the interflex project. In *2020 IEEE PES innovative smart grid technologies europe (ISGT-Europe)*. IEEE.

Klingler, A. L., Schreiber, S., & Louwen, A. (2019, 9). Stationary batteries in the eu countries, norway and switzerland: Market shares and system benefits in a decentralized world. In (Vol. 2019-September). IEEE Computer Society. doi: 10.1109/EEM.2019.8916537

Linders, M. J., Segers, R., van Middelkoop, M., Brummelkamp, S., Keller, K., Muller, G., & Houweling, S. (2021, 9). *Hernieuwbare energie in nederland 2020* (Tech. Rep.). CBS. Online. Retrieved from https://www.cbs.nl/nl-nl/longread/aanvullende-statistische-diensten/2021/hernieuwbare-energie-in-nederland-2020?onepage=true#c--2--Algemene-overzichten

Lund, P. D., Lindgren, J., Mikkola, J., & Salpakari, J. (2015). Review of energy system flexibility measures to enable high levels of variable renewable electricity. *Renewable and Sustainable Energy Reviews*, *45*, 785-807. doi: 10.1016/j.rser.2015.01.057

Moshövel, J., Kairies, K. P., Magnor, D., Leuthold, M., Bost, M., Gährs, S., ... Sauer, D. U. (2015, 1). Analysis of the maximal possible grid relief from pv-peak-power impacts by using storage systems for increased self-consumption. *Applied Energy*, *137*, 567-575. doi: 10.1016/j.apenergy.2014.07.021

Netbeheer Nederland. (2019, 5). *Basisinformatie over energie-infrastructuur* (Tech. Rep.). Netbeheer Nederland. Retrieved from https://www.netbeheernederland.nl/_upload/Files/Basisdocument_over_energie-infrastructuur_149.pdf

Netbeheer Nederland. (2022). *Capaciteitskaart.* Retrieved from https://capaciteitskaart.netbeheernederland.nl/ (Accessed on 16.09.2022)

Netbeheer Nederland, & Energy Storage NL. (2021, 11). *Een stabiel energiesysteem door afbouwen saldering en introduceren subsidies voor decentrale opslag.* Retrieved from https://www.netbeheernederland.nl/_upload/Files/Saldering_en_Opslag_-_Position_Paper_NBNL_en_Energy_Storage_NL_17-11-2021_228.pdf

Netbeheer Nederland, & Movares. (2021). *Betrouwbaarheid van elektriciteitsnetten in nederland in 2020.* Retrieved from https://www.netbeheernederland.nl/_upload/Files/Betrouwbaarheid_23_070a9735fe.pdf

NREL. (2021). *Annual technology baseline: Residential battery storage.* Retrieved from https://atb.nrel.gov/electricity/2021/residential_battery_storage (Accessed on: 10-02-2022)

Nyholm, E., Goop, J., Odenberger, M., & Johnsson, F. (2016, December). Solar photovoltaic-battery systems in swedish households – self-consumption and self-sufficiency. *Appl. Energy*, *183*, 148–159.

Olaszi, B. D., & Ladanyi, J. (2017, 8). Comparison of different discharge strategies of grid-connected residential pv systems with energy storage in perspective of optimal battery energy storage system sizing. *Renewable and Sustainable Energy Reviews*, *75*, 710-718. doi: 10.1016/J.RSER.2016.11.046

Phase to Phase. (n.d.). *Netten voor distributie van elektriciteit.* Retrieved from https://phasetophase.nl/boek/

Regelleistung. (n.d.). *General information on control reserve - technical aspects.* Retrieved from https://www.regelleistung.net/ext/static/technical?lang=en (Accessed on: 13.01.2021)

Rijksoverheid. (2019). *Klimaatakkoord.* Retrieved from https://www.rijksoverheid.nl/onderwerpen/klimaatverandering/documenten/rapporten/2019/06/28/klimaatakkoord

RVO Nederland. (2020, 12). *Monitor zon-pv 2021 in nederland.* (Retrieved from: https://www.rijksoverheid.nl/documenten/rapporten/2021/09/23/monitor-zon-pv-in-nederland)

Sani Hassan, A., Cipcigan, L., & Jenkins, N. (2017, October). Optimal battery storage operation for PV systems with tariff incentives. *Appl. Energy*, *203*, 422–441.

Schopfer, S., Tiefenbeck, V., & Staake, T. (2018, August). Economic assessment of photovoltaic battery systems based on household load profiles. *Appl. Energy*, *223*, 229–248.

Seydali Seyf Abad, M., Ma, J., Marzooghi, H., & Ahmadyar, A. S. (2022, March). Probabilistic impact assessment of residential BESSs on the HC of LV distribution systems. *Int. j. electr. power energy syst.*, *136*(107652), 107652.

SolarPower Europe. (2021, 11). *European market outlook for residential battery storage 2021–2025.*

Stedin. (n.d.). *Wat betaal ik aan stedin?* Online. Retrieved from https://www.stedin.net/tarieven (Accessed on: 5.4.22)

Stedin. (2021a). *Investeringsplan stedin.* (Retrieved from: https://www.stedin.net/over-stedin/jaarverslagen-en-publicaties/investeringsplan)

Stedin. (2021b). *Strategische investeringsplannen.* (Intern communication)

Stultiens, E. (2021, 11). *Zonneplan start eigen energiebedrijf onder naam 'slimme energie'.* Retrieved from https://solarmagazine.nl/nieuws-zonne-energie/i25845/zonneplan-start-eigen-energiebedrijf-onder-naam-slimme-energie

Stultiens, E. (2022a, 8). *2 op 3 nederlanders verwacht thuisbatterij te kopen, interesse bij eigenaren zonnepanelen grootst.* Online. Retrieved from https://solarmagazine.nl/nieuws-zonne-energie/i27694/2-op-3-nederlanders-verwacht-thuisbatterij-te-kopen-interesse-bij-eigenaren-zonnepanelen-grootst (Accessed on: 7.9.22)

Stultiens, E. (2022b). *Charged presenteert nieuwe thuisbatterij sessy voor eigenaren zonnepanelen.* Online. Retrieved from https://solarmagazine.nl/nieuws-zonne-energie/i27566/charged-presenteert-nieuwe-thuisbatterij-sessy-voor-eigenaren-zonnepanelen (Accessed on:12.6.22)

Tanrisever, F., Derinkuyu, K., & Jongen, G. (2015, November). Organization and functioning of liberalized electricity markets: An overview of the dutch market. *Renew. Sustain. Energy Rev.*, *51*, 1363–1374.

TenneT. (n.d.). *Congestiemanagement.* Online. Retrieved from https://www.tennet.eu/nl/congestie-management

TenneT. (2022). *Dutch ancillary service.* Retrieved from https://www.tennet.eu/electricity-market/dutch-ancillary-services/ (Accessed on: 13.01.2022)

Tresoor, S. (2022, 4). *We gaan naar een ander tariefstelsel voor kleinverbruik.* Online. Retrieved from https://www.warmte365.nl/nieuws/%27we-gaan-naar-een-ander-tariefstelsel-voor-kleinverbruik%27-64A7ADB1.html (Accessed on: 2.9.22)

van Langen, S., van Tol, P., Quak, T., Sinke, M., & van Bruggen, M. (2021). *Profielen elektriciteit 2022* (Tech. Rep.). NEDU. Retrieved from https://www.nedu.nl/documenten/verbruiksprofielen/

von Appen, J., Braslavsky, J. H., Ward, J. K., & Braun, M. (2015, September). Sizing and grid impact of PV battery systems - a comparative analysis for australia and germany. In *2015 international symposium on smart electric distribution systems and technologies (EDST).* IEEE.

VREG. (n.d.). *Nieuwe nettarieven.* Online. Retrieved from https://www.vreg.be/nl/nieuwe-nettarieven

VVD & CU. (2022, 2). *Opgewekt opslaan, actieplan thuis- en buurtbatterij.* Action plan. Retrieved from https://www.christenunie.nl/blog/2022/02/17/Opgewekt-opslaan

Wiebes, E. (2020). *Memorie van toelichting - wijziging van de elektriciteitswet 1998 en de wet belastingen op milieugrondslag ter uitvoering van de afbouw van de salderingsregeling voor kleinverbruikers* (Tech. Rep.). Economische zaken en klimaat. Retrieved from https://www.tweedekamer.nl/downloads/document?id=2020D39520

Wiebes, E., & Snel, M. (2019, 4). *Kamerbrief: Omvorming salderen* (Tech. Rep.). Directoraat-generaal Klimaat en Energie. Retrieved from https://www.rijksoverheid.nl/documenten/kamerstukken/2019/04/25/kamerbrief-over-omvorming-salderen

Zakeri, B., Cross, S., Dodds, P. E., & Gissey, G. C. (2021, May). Policy options for enhancing economic profitability of residential solar photovoltaic with battery energy storage. *Appl. Energy*, *290*(116697), 116697.

Zakeri, B., Gissey, G. C., Dodds, P. E., & Subkhankulova, D. (2021, December). Centralized vs. distributed energy storage – benefits for residential users. *Energy (Oxf.)*, *236*(121443), 121443.

Zhang, Y., Lundblad, A., Campana, P. E., Benavente, F., & Yan, J. (2017). Battery sizing and rule-based operation of grid-connected photovoltaic-battery system: A case study in sweden. *Energy Conversion and Management*, *133*, 249-263. Retrieved from http://dx.doi.org/10.1016/j.enconman.2016.11.060 doi: 10.1016/J.ENCONMAN.2016.11.060

Zonneplan. (2021). *Slimme energie.* Retrieved from https://www.zonneplan.nl/energie (Accessed on: 05.01.2022)

Appendix A Dutch energy transition

This appendix describes the transition the Dutch energy sector is going through. In section A.1, the ambitions are presented regarding the phase-out of fossil fuels, together with their translation into electrification scenarios. Then, the challenges this energy transition brings to the electricity network are explained in section A.2.

A.1 Future ambitions

The energy sector in the Netherlands is going to change rapidly due to the ambition to reduce CO_2 emissions in this sector (Rijksoverheid, 2019). This reduction can be achieved by the phase-out of polluting fossil fuels from the energy sector. As can be seen in figure A.1, the majority of the energy demand is supplied by fossil fuels. Natural gas is the largest source, followed by oil. Only 10% comes from cleaner renewable sources, which accounted for 300 PJ (EBN, 2021) in 2020. Renewable energy sources in the Netherlands are biomass, wind, solar and thermal energy, of which biomass is the largest with a share of 65%. The share of renewable energy sources will increase in the coming years because of the CO_2 reduction ambitions. Predictions show this increase in figure A.2.

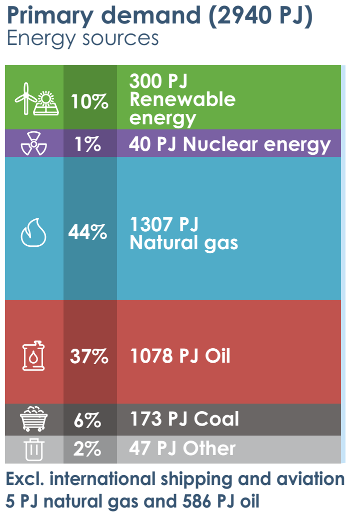


Figure A.1: Energy sources and their share in the total primary demand in the Netherlands in 2020. Source: (EBN, 2021)

The development in renewable energy sources is driven by the Paris Agreement of 2015 and the following Dutch Climate Agreement in 2019 (Rijksoverheid, 2019). The share of renewable energy of the total demand should be 27 % in 2030 and by 2050 the total energy supply must be climate neutral. In 2020 the share of renewable energy should have been 14% of the total energy consumption according to the Paris Climate Agreement (Linders et al., 2021). To cover the difference, the Dutch government made a deal with Denmark to buy 16 TWh renewable energy.

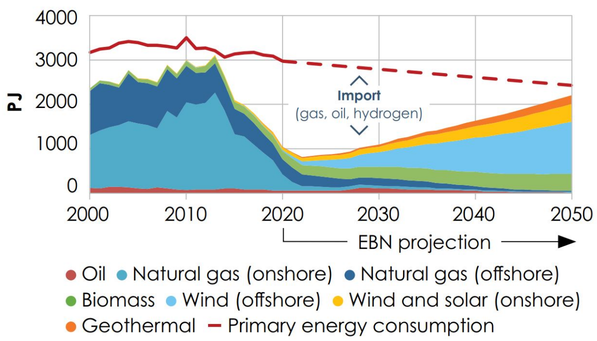


Figure A.2: The development of energy production sources and their projection over the years 2000 until 2050. Source: (EBN, 2021)

The Netherlands has the most photovoltaic (PV) capacity per capita installed of Europe (Dutch New Energy Research, 2021). In the year 2020, 31 PJ was generated with PV panels. There are two forms of PV installations, rooftop PV and large PV solar parks. During the past years, around 1/3rd of the total installed capacity was covered by rooftop PV. At the end of 2021, the number of households with a PV installations exceeded the 1.5 million (Dutch New Energy Research, 2021). Within the same year, 1.3 GW PV capacity was installed in the residential sector. The installed capacity of PV is still increasing each year. The growth declined in 2021, which is probably caused by disturbances in the supply chain and an increase in product and transport prices (Dutch New Energy Research, 2021).

The phase-out of fossil fuels does not only affect the electricity generation, also the energy consumption is changing. Heating, mobility and industry sectors will decrease their emissions. Electricity is widely used as new energy carrier. Vehicles shift from oil to electric, heating shifts from natural gas to heat pumps and industries use electricity as substitute for conventional energy carriers. Heat pumps will have a high electricity consumption during colder periods. The consumption of electric vehicles will increase after both morning and evening rush hours. Because of the phase-out of conventional fuels, the demand for electricity is increasing and changing rapidly.

Three future scenario's for electricity development are designed by the electricity network operators based on the Dutch climate goals (Stedin, 2021a). By backcasting from the year 2050, when the energy sector must be climate neutral, energy scenarios were formed (den Ouden et al., 2020). Quantification of these scenarios is found in figure A.3 specifically for Stedin area, which is approximately province South-Holland and Utrecht. The first scenario, Climate Agreement (KA), is directly based on the climate agreement to achieve a 49% reduction of the CO_2 emissions in 2030. The other two scenarios, called National Ambition (ND) and International Ambition (IA), aim for a greater CO_2 reduction with an eye on the climate goals of 2050. The main difference between these two is in short that the (IA) scenario has more focus on hydrogen import and non-electrical energy supply, whereas (ND) includes more renewables energy sources and a higher electric demand.

Generation	**Unit**	**2020**	**KA**	**ND**	**IA**
Renewable					
Wind on land	GW	0.8	1.7	2.5	1.3
Solar-PV	GW	1.7	5.7	6.5	3.1
Green gas	PJ	1.2	3.5	2.3	6.9
Demand	**Unit**	**2020***	**KA**	**ND**	**IA**
Transport					
Cars (full-electric)	amount (x1000)	43	359	505	225
Busses (full-electric)	amount	252	1,352	1,436	1,183
Trucks (full-electric)	amount	100	2,907	4,900	1,262
Built environment					
Heat pumps electric	amount (x1000)	136	264	414	181
Heat pumps hybrid	amount (x1000)	34	112	83	309
Heat network – connected dwellings	amount (x1000)	143	215	366	229
Industry					
Growth per year	%		2	1	2
Agriculture					
Growth per year	%		2	2	2

Figure A.3: Quantification of scenarios for the service area of Stedin of 2030. *current numbers of heat pumps and electric mobility are an estimation. Source: (Stedin, 2021a)

A.2 Challenges of the energy transition

One of the challenges of renewable energy sources is their volatility. The drawback of wind and solar energy, other than biomass, is that they are highly dependant on weather conditions and are thus uncontrollable. When an increasing share of electricity generation is fluctuating, it becomes harder to match the already fluctuating demand for electricity. The conventional energy system is designed on controllable energy sources to meet demand. To integrate renewable energy sources and still be able to match supply and demand, flexibility formerly only at generation side should now be implemented at both sides by means of storage or flexible demand (Brunner, Deac, Braun, & Zöphel, 2020).

The conventional power system was designed for mainly centralised conventional power production, whereas the increasing demand for renewable sources leads to more decentralised energy production. Therefore, the electricity grid changes from unidirectional transportation to bidirectional. This is schematically presented in figure A.4. Centralised energy sources were connected to high voltage levels, depicted on the top of the figure. Decentralisation leads to more electricity feeding on lower grid levels causing an increase in load pressure on these lower level transportation and distribution components, which they are not initially designed for. Also, the location of renewable energy generation is not necessarily close to demand because of the land area it requires. Then for example, in rural areas the generation increased whereas the consumption of electricity remains low. This requires more electricity transportation. The Dutch electricity network is explained in appendix B.1

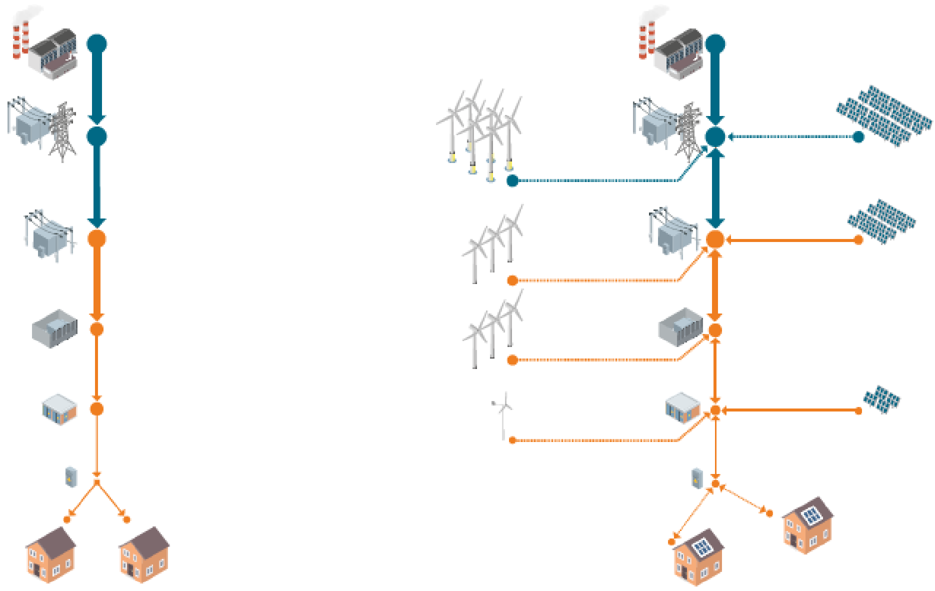


Figure A.4: On the left schematic conventional centralised electricity production, on the right additional decentralised production causing bidirectional flow. Blue lines are under responsibility of the TSO and orange lines of the DSO Source: (Netbeheer Nederland, 2019)

Appendix B Overview of the management of the electricity network

After liberalisation of the Dutch electricity market, the main activities are divided among producers, transmission and distribution operators (Netbeheer Nederland, 2019; Tanrisever, Derinkuyu, & Jongen, 2015). An overview of the physical and institutional tasks in the network can be seen in the overview in figure B.1. The system operators manage the physical network. Both the TSO and DSO and their tasks are described in section B.1. Small consumers can buy electricity on the retail market from retail companies. This retail market is described in more detail in section B.2. Electricity generation is done by electricity producers who exchange their generated power in the wholesale markets. These different markets are described in section B.3. Large electricity consumers can buy directly from the wholesale markets.

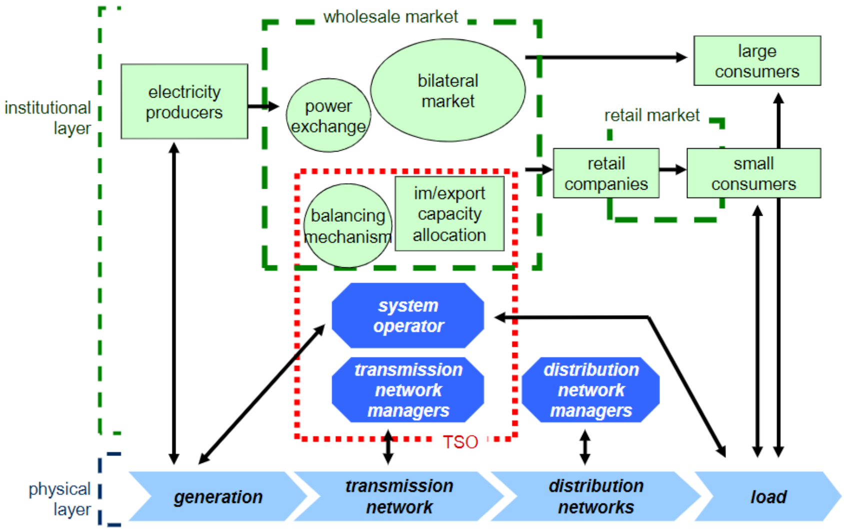


Figure B.1: A representation of the Dutch institutional and physical electricity market. (De Vries et al., 2012)

B.1 Transmission and distribution grid

The transmission system operator (TSO) TenneT operates the high voltage (HS) grids, which are all cables and lines with a voltage ranging from 110 to 380 kV. Centralised production of electricity is directly supplied to the national high-voltage grid. The grid of voltages lower than 110 kV are operated by the distribution system operator (DSO) and are called intermediate voltage (TS) for 25-66 kV, medium voltage (MS) for 3-23 kV and low voltage (LS) for 400 V. Decentralised electricity production is more directly used by the producer or supplied to the low- or medium-voltage grid. Additionally, the DSO is responsible for the connection of small consumers. DSOs have a regulated monopoly in their region, but the Authority Consumer and Market (ACM) monitors the efficiency and grid tariffs of all DSOs. Stedin is the DSO of the region South-Holland and Utrecht. The ACM is an independent supervisor of the energy market and create regulations for the users and operators of the electricity and gas network. Because grid operators are natural monopolies, the ACM regulates the grid tariffs the grid operators may charge, based on cost efficiency and security of supply (ACM, 2017). In this way the grid operators are stimulated to work as efficient as possible.

Figure B.2 shows the structure of the various transmission and distribution grids. Orange shows the transmission grid to which large power plants are connected. The interconnected grid connects the foreign transportation of electricity and on a national level the very large power plants are connected (>500 MVA). The interconnected grid feeds the transmission grid. This is the connection between the interconnected and distribution grid and large power plants and wind turbine parks (between 10 and 500 MVA) are connected. Large industry is connected to the transmission grid and sometimes even have their own electricity production. To the outer rings of figure B.2, the regional and local distribution grids are depicted. The regional distribution grids are fed by the transmission grid and by power plants with an output between 0.3 and 10 MVA. Large consumers are connected to this regional distribution grid. A regional distribution grid has typically a total power of 100 MVA. The local distribution grids distribute the electricity to individual households that also produce PV electricity on a small scale. The total power of a local distribution grid is typically smaller than 1 MVA.

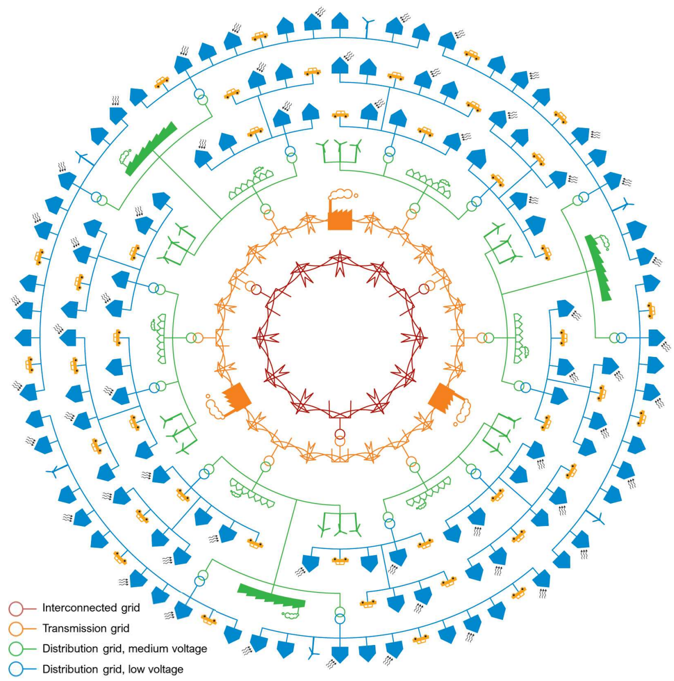


Figure B.2: The structure of the Dutch electricity grid divided by function. Red indicated the interconnected grid, orange the transmission grid, green is the regional distribution grid and blue indicated the local distribution grid. Source: (Phase to Phase, n.d.)

In order to prevent high power losses during transportation of high power levels, the voltage level must be high. Therefore, the voltage level corresponds to the function of the grid. Low voltage levels distribute electricity to the households and consumers. The level between transmission and distribution, so between low voltage and high voltage is called medium voltage. Grids at medium voltage sometimes have a transmission function next to their distribution function.

All these grids are connected to each other with transformer stations as can be seen in figure B.3. The capacity of these transformer stations indicates the size of the different grids. The capacity of transformer stations between the interconnected and transmission grid, a high voltage substation, has a typical size of more than 500 MVA. In the Dutch interconnected grid there exist a few dozen stations. A transformer station connecting the transmission grid to the regional distribution grid is called a medium voltage substation. It has a capacity in the order of 100 MVA. The Dutch electricity systems consists of about 200 of these substations. The lowest ones, the transformer stations between the regional distribution grid and the local distribution grid have a capacity of 0.2 to 1 MVA. There can be 250 to 500 low voltage substations connected to one medium voltage substation. On one low voltage substation, 50 to 250 costumers can be connected.

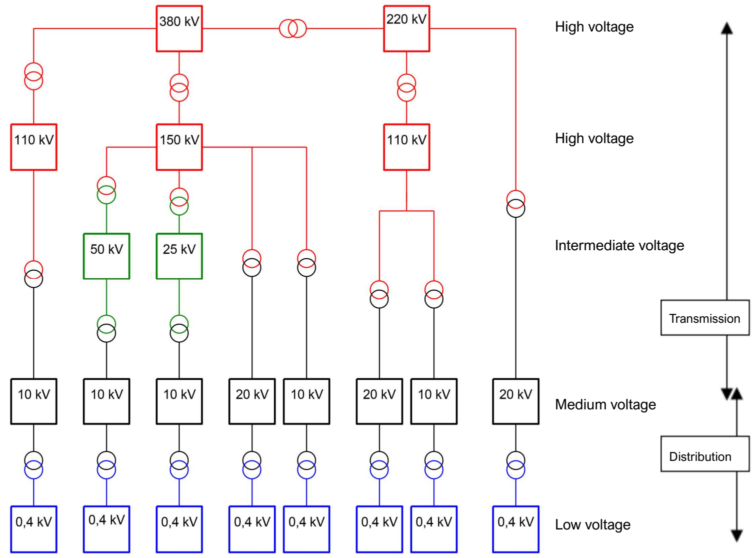


Figure B.3: Voltage levels within the Dutch electricity network and their transformer steps. With red the high voltage levels(110-380 kV) are indicated, the intermediate voltage level(25-50 kV) with green, medium voltage levels (10-20 kV) in black and low voltage (0.4 kV) in blue. Source: (Phase to Phase, n.d.)

The Dutch power system has a very high security of supply. In 2020, on average every connection had only a 20 minute breakdown (Netbeheer Nederland & Movares, 2021). This high reliability is due to its redundancy: most of the electricity network is double connected (Netbeheer Nederland, 2019). This is indicated as a 'N-1' connection, and this means that when a component is overloaded or breaks, the network does not have a breakdown. Transmission grids transport the electricity across the whole country. An outage in the high voltage grid has a lot of consequences. Therefore, the TSO installs all components of the grid in redundancy and the grid is designed in a ring structure. In case of an outage, the electricity can still be transported via a different route. An outage in the low voltage grid of the DSO has fewer consequences than in higher voltage levels. Therefore, connections on the low voltage grid are not necessarily double installed.

The medium voltage distribution grid is most commonly designed on 10 kV. However, recently because of the increase in decentralised production, these grids can be made at 20 kV. The advantage is that, although the material costs do not differ too much, the power that can be distributed is doubled. A substation is most commonly fed by the high voltage grid or sometimes the intermediate voltage grid and it feeds a medium voltage grid both for distribution and transmission. Usually the medium voltage grid is fed by means of about 20 connections. The substation is of such importance that it is designed with plenty of reserve components. In case of a failure, there is no interruption in electricity supply.

B.2 Consumers electricity retail

Because of the liberalisation of the electricity market, the transmission and distribution of electricity are separated from the retail of electricity. The generator and retailer of electricity to industry and consumers are part of a free market, and in the Netherlands those are mostly the same companies. Consumers may choose their own energy supplier. A few examples are: Nuon, Essent, Eneco and Vattenfall. The retail pricing scheme for Dutch households to be payed to the energy supplier nowadays is build up of four components: supply, taxes, network and metering costs (Fonteijn et al., 2019; Hage, 2020). The delivered amount of electricity is payed for with the supply costs to the energy supplier. There they can choose for a fixed or variable energy contract. The tariff of a fixed contract may not change during the contract period, whereas for a variable contract it may rise and fall. The electricity tariffs for the residential sector are either constant or consist of day-and-night tariffs, which consumers can choose based on their preferences. When households choose a double tariff system, there is a stimulation to shift electricity demand to night times. Also a dynamic pricing scheme was recently been launched in the Netherlands by some energy suppliers. For example Zonneplan (Zonneplan, 2021), easyEnergy (easyEnergy, 2022) and Frank energie (Frank energie, 2022) sell their electricity based on electricity market prices. The retail prices to consumers vary every hour and every day. This net scheme stimulates the use of electricity when the market prices are low and thus mostly when the generation of electricity is high. Normally, during the evening the electricity prices are at its peak and thus with this pricing scheme the use of electricity is discouraged.

Secondly, electricity taxes are paid to the government for both the tax per kWh and the VAT over the total price. Metering costs are used to install the meter and maintenance costs. The network costs are used to cover transmission and distribution costs. Because the DSO and TSO have a natural monopoly position, the network tariff is determined by the ACM. Within the network costs, there are multiple connection capacity options. The most common connection is 3×25 Ampère, which is sufficient for standard households even with installed rooftop PV or a electric vehicle. The connection capacity must be increased when a heat pump is combined to 3×35 A or higher. This increases the connection tariff for the grid operator from €254,27 for 3×25 A to €995,94 for 3×35A (Stedin, n.d.). In 2021, the Dutch grid operators have started revising the current tariff system (Jetten, 2022b).

To stimulate the installation of rooftop PV with households, the net-metering scheme is in place. Currently, the net-metering policy ensures that your excess generated electricity by your PV installation is subtracted from your electricity bill one-on-one. The pay-back time of rooftop PV is about 7 years (Rijksoverheid, 2019). When the amount of generated electricity exceeds the annual demand, a feed-in tariff is paid to the customers per kWh.

B.3 Electricity markets

As can be seen in figure B.1, the wholesale electricity market consists of multiple submarkets. An overview of all markets is shown in figure B.4. The various markets are divided in wholesale, balancing, and congestion markets.

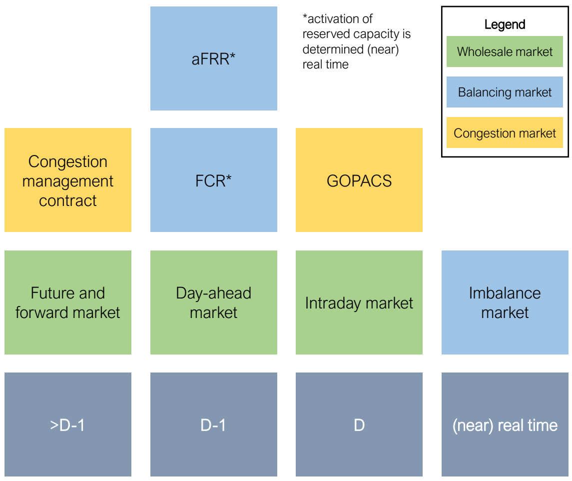


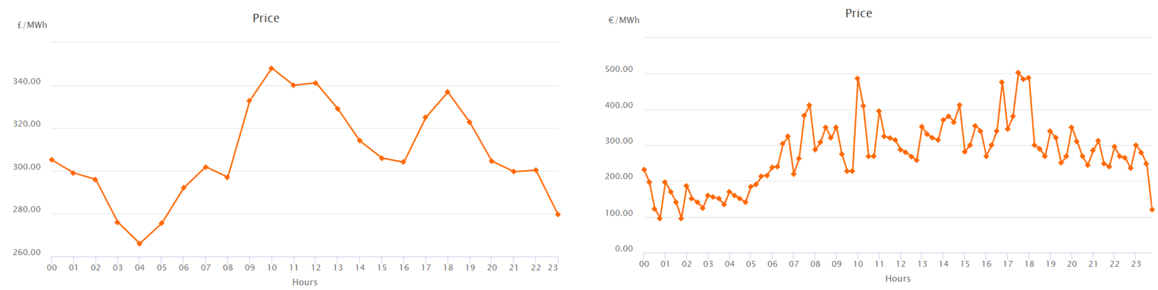
Figure B.4: An overview of the different electricity markets batteries can participate in. Source: (Janssen & Jansen, 2022)

The TSO regulates the power exchange markets including cross-border transactions (Tanrisever et al., 2015). The Dutch TSO TenneT connects Germany, UK, Belgium and Norway to the transmission grid via HS connections. The wholesale market creates a first supply and demand schedule based on bids from market parties. These bids are based on predictions and thus the actual demand or supply will differ. These prediction deviations will be traded on the balancing market to balance the system real time. This latter market values the flexibility of the market players and the spot and forward market value the actual power. The different markets are described in more detail below.

B.3.1 Wholesale market

The first market of figure B.4 consists of bilateral contracts and is mostly called forward or future market. These contracts are long-term and the price is fixed for generators and consumers to lock in their revenue and costs. Because these contracts are private, there is no information about the actual agreements.

The spot market consist of the day-ahead and intra-day market. First, there is the day-ahead market of the EPEX (European Power Exchange). The largest share of electricity is traded on this day-ahead market. This market matches supply and demand of electricity each day at noon for every hour of the next day. All sellers and buyers of electricity place their hourly bids before noon the day before. This results in two total supply and demand curves. The intersection of these curves determines the market clearing price. All electricity is bought and sold for this same price. In figure B.5a, an example of one day of day-ahead market prices is shown. The EPEX also introduced the intra-day market. This is a continuous trading market. Figure B.5b shows the electricity prices of the same day for the intra-day market. Market players use this platform to match their projected amount of electricity of the day-ahead to the real electricity supply or demand. A trade can be made up to 5 minutes before with 15-minute contracts. Because this market has a resolution of 15 minutes instead of the 60 minutes resolution of the day-ahead, the market parties can 'smoothen' and optimise their projected electricity supply.



(a) Day-ahead market prices of 24 December (b) Intraday market prices of 24 December

Figure B.5: Example of the day-ahead and intraday electricity market prices. Source: (EPEX, 2021)

Starting in the end of 2021, the wholesale electricity market prices are increasing enormously. This can be observed in figure B.6. The electricity price has been quite constant over the past years and now since the end of 2021, because of multiple factors, including the Russian-Ukrainian war, the prices have increased.

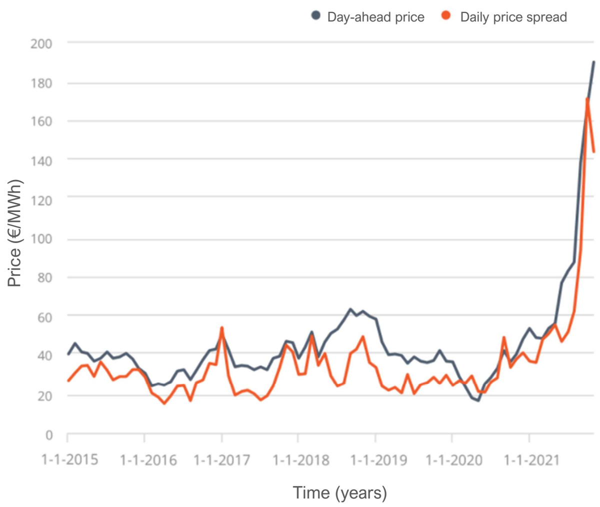


Figure B.6: The trend in prices on the day-ahead market in grey and the daily price difference in orange. A recent steep increase in electricity price can be seen in 2021 and the correlation between price and price difference is observed. Source: (Janssen & Jansen, 2022)

B.3.2 Balancing market

When there is more electricity supply to the grid than demand, the frequency will rice over 50 Hz and when there is more demand, the frequency will drop under 50 Hz. As soon as the electricity frequency on the grid deviates too much from this value of 50 Hz, Balance Responsible Parties (BRP) are responsible for restoration. The imbalances can be restored by control reserves. There are three types of balancing power within varying time frames, as can be seen in figure B.7. The Frequency Containment Reserve (FCR) can be activated within 30 seconds to restore the frequency and can be turned on for 15 minutes maximum. The TSO should have a certain capacity readily available for FCR. In 2022, TenneT must have 116 MW FCR available (TenneT, 2022). For the FCR there are daily auctions for available capacity instead of a payment for power as in the previously described markets. The secondary control reserve (SCR) activates within 5 minutes to restore the energy balance. The SCR is partly covered by yearly contracts and partly by daily actions. Similar as for the FCR, the SCR is contracted for available capacity and not power exchange. The capacity of the tertiary control reserve is contracted by TenneT and there is no market available.

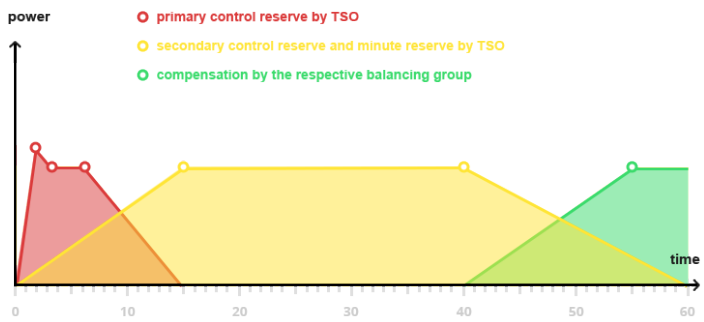


Figure B.7: Activation and covering times of the three control reserves. Source: (Regelleistung, n.d.)

There are several balancing markets. The main difference between the (FCR) and Frequency Restoration Reserve (FRR) on one side and the imbalance market on the other is that for the imbalance market there is no contracted power the day before and payment is on the basis of activated power. Within the FCR market parties can bid in blocks of four hours to provide bidirectional flexible power. On a yearly basis the price between these different blocks is similar. However, because the amount of flexibility supply is increasing, the FCR prices are expected to decrease. When the imbalance is too large despite the FCR market, the FRR is activated. Within frequency restoration there are two reserves, the automatic activated reserve (aFRR) which is also called the secondary control reserve, and the manually activated reserve (mFRR) also called the tertiary control reserve. The main differences of the aFRR market and the FCR market are the payment basis, the direction of activation, and the time range. At aFRR there is paid for both the available capacity (in kWh) as the activated power (in kW), the bids go in one direction which is either supply or demand, and the bid blocks are 15 minutes.

B.3.3 Congestion market

The electricity markets previously mentioned ensure to match supply and demand, yet they do not include the (local) grid capacity. A congestion market will ensure that the load is within the grid capacity and acts locally. There are two types of congestion markets, bilateral contracts and the congestion market platform GOPACS. On the GOPACS platform, both transmission and distribution grid operators can request a location specific flexibility on which market players can bid. An opposite request is automatically done at a different location to secure the national power balance. However, currently GOPACS does not encounter grid congestion of both transmission and distribution at the same time. So TenneT may solve their power peak simultaneous to causing a power peak in the distribution grid. This is currently being solved by adding location-specific restrictions to market players.

Although congestion management is currently not often performed by the DSO because grid reinforcement is cheaper, reinforcement is lagging behind the increase in congestion problems. Therefore, GOPACS will to an increasing extent be used for congestion problems. On the long term the congestion is now solved with grid reinforcement, on the short term there are congestion market possibilities. For example grid connection agreements or market based flexibility. The latter one can be done on the platform GOPACS. Currently, this type of congestion market is still under construction for ideal use by the DSOs and is now mostly used by the TSO. Curtailment agreements are nowadays by contracts and are done by direct contact and not by using the platform.

Grid operators may not participate in the electricity market as stated in the electricity law of 1998 because of their monopoly position on their grid, which means they cannot own and control a flexibility source themselves. One possibility for them to use batteries to prevent congestion is either a congestion market to make peak reduction profitable for battery owners, or a bilateral contract with flexibility owners to alter generation or demand when necessary. The main difference is that a congestion market would be profit based and bids can be accepted or not. The costs for the DSO would be uncertain beforehand. With contracts, the flexibility provider has no choice to scale up or down, and is also paid when the source is not used.

Khomami, Fonteijn, and Geelen researched the working of a platform to connect aggregators with the DSO to enable flexibility in the grid. This has been tested on a field research and this system is capable of solving the expected day-ahead congestion. You can think of an aggregator who is willing to curtail PV power or an aggregator who is able to control electric vehicles. However, the design of the flexibility market is still in progress, since the complexity of the trading process and the uncertainty of providing flexibility cause bottlenecks in the system. Flexibility aggregators have different methods to provide flexibility. Electrical storage systems are one way of providing both generation and demand flexibility. Curtailment is a method to decrease the generated input.

Appendix C Residential battery context of neighbouring countries

In our closest neighbour countries, the number of residential batteries is increasing for different reasons. In Belgium a load peak dependant capacity tariff is introduced and in Germany batteries are stimulated and the feed-in price gap is significant.

The capacity tariff of Flanders in Belgium is adjusted since the year 2022 and the net-metering is removed (VREG, n.d.; SolarPower Europe, 2021). The capacity tariff was previously based on annual electricity demand. Now, the capacity tariff is based on the maximum power peak per month. The VREG (the Flemish version of ACM) wants to stimulate efficient use of the grid capacity. This will mostly affect electric vehicle and heat pump owners that do not spread their usage or use smart applications.

In Germany currently about 60% of newly installed PV systems are combined with a battery system (SolarPower Europe, 2021). The residential battery uptake in driven by the dropping feed-in tariff, the rising electricity prices and their expected increase, and for the thought of contribution to the "Energiewende" (Figgener et al., 2020). 70% of all residential batteries in Europe was installed in Germany in 2020 (SolarPower Europe, 2021). In figure C.1, the cumulative capacity of residential batteries in Europe is shown. Figgener et al. estimates the amount of residential batteries in Germany in 2018 at 125,000 installations, with a total capacity of 930 MWh. 90% was installed simultaneously with a new PV system.

Germany already has several support schemes for the installation of residential batteries. As the rooftop PV was already at 1 million installations in 2012, the grid operators were concerned about the effects of this decentralised generation on the grid (SolarPower Europe, 2021). So in 2013 a federal bank started a support scheme for batteries in combination with PV. Simultaneously, the German electricity prices increased rapidly and the feed-in tariff decreased, as shown in figure C.2a. The growing prices mainly caused by the ambitious 'Energiewende' plan and the goal to close all nuclear power plants. In 2020, the gap between retail and feed-in prices was 31 to respectively 7 eurocent per kWh. Additionally, a feed-in maximum is set on 60% of PV generated power. Because of these latter regulation, the use case of batteries in Germany is based on maximising self-consumption (SolarPower Europe, 2021).

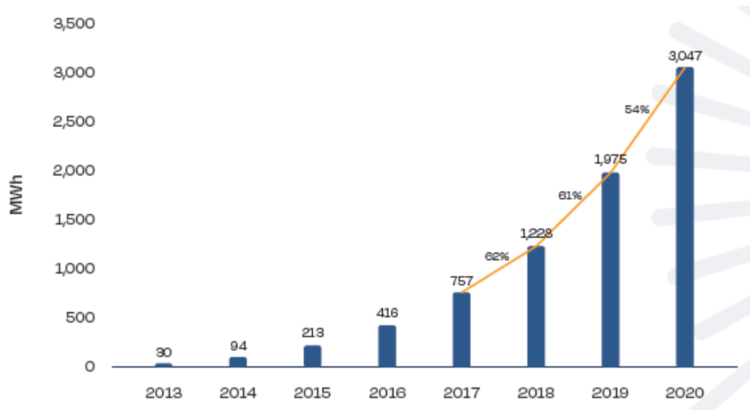
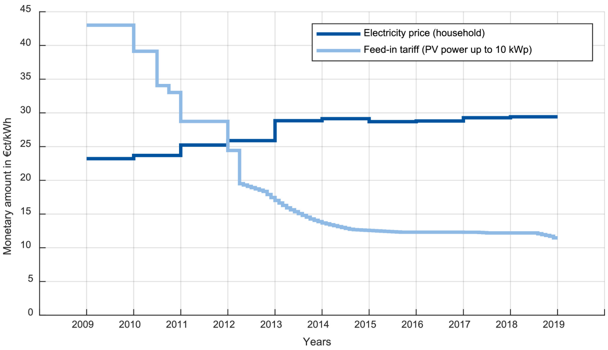
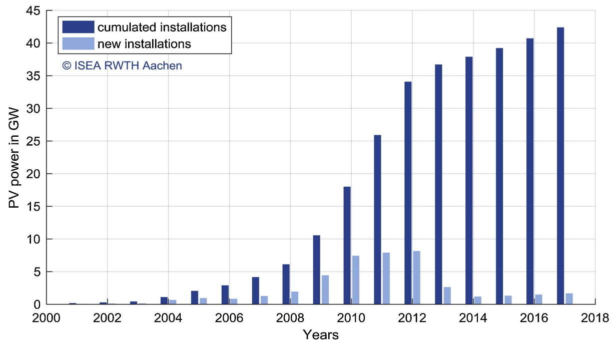


Figure C.1: The cumulative market of residential battery systems in Europe. Source: (SolarPower Europe, 2021)

This feed-in gap still is insufficient to earn back the investment costs of the battery. However, the expected increase in electricity prices did motivate the battery market. From 2013 till 2015 the German government stimulated batteries by subsidising 55% of the new residential battery installations. As soon as this market had started up, the governmental support declined after 2015. Because of the low feed-in tariff, the motivation for installing rooftop PV is reduced. Since 2012 the installation of PV has dropped as can be seen in figure C.2b. Because the Dutch government has still ambitions for a significant increase in residential rooftop PV, the net-metering phase out and thus lower feed-in could jeopardise this.



(a)



(b)

Figure C.2: (a) Trend of electricity retail prices and feed-in tariffs of households in Germany. Source: (Figgener et al., 2020) (b) New and cumulative installation of PV power in Germany. Source: (Kairies et al., 2019)

Appendix D Load flow computation model: SETIAM

For the simulation of the distribution grid load flow, the 'Stedin Energy Transition Impact Assessment Model' (SETIAM) will be used. This model represents all components and their connection hierarchy within the real Stedin network. Their load profile is computed. The expected increase of technological features impacting the grid like electric vehicles and PV parks is implemented based on different scenarios as can be seen in figure A.3. The yearly load profiles of these new technologies are added to the initial load over the network by load summation. The model works with yearly load profiles, which means that voltage changes are not taken into account. Using hourly load summation, the load on all grid components can be simulated over one year. By comparing these summed load profiles per substation with there load capacity, congestion bottlenecks can be identified. For the initial year, in this case 2021, the initial load profiles are known from actual measurements. The changes over the years are caused by different technology emerges: for example an increasing amount of electric vehicles, heat pumps or rooftop PV. The corresponding load profiles of these technologies is summed to the initial load values, based on the expected increase per technology.

Stedin uses the model SETIAM to analyse the future load on the stations to determine when they would require reinforcement (Stedin, 2021a). Their investment plan is based on these predictions. Currently, the SETIAM model does not include any flexibility potentials. Although the potential of flexibility is recognised by Stedin, the capacity effects and concrete applications are not included in the model.

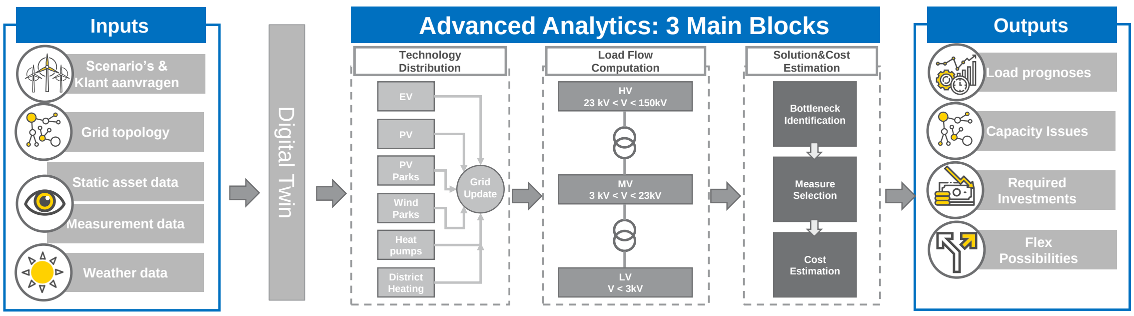


Figure D.1: Overview of inputs, working and outputs of the SETIAM model

Model inputs

Scenarios - The electrification caused by the rise of technologies are quantified in scenarios. These scenarios are based on national scenarios for 2030 made by grid operators (Netbeheer Nederland) and on the climate neutral energy scenarios 2050 (den Ouden et al., 2020). Scenarios are created for the cumulative expected amount per year until 2050 of all technologies. Examples of new technologies are number of electric vehicles, capacity of rooftop PV, number of heat pumps, and newly built residential areas. All scenario drivers that are included in the model are named in figure D.2. For this research the scenario of National Ambition (ND) is chosen as a base case, which is described in appendix A. The scenario for the emergence of residential batteries will be added. The quantification of this scenario can be found in figure A.3. The ND scenario includes the most electrification, energy-autonomy, and increase of renewable energy sources PV and wind.

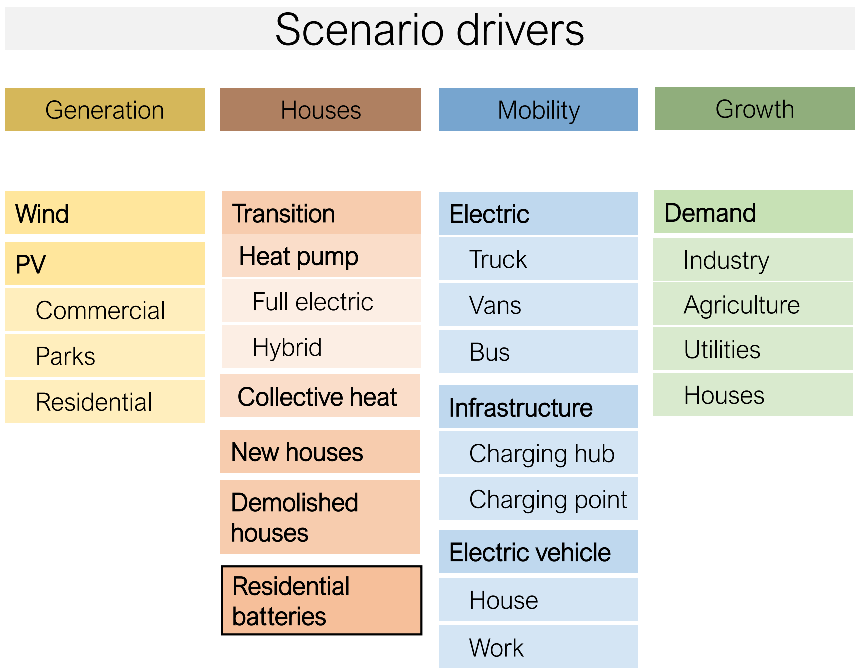


Figure D.2: The drivers to scenarios that influence the load of the distribution grid in the future

Grid topology - All substations and connections of the Stedin distribution area are included in the simulation. This grid topology is build up by low, medium and high voltage hierarchy data sets, which describe all customers by ean code, the connections, transformers, and cables. Over 2 million customers are included in this data set.

Static asset and measurement data - Data of the connected customers of Stedin are included in the model like, annual electricity and gas use, PV size, and collective heating connection. All connections are assigned to a specific standard 'Nedu' load profile in SETIAM (van Langen et al., 2021). This profile is scaled with their annual energy consumption. The load profile of small customers is averaged and general for all connections. This is justified for consideration of station level is considered because averaged profiles add up. The initial load profile of substations is created by comparing measured data with SCADA on the substation with calculated data from profiles of large consumers and standard profiles of connected costumers. In this way the initial connection loads are validated as well as the missing or false data points are filtered. The resolution of SETIAM is hourly and the input and resulting output has a span of one full year.

Weather data - The temperature data is used in the model for calculation of heating amount. This data is chosen as a worst case cold winter, which is the year of 1987. A PV and wind energy profile are included to determine generation.

Model running

Technology distribution - All technology components described in the scenarios are distributed over the Stedin area and assigned to a specific location. This distribution is done stochastic. Probabilities for particular technologies are assigned to locations. As an example, the distribution of rooftop PV is as follows: The installation of PV per household is estimated based on data of the house like build year, building type, roof area, and rooftop PV of its surrounding neighbours. This is based on the fact that the chance is higher to install PV when your neighbors have them.

Load flow computation - Based on the simulated grid topology, the load profiles of the cumulative technology scenarios are added to the initial load year. Power quality of the distributed electricity is not part of the scope of the research.

Solution and cost estimation - The capacity limit of all substations are included in the model. Therefore, when the load exceeds this limit, the necessary reinforcement costs can be calculated.

Model outputs

Load prognoses - The load peak prognoses over the years up till 2050 are computed as well as the expected hourly load on the stations. The resolution of the used model is hourly data over one year. The load profile calculations on HS/MS substation level are more accurate than on the lower MS/LS level.

Capacity issues - By comparing the yearly load prognoses over all grid components with their load capacity, capacity issues are mapped. When load peaks exceed this capacity limit structural, the is a high change of failure and black-outs.

Required investments - As soon as the grid components are not sufficient and capacity issues are occurring, grid reinforcement is required. The necessary investments are analysed and choices are made.

Flex possibilities - Because of the limited financial resources of Stedin, not all reinforcements can be finished on time. Therefore, the possibility of flexibility is analyses to absorb the load peaks and relieve the grid pressure. This model feature is still in the development phase.

Appendix E Station scenarios and load profiles

In this appendix the scenarios for the selected substation and the resulting station load are shown. Section E.1 provides the scenarios corresponding for the selected medium voltage substation without the emergence of residential batteries taken into account. Then, in section E.2, the resulting load profiles are presented.

E.1 Before distribution of batteries

The selected substation is a 10 kV (medium voltage) substation with a safety capacity of 27 MWh. There are 20 medium voltage feeders, 950 transformers and 834 fields connected to the station. Figure E.1 shows the increasing generation technologies for the years 2021-2037 of the selected station. As can be seen, residential rooftop PV (LV-PV residential) increases significantly faster than the other technologies. The substation is expected to be overloaded in 2024 on the demand side and in 2030 on the generation side, as can be seen in figure E.2.

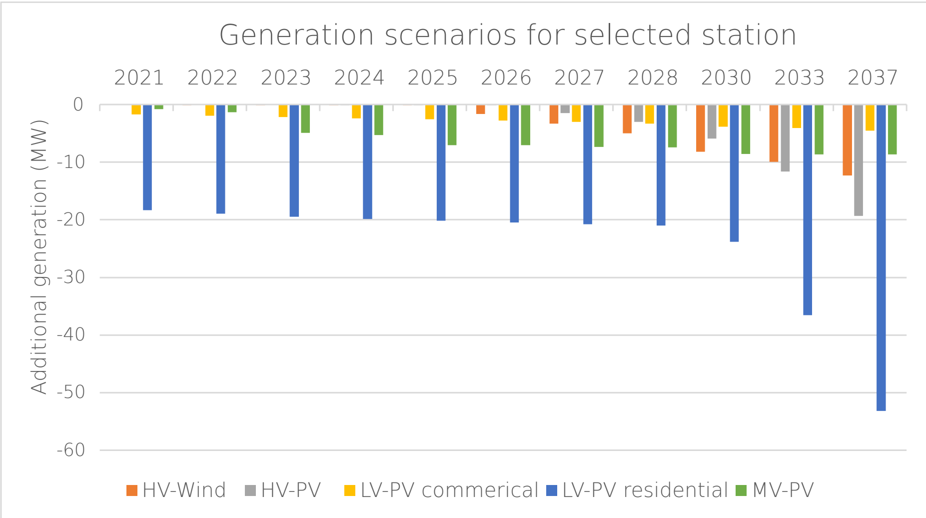


Figure E.1: Scenario for generation technologies for the selected station of the years 2021-2037

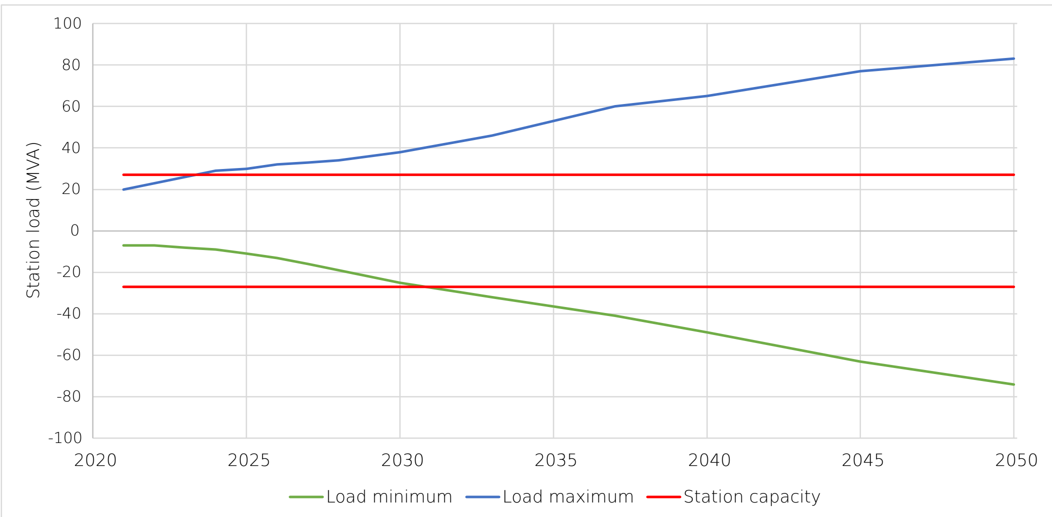


Figure E.2: Expected load increase on selected station leading to congestion. In 2024 the station is expected to overload its maximum capacity and after 2030 the generation exceeds the minimum safety capacity.

E.2 After distribution of batteries

To analyse the effect of the emergence of residential batteries on the selected medium voltage substation, the battery profiles are added to the yearly station load in the years 2030, 2040 and 2050. The effect of three different control methods are analysed: maximising self-consumption, market prices arbitrage and load peak reduction. Additionally, three emergence scenarios for residential batteries are considered, a high, medium, and low emergence scenario. The results of the yearly station load profiles are shown in figures E.3, E.4 and E.5. Please note that the y-axis limits of the graphs from 2030 differ from the others. In order to analyse the effect of the residential batteries, the overload and minimum and maximum peak values are determined. When the load exceeds the safety capacity of the station there is overload. The cumulative size of all the overload hours per battery scenario and control is presented in figure E.6. At last, the minimum and maximum station load peak per year is determined after the distribution of all residential batteries. The results can be found in table E.1. The load peak is maximum on 11 January at 18:00 and the minimal load occurred on 18 April at 12:00.

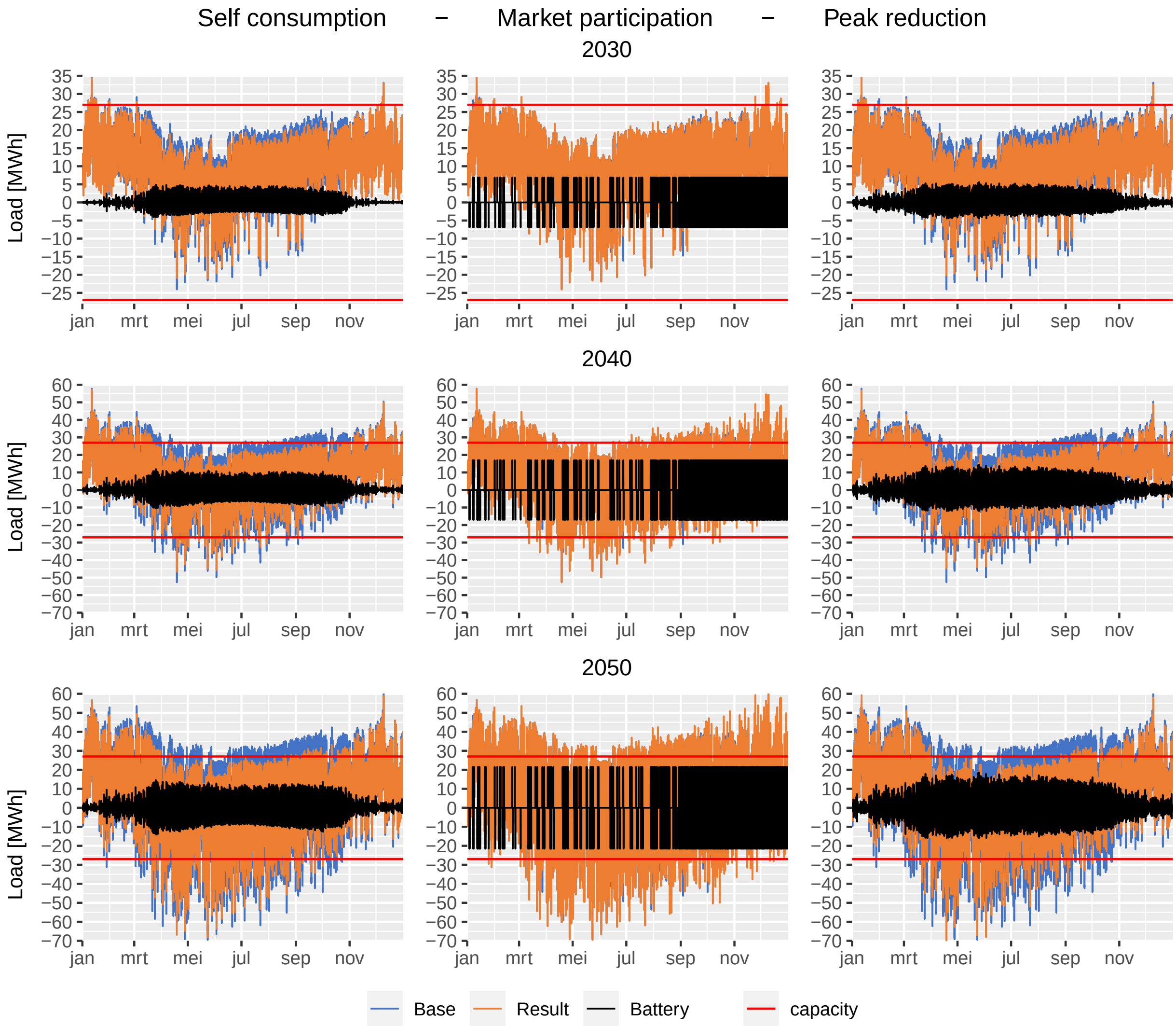


Figure E.3: Station load in high scenario for 2030, 2040 and 2050

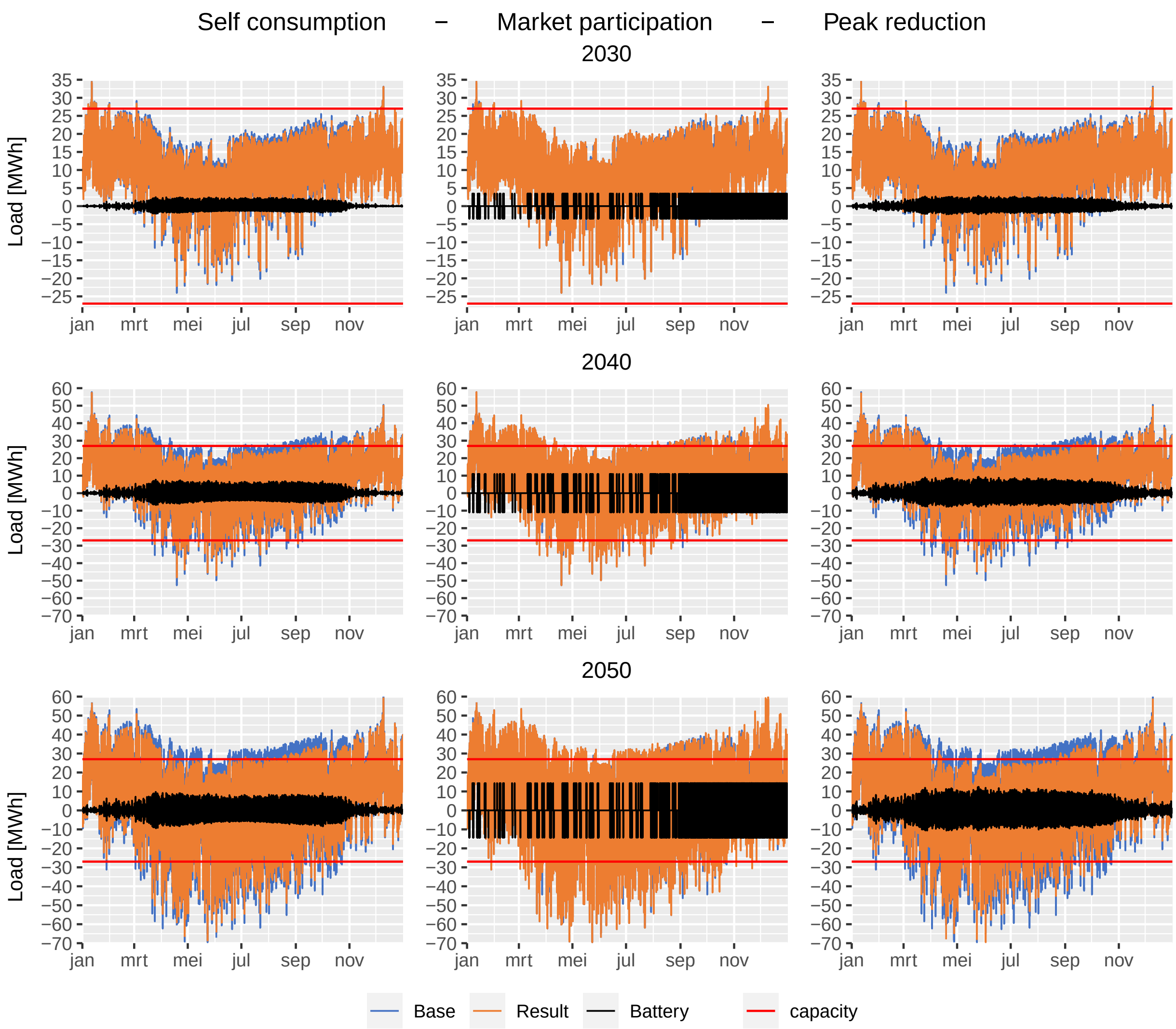


Figure E.4: Station load in medium scenario for 2030, 2040 and 2050

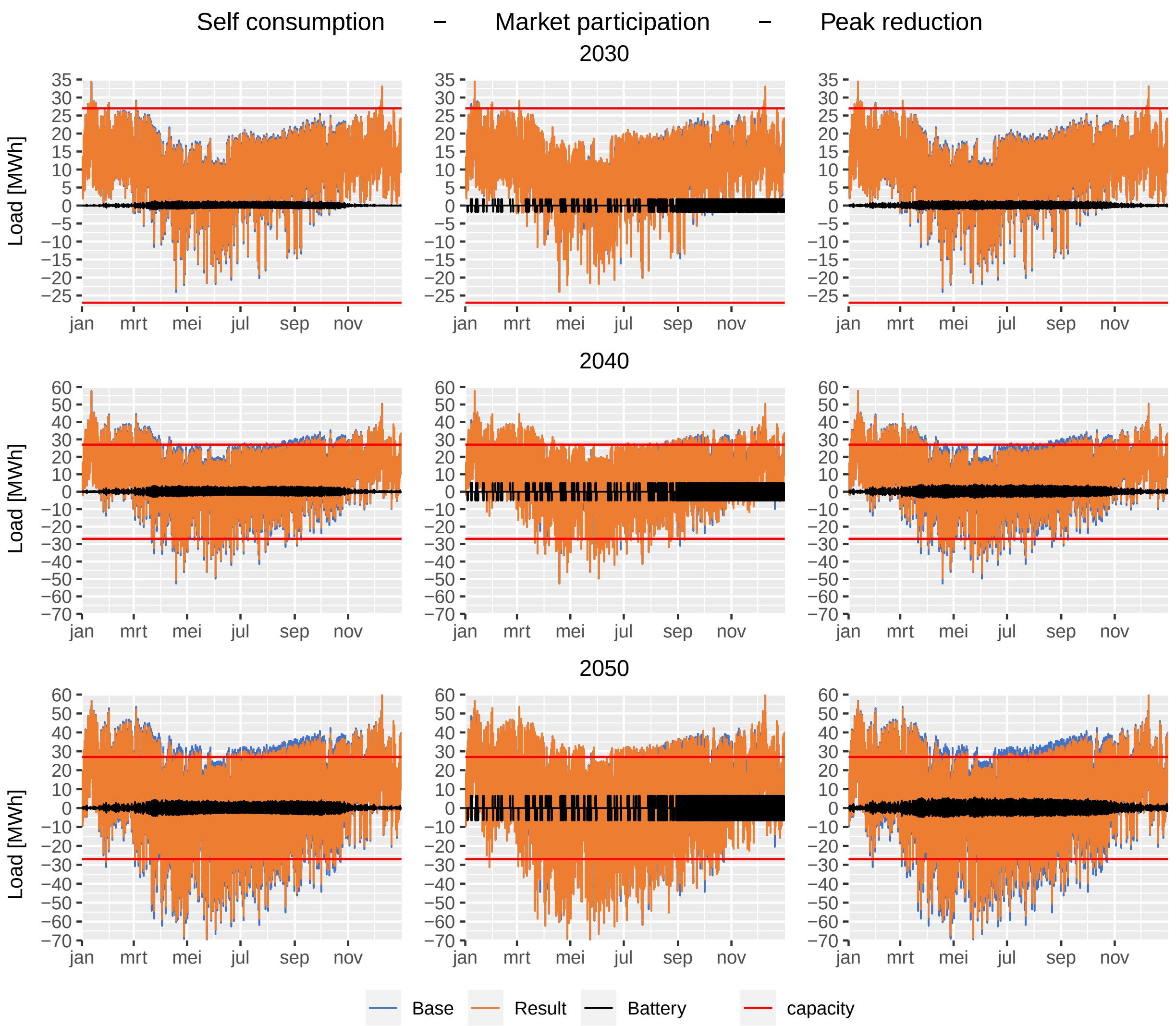


Figure E.5: Station load in low scenario for 2030, 2040 and 2050

Max peak (MWh)	Base	High			Medium			Low		
		Self	Market	Peak	Self	Market	Peak	Self	Market	Peak
2030	36.2	36.1	36.2	35.8	36.2	36.2	36.0	36.2	36.2	36.1
2040	57.8	57.2	57.8	56.8	57.4	57.8	57.1	57.6	57.8	57.5
2050	68.7	67.8	68.7	67.4	68.1	68.7	67.8	68.4	68.7	68.3

(a) Maximum station load peaks

Min peak (MWh)	Base	High			Medium			Low		
		Self	Market	Peak	Self	Market	Peak	Self	Market	Peak
2030	-24.1	-20.4	-24.1	-19.5	-22.2	-24.1	-21.8	-23.1	-24.1	-22.9
2040	-52.7	-45.8	-52.7	-42.3	-48.2	-52.7	-45.9	-50.7	-52.7	-49.6
2050	-80.2	-72.3	-80.2	-67.8	-74.9	-80.2	-71.9	-77.8	-80.2	-76.4

(b) Minimum station load peaks

Table E.1: Change in the maximum and minimum station peak by the emergence of residential batteries

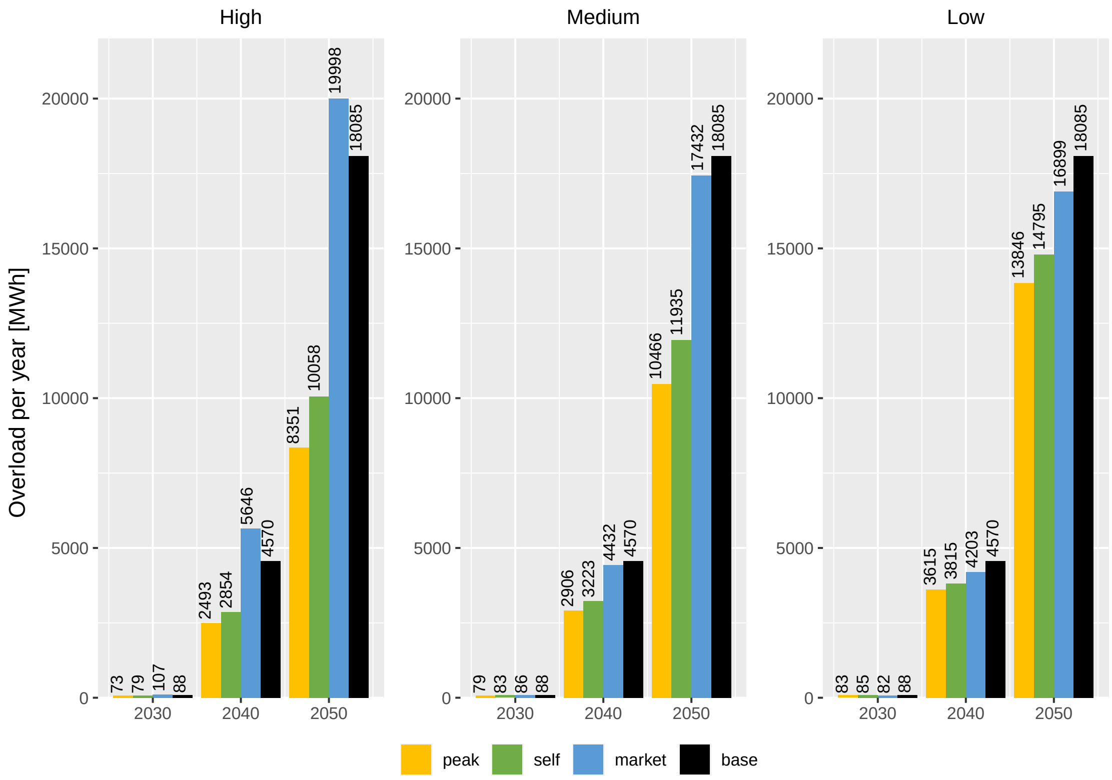


Figure E.6: Change in annual overload size of the selected station with the emergence of residential batteries in different controls and scenarios