The effect of battery storage on local residential distribution grid

How can batteries help reducing peak loads on low voltage residential electricity grids

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Summary

Electrification is an impactful consequence of to goal to reduce carbon emissions. In the household environment this entails electric cooking, heating with electric heat pumps, charging electric vehicles and the installation of solar PV installations. All these processes put a bigger claim on the electric grid houses are connected to. These new appliances have a higher peak power draw than current situations. Moreover, the new peaks are also highly likely to occur in different houses at the same time. This combined results in the power use of residential neighbourhoods becoming more volatile and with higher total peak power loads. The Low Voltage (LV) electricity grid is faced with a big challenge and must be expanded in many places in a short period of time to facilitate the above mentioned part of the energy transition

Distribution System Operators, or DSO's, are responsible for the maintenance and expansions of the LV grid. In order for the existing LV grids to be able to deal with the increase in peak loads, a DSO can choose to increase the capacity by replacing cables and transformers by new ones with a higher capacity. This is a costly and time consuming process. Furthermore, due to labour shortage it is simply not possible to do all the needed work at all the necessary places at the same time. Therefore, DSO's are also looking into the possibilities of flexibility as a way to facilitate the higher demand and more peak loads with less need to upgrade the existing infrastructure. Batteries are a type of flexibility that have the potential to reduce peak loads.

This research is focussed on the effect of battery storage on LV grids. For a DSO to be able to effectively deploy battery storage, they need to know the potential, and what possible preconditions for a successfully deployment. In this study two scenarios with different storage types are compared in a simulation to a baseline without storage. One scenario has a number of home batteries, and the other has a single neighbourhood battery. To be able to arrive at representative conclusions while dealing with limitation in computational capacity, the Netherlands is divided into several archetypical neighbourhoods based on a classification based on characteristics of the build environment combined with demographic data. Real existing LV grids samples from these different are sampled from the archetypes are then used for simulation. This makes that the differences in the effect of battery storage between different geographic areas can be discovered based on a real world examples.

The results showed that loads on the grids in different geographic areas are indeed quite different. In neighbourhoods with many detached houses or terraced houses the solar production peak is much higher compared to areas with a higher share of tenements and apartment complexes. This limits the potential peak reduction of the battery storage as the solar peaks are too high for available battery sizes.
The results also showed that the deployment of distributed home batteries in 30 percent of the connected houses have a much smaller potential impact on peak reduction than using a single neighbourhood battery with the same combined capacity. This is based on the home batteries being controlled by a simple self consumption optimisation algorithm. This type of control is shown insufficient for peak power reducing on a grid level. The neighbourhood battery had a higher impact on total peak reduction due to a forecast based and centralized control. However, the results show the the neighbourhood battery has an impact of 20 percent in the best case. A reduction of this magnitude still will not free up enough capacity on a single LV grid that the impact would be great.
Concluding from this study, home batteries with basic controls have proven to be insufficient for peak reducing on a grid scale. More advanced controls and regulatory requirements are needed for this to start to have a significant effect. Neighbourhood batteries on the other hand can result in a reliable peak power reduction between 10 and 20 percent. However, it is doubted that this reduction is significant enough for the DSO to be able defer, cancel or reduce expansion. Additionally, the potential reduction is the most meaningful in areas without the presence of a dominant solar peak.

Introduction

1.1 Relevance of research

In the effort to reduce climate change, the reduction of the emission of greenhouse gasses is the most important challenge. The Dutch government set itself the goal of 55 percent reduction of CO_2 emission by 2030. An important way of achieving this reduction is the increase of renewable electricity and the electrification of previously non-electric processes and activities. This results in a higher electricity use, expected to be 66 percent higher in 2030 than it is now (TNO, 2022; CBS Statline, 2022). A significant part of that reduction has to come from the build environment, especially in residences.

In private residences all activities have to be adapted to avoid emitting CO_2, and electrification is a major solution. All processes from heating and cooling, cooking and also driving are heading to electric, combined with local solar generation. This results in a large increase of the electricity consumption of Dutch homes. Not only is the total energy consumption about to increase, these new electric applications have a high simultaneity in their energy use. This means that different energy consumers in an area use energy at the same time. This results in power peaks in periods of the day with high use, and periods with lower use. These periods of high peak demand, and also supply by PV installations, will increase with the adoption of heat pumps, EV's and solar generation, due to their simultaneous use of the grid (Phase to Phase BV, 2012).

Electricity is distributed to all homes and small businesses via the low-voltage (LV) grid. This is the last step in the multiple layers of the electricity grid and form the arteries of the grid. The LV grid is also the most extensive grid, with cables under most of the side walks and multiple transformer stations in each neighbourhood. This infrastructure now has to deal with more and more simultaneous energy use than before. The electricity grid is required to be able to supply the peak loads, thus the expected peak load is normative for the capacity of a grid section. With increased peak loads, parts of the grid could currently lack the capacity to supply enough power during those peak hours. Therefore, if nothing else is done, the capacity of the LV grid needs to be expanded. Netbeheer Nederland (2021) expects 30 percent of all the LV cables requiring replacing or upgrading before 2050.

In the Netherlands the responsibility for this part of the grid is with in total six Distribution System Operators (DSO's). The DSO is as the owner responsible for the maintenance and expansion of it's network to be able to facilitate the energy supply and demand of its customers. The challenge of upgrading 30 percent of all cables is an immense task that has many limitations. Time, money and labour are a few of them. Also to replace all those cables streets have to be dug open, which is a disruptive activity. Therefore DSO's are also looking for more effective methods increase the effective use the of existing infrastructure. The strategy for this is flexibility. This is a collective term for all technologies used to shift load and supply away from peak moments, reducing bottlenecks on physical infrastructure. This facilitates the transport of more power with the same infrastructure, just by shifting the timing of the supply and demand. An example is shown in Figure 1.1, where the maximum, peak load is reduced in that case with a battery. Batteries are a promising technology for this purpose (Netbeheer Nederland, 2021). They can discharge during high demand and charge during periods of high generation, thus shifting loads away from peak moments which can eliminate the need for new cables of transformers. On a large scale at large solar farms this is already in place, but the possibilities on LV grids are yet to be fully discovered. To maximise the capabilities of batteries as a tool to make more efficient use of the existing LV grid more knowledge is needed on how to implement this in the thinking and methodology of DSO's.

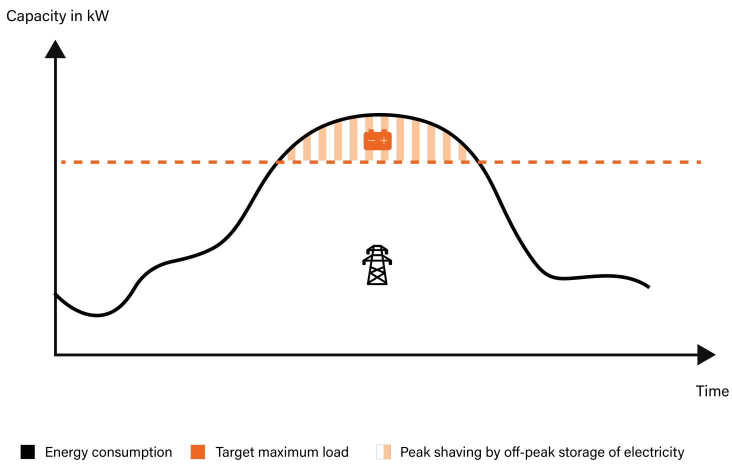


Figure 1.1: Example of peak shaving (Intilion AG, n.d.)

1.2 Problem definition

Flexibility can be used as way to reduce peaks in power consumption and generation on the grid by shifting consumption or generation away from high load times. This principle can be used with different techniques and on different parts of the grid. Battery storage is an example of this, but also simply delaying energy consumption to a moment without peak conditions fits this strategy. Flexibility is recognized as an important part of our future energy system (TenneT TSO B.V., 2022), and is studied from a number of perspectives. For DSO's to utilise flexibility in their grids as a measure to reduce peak power levels, they need to be informed about the circumstances it can be used in and the potential it can have. Studies on the topic of flexibility and storage often have a focus on how the potential of flexibility could have an impact on a national scale (Netbeheer Nederland, 2021; Jongsma, van Cappellen, & Vendrik, 2021; Eyer & Corey, 2010). This concerns mostly topics like the choice of power generation facility and the load on transmission lines. The other end of the research spectrum is very focussed on individuals and how the demand and also supply of a single connection can be optimised (Enpuls, 2020; Velik, 2013). Here the focus is on how solar energy can be used in a home more effectively and how peak power on a home power connection can be reduced.

The service area of a DSO is a highly diverse mix of different power users and consumers. Even within the focus of residential neighbourhoods there are different ages of buildings impacting the energy use and different techniques and different guidelines used when the grid was laid out at that moment in time. This makes the decision to use a certain new development, as in this case is battery storage, a very case-by-case process due to the many differences. To generalise this, insights in the relation between the impact of battery storage and characteristics of the area are needed. Additionally, the relation between different types and layouts of storage and its potential impact on peak power reduction are required to find out if the benefit is worth it. Liander as DSO is doing exploratory studies to assess the possible effect of using batteries in. When used effectively, this can help prolong the useful life of existing infrastructure subject to an increase in power generation and consumption. This way investments in existing infrastructure can be deferred. For this knowledge to be applicable in the context and workflow of Liander, the research should be based on the context and workflow of the company.

1.3 Research objective

The main goal of this research is to look into the possible effects of using battery storage on capacity problems on low-voltage grids. This leads to the following main research question:

To what extend can battery storage reduce peak power levels on the low-voltage grids in residential areas?

From this main question, the following questions are answered:

1. What are applications of battery storage technology suitable for use on the low-voltage grid?
2. How can a low voltage grid be simulated in a representative way?
3. What are the characteristics of the loads in the different geographic areas?
4. In which type of geographic areas can battery storage have the most impact?

1.4 Research outline

The remainder of this report is structured the following way. First, chapter 2 describes a literature study to find battery technologies that are available and suitable to use in an application on the LV-grid. Additionally information about common capacities and control algorithms necessary for following steps are included. This also answers research question 1. The research methodology is presented in chapter 3. Here question 2 is answered, and also the details of the research process are explained. The results of the study are presented in chapter 4, answering question 3. Lastly, the last question is answered in chapters 5 and 6, together with the conclusions and takeaways of the study.

Literature and background

In this chapter a literature study is presented. More details are given about the situation on the electricity grid and current forms of battery storage for grid use. This answers research question 1. Additionally, an introduction is given about the modelling strategy for this research and its background. This is also covers part of research question 2.

2.1 The electricity grid

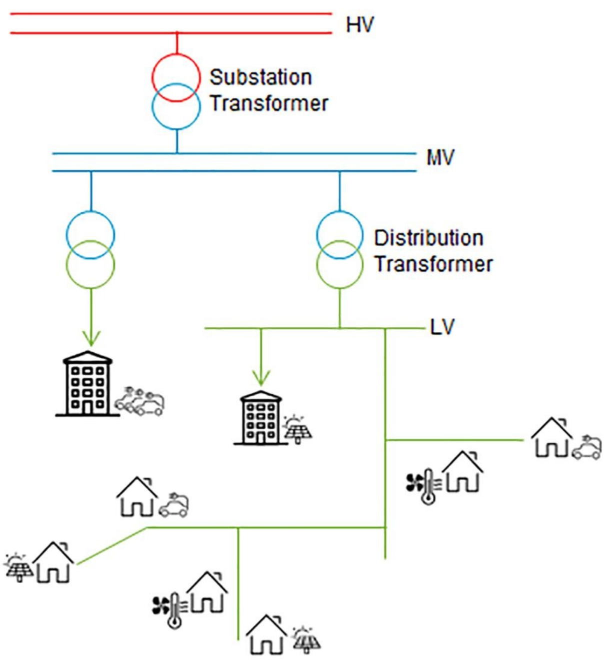


Figure 2.1: Dutch electricity grid structure (van Westering & Hellendoorn, 2020)

The electricity grid is used to transport and distribute electrical energy over a large interconnected area. There are several levels in this grid with each a different voltage level, and also a different role. These layers are connected via transformer stations that step the voltage up or down. An overview can be seen in Figure 2.1. The highest level is the high voltage (HV) grid with a voltage of 220 or 380 kV. This layer is for transportation of electricity over larger distances within and also between countries. It connects different populated areas, central production facilities and very large energy users. The second layer is also high voltage but with a lower voltage of 110 or 150 kV. The role is similar to that of the previous layer, but on a more regional scale. It also connects large production facility, industrial customers and feeds the regional distribution grid. The entire high voltage grid is owned and operated by the TSO (Transmission System Operator). In the Netherlands this is TenneT, which is a state owned company.

The next layer is the medium voltage (MV) grid. This layer is fed by the precious high voltage grid layer. The MV network has a voltage between 6 and 26 kV. This is mostly a distribution grid that distributes the power from the transformer stations over the surrounding area, both in cities and rural areas. The lowest layer is the low voltage network with a voltage of 230 and 400 volt, which is fed from the MV network via transformer stations that are visible in all neighbourhoods (Figure 2.2). From this transformer low voltage feeder cables go through the streets and connect to houses and businesses. A typical residential LV grid consists of up to around 300 houses in urban areas. The MV and LV grids are managed and operated by a DSO, or Distribution System Operator. In the Netherlands there are six of those with each a separate service area. These companies are also owned by local governments. They operate and maintain the LV and MV electricity grids and are also responsible for connecting new customers and investing in the grid if the capacity needs to be upgraded.

Figure 2.2: Typical modern MV-LV distribution transformer

The MV and LV grid levels are historically only used to supply power from central power plants to the end users. This has implication for when the load flow is now also reversing, due to the adoption of rooftop solar generation.

2.2 Battery types and applications

Battery storage is often cited as a major solution for problem related to the electric grid as a result of the decarbonizing the electricity generation. The theory behind this idea is that batteries could be used to smooth out peaks in both supply and demand. On a nation wide scale batteries can be used to reduce the need for fossil fuel powered peak power plants by shifting the power generated by wind and solar to periods without much wind and solar power generation (Chowdhury et al., 2020). This can reduce the total fossil fuel needs. This use is visualized in Figure 2.3. On lower grid levels batteries can be used to expand the capabilities of existing infrastructure by reducing peak loads (Sidhu, Pollitt, & Anaya, 2018). Here the main focus of reducing the peaks is not necessarily the reduction in emissions or fuel use, but that with the lower peaks the infrastructure, e.g. cables and transformers, can be used more efficiently. An example of this application is shown by Enpuls (2020) where a battery is used to facilitate a solar farm on a connection to the grid with a lower capacity than the peak solar generation. This saves cost

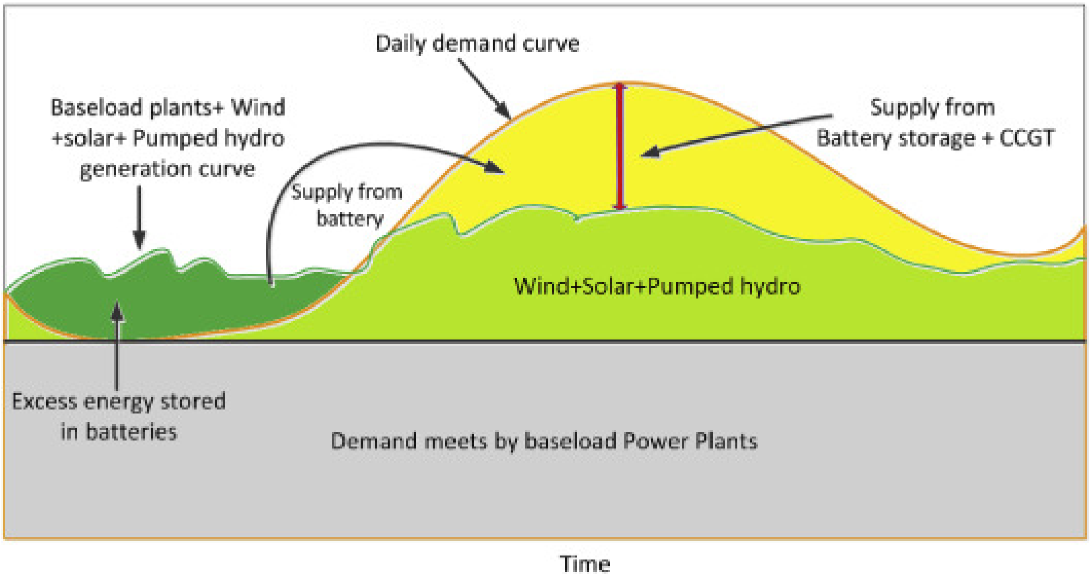


Figure 2.3: Battery deployment for load shifting (Chowdhury et al., 2020)

on the smaller connection, while also making the solar power available after the sun has set.
Van Cappellen (2022) mention that home batteries could be used to reduced the need to upgrade parts of the grid. They do however acknowledge that this effect is very conditional. A suitable structure and strategy is not mentioned.

A subset of batteries for grid use are home batteries. It is a battery installed behind the meter of a single house or other building. This is the type of battery that can have an effect on loads on low voltage grids. They are often only installed if the property also has it's own generation, mostly solar panels. The use cases here are similar as on a grid scale as described above, however, there is different use case and often the main driver in the adoption of home batteries. This is highly dependant on the tariffs for electricity that apply in the local area. The main use consists of the increase of local use of the locally generated electricity with the goal of reducing costs. This means the battery charges with the energy that would be exported to the grid, and discharges to prevent energy from being imported from the grid. This is limited by the power and total energy the battery can provide. Currently in the Netherlands there is no incentive to install such a battery other than personal interest or sustainability aspirations. This is because of the 'salderingsregeling' or net metering scheme which means that over a period of a year the total exported energy is subtracted from the total imported energy and only the difference is billed, effectively using the grid as a battery for the end user. The financial return of the battery in this situation is dependant on the difference between the normal electricity rate and the feed-in tariff.

A different use of batteries is not using it to increase PV self consumption, but to use the battery to make use of dynamic energy tariffs or general electricity markets. Energy prices are constantly fluctuating. Batteries can be used to profit from this mechanism by charging the battery with cheaper electricity and later discharging when the price is higher. For home batteries this is not a way that they are used often, due to a high number of cycles on the battery, and limited accessibility to day-ahead electricity markets. Beside those limitations the potential return is much higher in areas without net metering. Common sizes for home batteries available are storage sizes of 4 to 12 kWh, with a power between 2 and 5 kW. The way these batteries are controlled is also mostly based on amount of imported or exported energy at the meter. Studies about home batteries are very focussed on the individual. Those are about the sizing of storage capacity and the optimisation of self consumption of solar power. The bigger picture of grid effects are often not included in these The optimal size of the storage is related to the amount of daily generated power and the daily used power, and these relations are well studied (Ru, Kleissl, & Martinez, 2013; Velik, 2013; Mulder, Ridder, & Six, 2010; Leadbetter & Swan, 2012). To increase self consumption only 0.6 times the daily demand in storage size is economically an optimum, with after that the added benefits do not substantially increase when the storage size is increased up to 1 or more times the average daily demand. This is very much based on optimizing for the end-user, and not for the electricity grid as a whole. That is also not there reason these batteries are deployed.

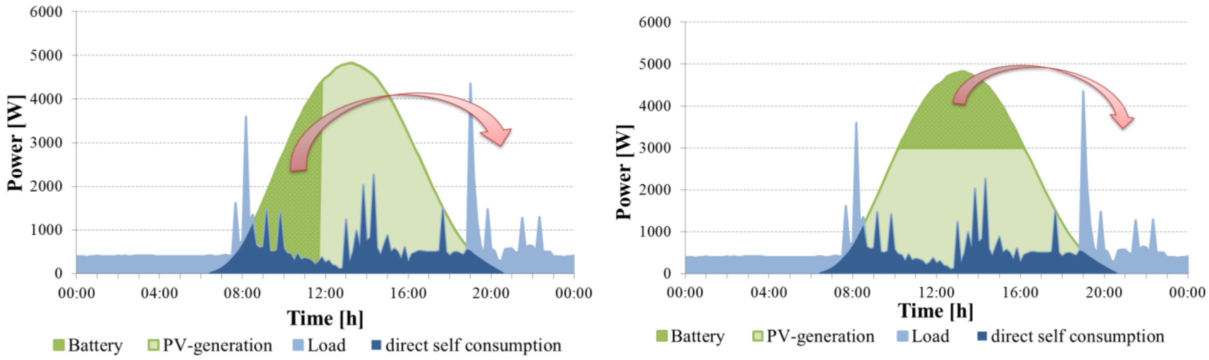
2.3 Effect on grid

The research found does not have a focus on how DSO's should evaluate and work with the potential benefits of grid storage. For example, Santos, Moura, and de Almeida (2014) did a quite extensive study into some larger scale implementation of house batteries in an area, but how those results, which are presented in the form of a percentage reduction in peak power, can be translated into actions in the physical infrastructure is not studied. They did look into the effect of the use of grid storage as a function of the storage role, the way that determines if and how the storage is charged or used. This is important to know as those roles can sometimes be conflicting. The grid effect as stated by the authors was viewed from a national perspective. So the total peak load reduction of a group of dwellings is the metric used for this. However, this looks over the limitations of the grid itself, especially the distribution grid. To have the stated effect on a national level, the solution and strategy might ask too much from the intermediary grid sections, especially on low voltage. The study did not include this effect. The effect of this study are therefore more from an energy perspective, and not the power perspective. The latter is what the grid should be capable of.

Other studies state that the peak power use of individual household can decrease when deploying a home battery. However, this is not necessarily the case is and also very dependant on control algorithm of the battery (Moshövel (Struth) et al., 2013). The main deployment goal of a home battery is to increase the self consumption of solar energy. This does not reliably reduce peak power, sometime only as a side effect of another strategy. This can be seen in Figure 2.4a. When using a different control strategy the grid effect can be much larger, but this comes with a reduction in self consumption, thus in profitability. A different control strategy compared to the previous one can be seen in Figure 2.4b. Here the same energy is stored, but the charging is timed differently resulting in a lower power peak.

2.4 Modelling tool

As this research focusses on the effect of batteries on a single LV grid, the number of connections to a single grid is low, around 150 to 250 individual connections. This number is very low to used deterministic models for loads and generation. The behaviour of a single, or low numbers of households in terms of power use is very difficult to approximate and predict using deterministic models. The spread and the number of impacting factors is very large. For this reason the load generation model used in this study is a stochastic model. This model is developed within Liander to make better load forecasts for low voltage networks. The strategy of this model is based around sampling. In each sample a household load profile is randomly picked for every connection. This selection is done from a database of measure household



(a) Self consumption optimized

(b) Grid optimized

Figure 2.4: Two different home battery control strategies (Moshövel (Struth) et al., 2013)

load profiles collected using the smart meters, resulting is representative profiles for actual households. For the adoption of PV, heat pumps and electric vehicles profiles are also sample from a database with measured real world profiles from these technologies. This sampling is performed for every connection, after which a load flow calculation is performed. This process is then repeated 30 times to capture the variability in the loads on the grid. The output from the 30 samples can than be processed depending of the desired use. For example, the most extreme sample could be normative for the most extreme and adverse high load scenario. On the other hand based on the 30 data points an estimation could also be made for which load scenario is the most likely. This gives a lot more information and use than a deterministic model in these situations with a low number of connections. The exact approach and integration of the battery scenarios into this model framework is described in more detail in the methods section.

Methodology

In this chapter the methodology for this research is presented, and also research question 2 is answered. Summarized, the methods for the research consists of running simulations to compare two different situations with battery storage with a baseline to see potential differences. To be able generalise between geographic areas, each scenario is simulated on a total of 15 different existing individual low voltage grids. These grids are categorised in three groups based on characteristics of the local buildings and its inhabitants. This way an attempt is made to generalise the potential of battery storage based on characteristics of the local grid. For the simulation a tool from within the organisation of Liander is used, which also provides the loads on the grid that are used. This tool is then adapted to fit the goal of this study. This makes sure that the results can be reproduced and used within the context of Liander.
In the next section a more in depth explanation is given on the different parts of this method.

3.1 Neighbourhood archetypes

One of the research questions is to find geographical differences in the effect of battery storage. To be able to generalise the results to use for a larger set of LV grids, this cannot be a case study were just a few distribution grids are used. On the other side, modelling a large number of grids is infeasible due to long computation times. A characterisation of typical grid situations in differen geographic areas is needed to limit the number of necessary calculations while still being able to generalise the results. To address this issue an existing method is used to characterise low voltage grids based on common characteristics. GO-E, a consortium researching options for flexibility on the grid as an alternative for grid reinforcements in the build environment, devised 8 neighbourhood archetypes to discriminate between neighbourhoods on a higher level (TNO, n.d.). This is based on characteristics of the buildings and also of demographics. This is clustered in 8 categories. These archetypes are adopted here to use for the same purpose.
From the eight archetypes three are selected to model in this study due to time constraints in the modelling process. The three selected are post-war terraces houses, post-war tenements and detached houses. This selection is made based on the relative share of electricity connections in the service area of Liander, see Figure 3.1. The largest number of total connections falls within these categories, that is 41, 15 and 17 percent respectively. This makes the results applicable to the largest group of neighbourhoods. For each archetype 5 grids are selected and modelled for this research making it possible to generalise between different types of residential neighbourhoods. These five grids for each archetype are regarded representative for the archetype and are picked from the corresponding neighbourhoods. This selection is also spread geographically, the five grids are located in all geographic areas covering the Liander service area to also capture influences from regional differences.

3.2 Modelling

For this research the main focus is to look into the effect of the use of different types of battery storage on the low-voltage grid level. For this first a model is developed to do grid calculations that can handle the implementation of storage in that model. This consists of a grid model, the loads on that grid and the integration of the batteries into the model as a whole. These parts are discussed separately in the next sections. The basis for this is the tool DELVI (Decision Enabler on Low Voltage Impact) internally developed within Liander with the goal of simulating the impact of increasing loads specifically on the low voltage grid, as before this methods to quantify this problem were not available. This tool is programmed in R, therefore making it relatively easy to adapt it for the purpose of the research.

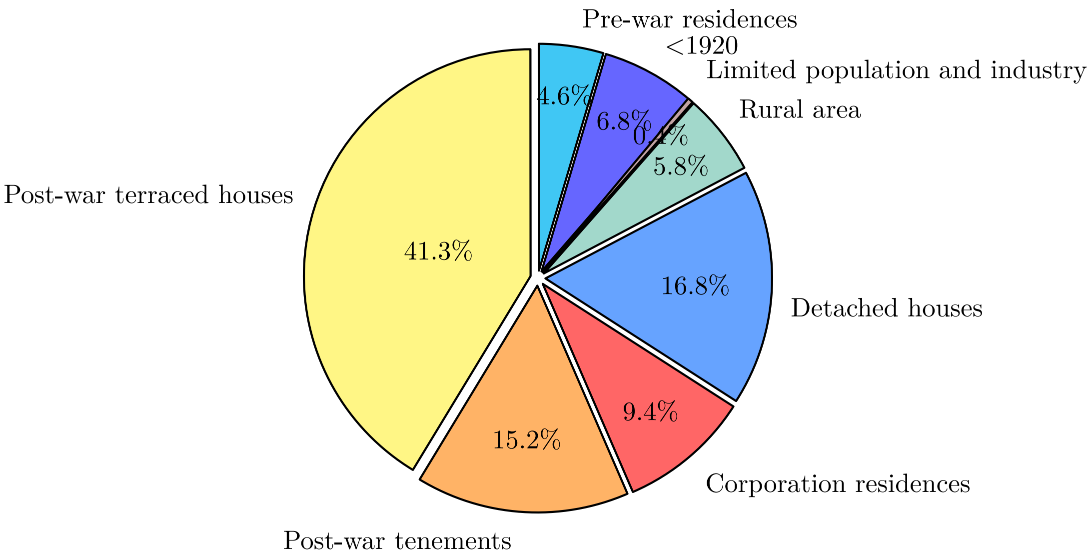


Figure 3.1: Distribution of archetypes by number of connections in Liander service area

Additionally, it is already equipped with load generation and load flow calculation already integrates within the same interface.

3.2.1 Grid model

The grid model is the part of the model that carries the information about the physical infrastructure that is modelled. The data used in this study is the actual grid layout of 15 existing grids. In 3.1 more details are presented about the selection of this number of grids. The data is stored in the Liander internal databases in the form of points and nodes (Figure 3.3) with coupled geographic information, as well as the physical and electrical properties of the element e.g. cable diameter and transformer capacity. This data is pulled by the model to perform the load flow calculations. Data about the number, average yearly consumption and type of connections on a specific LV grid are also used for the load generation part described below. An overview of the structure of such grid networks can be found in Figure 3.3. The grid extends from the distribution transformer via main cables to which houses are connected via a connecting cable. A single transformer feeds multiple main LV distribution cables.

3.2.2 Grid loads

In the simulation a time frame of 15 weeks spread over a year with a time stem of one hour is used. This results in a input for the load of 2520 data points. For all connection on a grid a load profile with this length is generated and used for the load flow calculation. The load generation of the tool used works in a stochastic way. The generated profile is based on a household baseload, and sampled loads for the new technologies heat pumps, electric vehicles and solar PV. The choice for using these three new technologies besides the base household load is made implicitly within Liander. These are the main topics of which they estimate the highest effect on household loads. Therefore these three load types are included in the

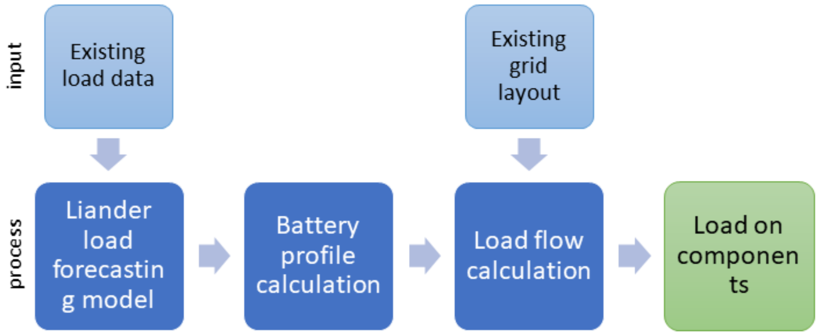


Figure 3.2: Modelling process visualisation

internal load forecast. Other developments such as electric cooking are not included here as their impact is estimated to be of less significance.
The household baseload is based on the current consumption data that Liander already has available by readings from smart electricity meters. This a single value with the annual consumption for every connection. To generate an hour based profile, profiles are sampled from sample profiles produced by clustering measured consumption. This represents the current state of the grids. The loads resulting from the EV, WP and PV are based on adoption and distribution models developed within Liander. That is the method used to estimate the impact and physical distribution of certain new types of loads on the grid. These models are integrated in DELVI to estimate the adoption of these technologies with a adoption chance for the year 2030 in each sample. In each model run every household is assigned the adoption of one of the three technologies based on the assigned adoption chance. When a household is assigned a certain technology in a model sample, a load profile is selected from a dataset of sample profiles for that specific technology. The total household load is then generated by the sum of the baseload profile and the selected profiles for EV, WP and PV. This combined profile is also generated for all the other connections in the grid, and then the load flow calculation can be performed with all the profiles as input. As the load generation is stochastic, this process of profile selection based on adoption is performed 30 times. The highest value of the load flow calculation on the transformer is then normative for the needed capacity.

3.2.3 Battery integration

The above two section describe how the model is set up to use a grid structure, generate load and perform a load flow calculation. That is the basis for this study, and that is the starting point for the modelling by representing the baseline. Two battery scenarios are added to this framework to introduce the effect of storage in the grids. This is done by intercepting the models input for the load flow generation, so the generated profiles for each connection, and use this information to generate a battery profile, as visible in Figure 3.2. The battery profile is added to the original household profile, and the resulting profile is used as normal for the load flow calculation. Now the exact working for the two scenarios are described in the next sections, and a graphic representing these two scenarios is visible in Figure 3.5.

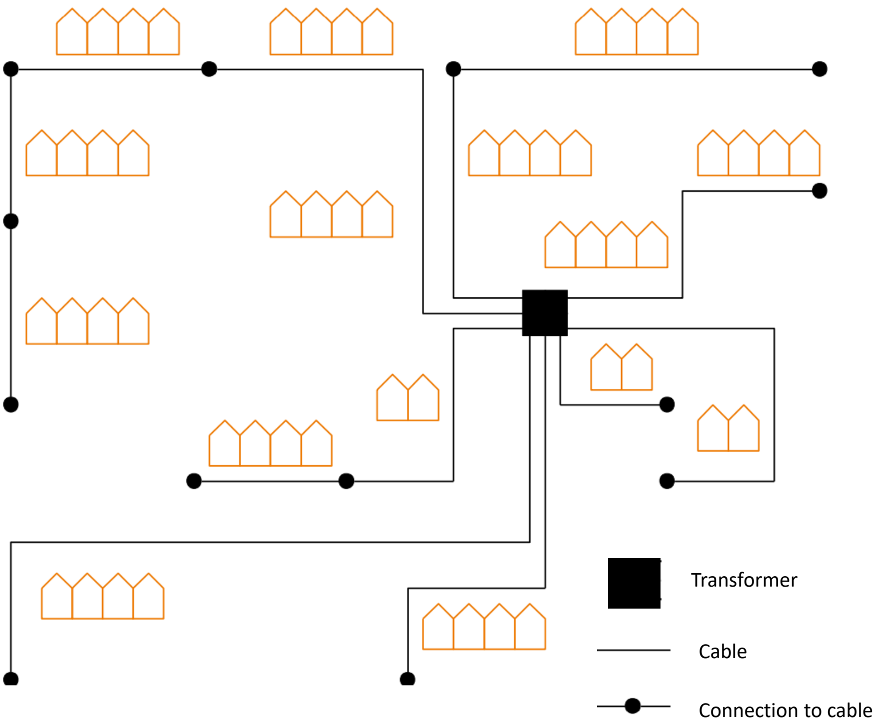


Figure 3.3: Schematic of LV grid

Base home batteries

The first battery scenario besides the baseline is one with home batteries. This is based on a penetration rate of 30 percent of the connections. This number is based on projections of Liander about the expected adoption of home batteries in their service area. In their growth model the high scenario assumes around 20 percent penetration of home batteries in 2030 by PV owners. This number is rounded up to 30 percent of all households to come to an estimation that is higher than expectation, but not totally unrealistic. Results based on this give therefore a best case scenario that is not autonomously achieved.
The premise of this battery scenario is that it is a base home battery case. This means that the control strategy of the individual batteries is based on how standard home batteries operate out of the box. The goal of the control algorithm is to maximise the self consumption of generated solar power. This is achieved by feeding all generated solar power that would be exported into the battery until it is fully charged, and take all consumption first from the battery until it is empty, as in the expression below.

$$P_{battery} = -P_{house}$$

when

$$|P_{battery}| < P_{max}$$

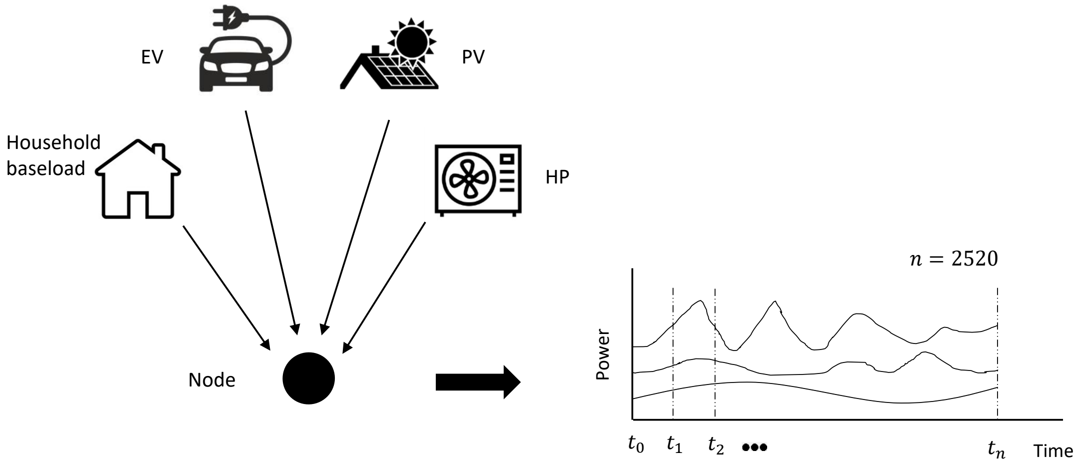


Figure 3.4: Schematic of input variables for load generation

$$E_{battery} < E_{max}$$
$$E_{battery} > 0$$

That formula holds when the battery is not empty when discharging or full when charging. This result in the battery controller trying to keep the net power at the electricity meter at zero. This strategy is for consumers the best choice financially in a situation where a lower tariff applies to exported energy than for imported energy. That exact discrepancy would motivate consumers to invest in a home battery in the first place, so this control strategy is chosen here to represent this base behaviour. The load profile of a household with this strategy is illustrated in Figure 3.6. The blue line represents the hourly power demand of a household. The red is the same profile, but with a battery that operates to optimise self consumption.

Besides the control of the batteries, the size also impacts the effect, both on the level of the connections as well as on a grid scale. According to multiple studies an optimal storage size exists from a financial perspective. In other words, investing in large battery faces diminishing returns, so an optimum battery size exists. This optimum is depending on the study around 0.7 times the average daily power consumption. This means that that investment is recovered in the shortest amount of time. This is in this battery scenario the way the sizes of the batteries on the grid are determined, trying to represent the rational purchasing behaviour of consumers. In the model the size of battery is for every sample run calculated again for the connection it corresponds to. The

Based on the profile of 2520 hourly power values the total yearly energy use is calculated. From this a daily average is calculated, which is used to define the battery size for each connection as 0.7 times the daily average energy use. The value is rounded to the nearest integral, and also a minimum capacity of 4 kWh is set to prevent very small batteries in the model that are not even available.

$$E_{year} = \frac{2520}{8760} \cdot \sum_{t=1}^{2520} (P_t * \Delta t)$$

$$E_{battery} = 0.7 \cdot \frac{E_{year}}{365}$$

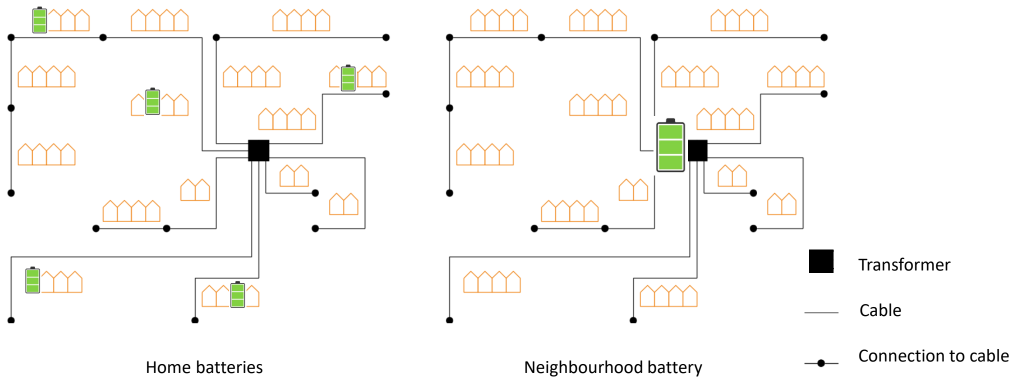


Figure 3.5: Overview of two battery scenarios

The capacity of the battery is determined as stated above. The maximum power is sampled randomly from a value between 3 and 6 kW, and rounded to the nearest integral. This is done to include differences from consumer behaviour and differences between manufacturers. In the modelling the batteries are assumed to have all the capacity assigned to it available for use and also a 100% round trip efficiency.

Battery at distribution transformer

The next use case that is evaluated is with a battery at the distribution transformer. Here the storage is more centralised, with one larger battery in a central location. This variant is compared with the two de-central storage options to see a possible difference in the effect.
The power and capacity of the battery in this use case is based on the largest battery system available that fits in a standard 10 foot shipping container. This is the most likely to be used in such a setting due to it's transportability and ability to be integrated in tight existing situations. This results in a power of 250 kW and a capacity of 400 kWh (Alfen, 2023). This capacity is similar to the average total installed capacity in the home battery scenario, so the battery characterics are similar between the two scenarios, aside from minor differences. The use case consists of a battery placed at the transformer and also connected on the secondary, low voltage side.
The control of the battery in this scenario is based on peak shaving based on a load forecast. The load on the transformer is expected to be forecasted with perfect accuracy for this study. This means that the controller can anticipate on a high peak demand by having the battery full before the peak to have maximal reducing impact on that peak. The algorithm is visualised in Figure 3.7 The algorithm searches first for the highest absolute power value P_{max}. Then in the next step the limit of maximum power is lowered with a fixed step ΔP. The battery power is then the difference between P_{max} and $P_{max} + \Delta P$. The stored energy is represented by the area between the lowered max power line and the power profile. In the example this is$E_{batt,c}$ or charged energy. Then is checked if the preconditions are still met:

$$E_{batt,c} < E_{batt,max}$$

$$P_{batt} < P_{batt,max}$$

This makes sure the capacity and power rating of the battery are not exceeded. The next step is to check if the energy that is in the example stored in the battery can be discharged without exceeding the new

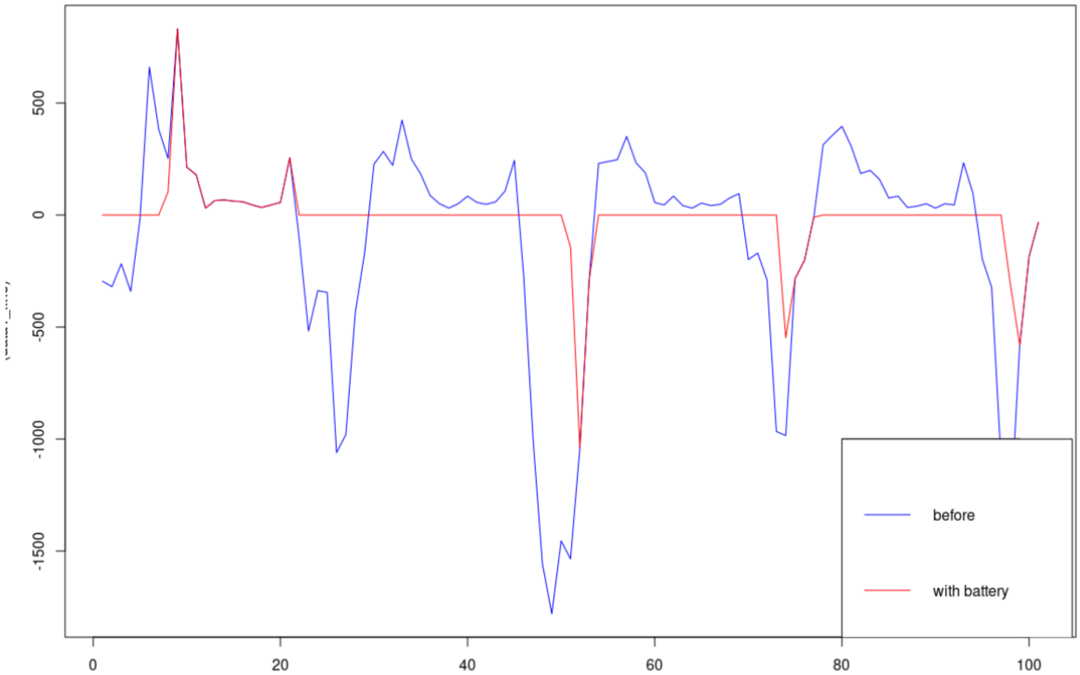


Figure 3.6: Profile of household with self consumption optimised home battery

lower max power$P_{max} + \Delta P$. So $E_{batt,c} = E_{batt,d}$. If $E_{batt,d}$ can fit in the time the battery is not lowering the peak, so if $E_{batt,d} < E_{spare}$ the battery can be discharged on time again for the next cycle. These steps are repeated by lowering P_{max} with more, e.g. n times ΔP. At some point the conditions are not met any more, at which point te calculation stops and the maximum peak reduction is reached. This is the case if one of the next conditions happen:

- $P_{batt} > P_{batt,max}$
- $E_{batt,c} > E_{batt,max}$
- $E_{batt,d} > E_{spare}$

For a positive peak the same process still holds, but all in opposite direction.

3.2.4 Model output

After the model is build as described, it returns the loads on the elements of the selected grid for all 30 samples. The power level at the distribution transformer is picked as indicative for the general effect on the grid, so no cable loads are included in the conclusions. A single value for every grid is calculated by taking both the 95th and the 5th percentile of the 30 power values from the 30 samples. This gives then a lowest and a highest value, for supplied and demand power respectively. The percentile are used to smooth out extreme caused by the stochastic model. Because of that model simply picking the highest and the lowest values introduced to much variations to give a clear result.

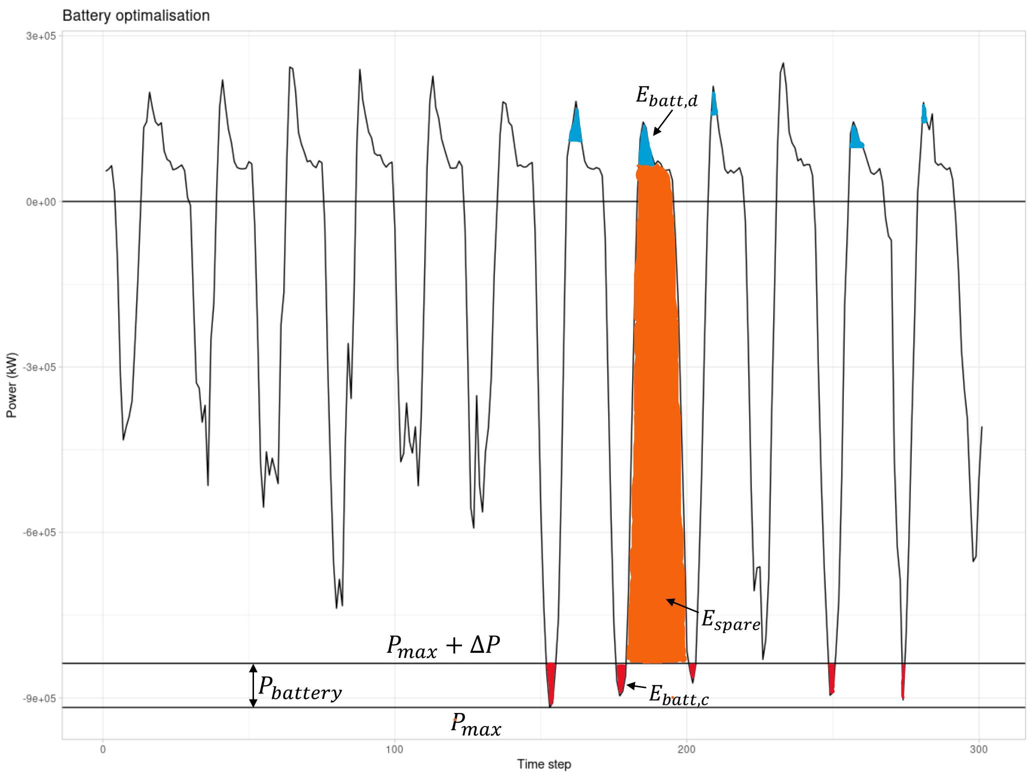


Figure 3.7: Modelling process neighbourhood battery

Results

In this chapter the results of the modelling are presented. This is to answer question 3 and 4. This data is the results of simulating three different use cases of batteries on different low voltage grids, as is described in the methodology section. The resulting data is for each grid the 95 percentile value of the peak power level from the 30 samples in the simulation. This is done to remove outliers caused by the stochastic modelling process. Visualised are the peak power levels at the distribution transformer for both supply and demand for each of the three use cases. An overview is given in Figure 4.1 for the demand peak and in Figure 4.2 for the supply peak. The division between the three neighbourhood archetypes are also visible in the figure. The raw data can also be found in Table 7.1 in appendix A.

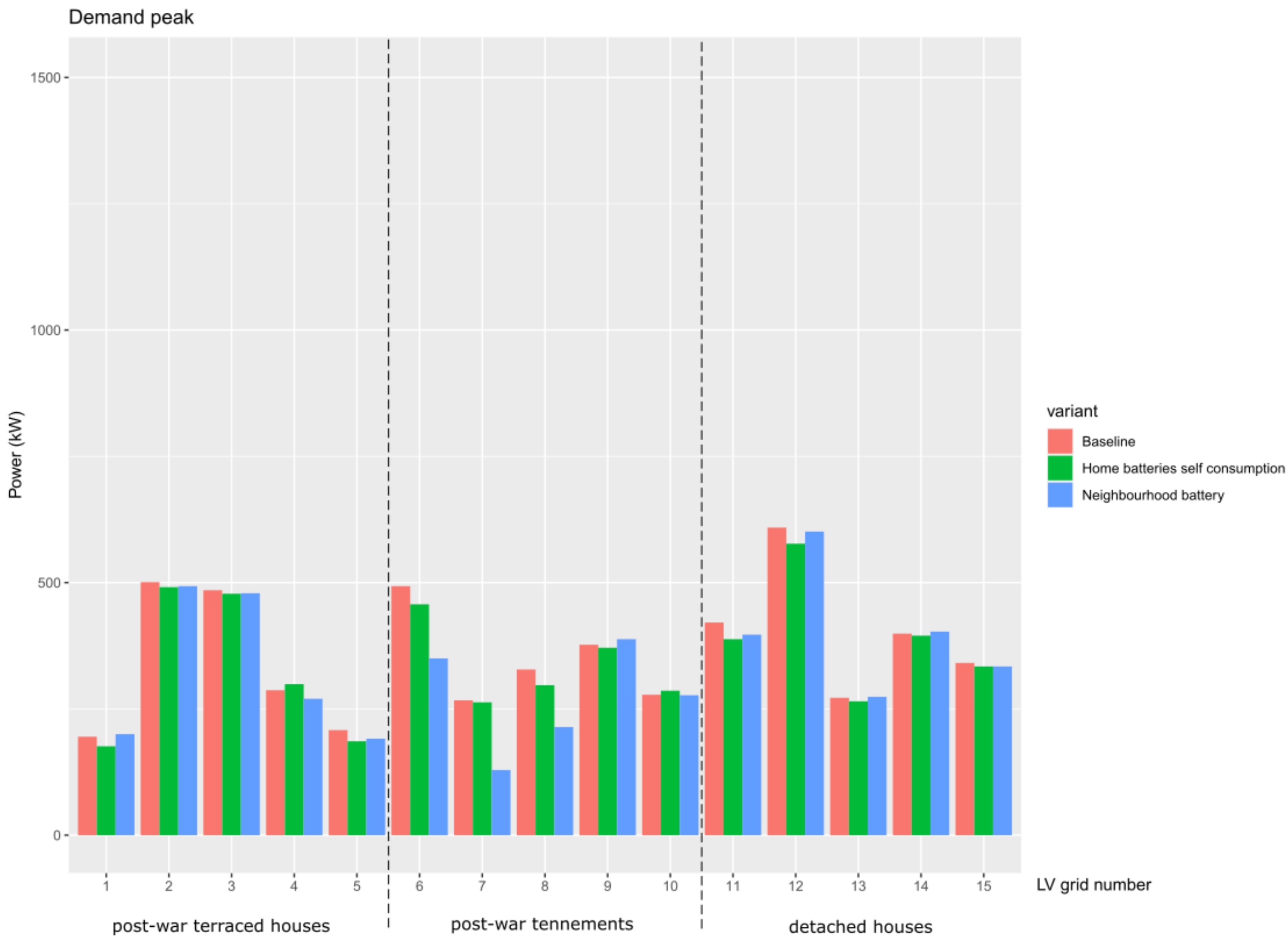


Figure 4.1: Peak demand power levels at transformer for fifteen low voltage grids

First, the results show big differences in the power level for demand and supplied power in the baseline

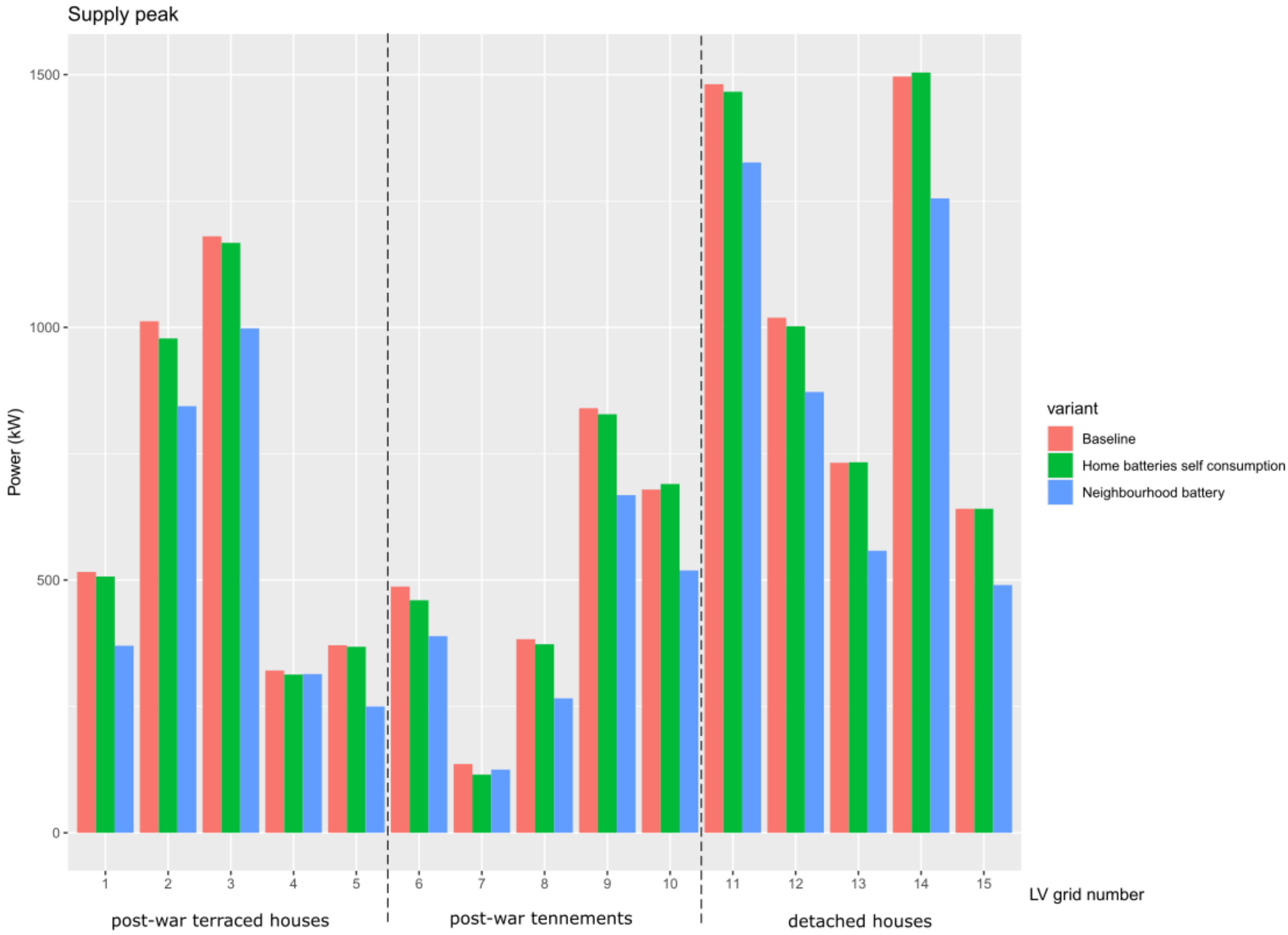


Figure 4.2: Peak supply power levels at transformer for fifteen low voltage grids

scenario, and also throughout the other scenarios. On average the supply peak over the fifteen grids is 2 times higher than the demand peak in the baseline situation. However, for individual grids the difference can be higher, up to 3.5 times the demand peak. This is caused by the growth in installed solar PV systems. The power of such systems are often much higher and of longer duration than regular residential loads. Additionally the simultaneity within a single LV-grid of solar power is very high, meaning that the likelihood of multiple homes supplying high power PV power at the same moment is very high. This is as the meteorological circumstances within the service area of a singe LV-grid are virtually the same. Related to this point are also the differences between the neighbourhood archetypes concerning the magnitude of the supply power peak. It was found that for the post-war tenements this was lower than for the other two studied archetypes. This is also related to the penetration of PV systems in different neighbourhoods. This is lower in the neighbourhoods with tenements, as there is less roof area for each individual home. This results in lower PV production in these neighbourhoods, which is supported by the data.

Looking at the results for the effect of the home batteries, it can be seen that the effect of the 30 percent house batteries on the reduction of peak power levels is very low with around 3 percent on average, for both supply and demand. This results in an absolute reduction of around 10 kW, which on the power levels of a single distribution transformer of between 200 and 600 kW in a typical Dutch residential area is not resulting in any more opportunity to connect more households or use a lower power transformer. Home batteries are often nudged as solution to reduce PV power peaks in the middle of the day, but this effect was not visible in the data. This can be partially explained by the relation between the solar power and the capacity of a battery. For higher power PV system on larger roofs an average sized battery is full before the peak ends. This is a bigger problem the larger the PV systems become. This can be seen when observing a single connection's profile with a home battery (Figure 3.6). The solar peak can only be cancelled out partially. Near the end of the peak, so in the end of the afternoon, the battery is full and the remaining solar power is exported to the grid. This behaviour can be seen throughout all the data points and is caused by the type of battery control algorithm.
This is also supported by the data that shows that the relative peak reduction for supply power in the tenements archetype is at 4.6 percent is a bit higher that that in the other two archetypes with on average 1.1 percent. This is again a results of the lower number of pv systems on a single LV-grid and lower peak power of single PV installations. This indicates that in neighbourhoods of this archetype batteries can be deployed to have a larger impact of reducing peak supply power levels than in other neighbourhood archetypes.

The data indicates a bigger impact of the neighbourhood battery. Here the reduction on the supply power level is between 9 and 20 percent or 31 and 137 kW. This is more significant than for the home batteries. Also when accounted for the total of installed capacity between the home battery and neighbourhood battery scenarios. In the first the total installed capacity is on average around 400 kWh distributed over an average of 260 homes, where for the second the capacity of the neighbourhood battery is of similar size, namely also 400 kWh. This tells that a neighbourhood battery can results in a more effective deployment of the same battery capacity. The utilisation of the neighbourhood battery is also logged during the simulation, and this comes to an average utilisation of 5 percent of the time that the battery is either charging or discharging to achieve the given reductions. The other 95 percent of the time the battery is not needed and sits idle.

Conclusion

This research aimed to explore the effects of two different applications of battery storage on the loads in different low-voltage electricity grids. The results should inform DSO Liander which types and locations of battery storage could help extend the capacity of existing low-voltage infrastructure in certain neighbourhoods. An existing model from Liander was used and adapted to simulate multiple LV-grids based on a stochastic load forecast model for the year 2030. This model is adapted to simulate one scenario home batteries and a scenario with a neighbourhood battery. Different existing LV grids from different geographic areas were simulated to find the effect of adding the batteries and differences between the different cases.

The study showed that for the year 2030, which was the reference year for this study, the most significant peak is in caused by solar production. In most of the simulated grids this was the largest in magnitude, often multiple times the power demand peak. This is then normative for the capacity of the infrastructure. Given the magnitude of this solar peak, no battery with a reasonable capacity can have a significant impact on the total peak power levels. The possible reduction was low on this part for both home batteries and neighbourhood batteries. The latter did show a larger but still not significant reduction. Central control contributed to the advantage of the neighbourhood battery.
The study does also provide new insights in the relation between the possible effectiveness of LV battery deployment and neighbourhood characteristics. In areas with many high power solar installations the resulting power peak is so high that battery solution as modelled cannot provide much reduction, although the neighbourhood battery proved to be more effective than home batteries. The neighbourhood archetypes where this would be the case are detached houses and to a lesser extend post-war terraced houses. The expected PV power levels for 2030 in these areas are much higher than demand power, and batteries cannot reduce this by much. Grid updates are unavoidable in areas with these PV growths. However, in the neighbourhood archetypes of post-war tenements the dominance of PV power is much lower, due to less roof area per house. First there is a larger share of LV grids fitting the archetype that in 2030 have not a expected solar peak higher than the demand peak. This could mean that for grids where the capacity is reaching it's limits, battery could be an option in 2030 to postpone grid updates for some time. If the solar peak is around the same magnitude as the demand peak or less, then the demand peak reduction can help reach an actual effect. Here the effect of the neighbourhood battery is again much higher than for home batteries. This points to a clear geographic component to the possible extend batteries can help reduce the need for LV grid updates.

Overall the reduction found in this study does not provide the ability to extend the capacity of the infrastructure, mainly due to the limited effect. Even the highest reduction of 20 percent or around 100 kW for neighbourhood batteries could only possibly result in postponing upgrades, not reducing the scale of the needed upgrades, for example a smaller transformer. The home batteries had a very low impact overall. The results show that basic home batteries with a control strategy focussed on the increase of self consumption have a very limited effect on reducing peak power levels on LV-grids. Thus home battery deployment does not contribute to the delay of deferral of grid investments for the DSO up to 2030. The control strategy of the batteries in that case is not focussed on reducing peak power use, but only on the maximisation of the self consumption of generated solar power, so only provide benefits for the individual. Only the total energy transported to and from the grid does go down with this battery application, not the peak.

However, there are large differences in the reduction when comparing individual grids, not aggregated into averages. This shows that in specific cases either of the two studied battery solutions could help prevent upgrades. In some individual grids the reductions found was up to 10 percent with home batteries or 50 percent with a neighbourhood battery. This means that the potential of batteries could be unlocked in specific individual cases in certain circumstances, but in general this effect is not there.

Discussion

In this section the limitations of the research are presented. additionally recommendations are made for future research and the implications of the conclusions from this study.

Limitations

The results show a general image of the effect of the application of battery storage in a selection of LV grids. This is modelled using a stochastic approach. That presents a limitation in the model results. A sample size of 30 is used in the model. However, this still caused outliers that impacted the comparability between different scenarios. A 95th percentile interval is used to filter this out, but a larger sample size could be used to improve on this issue.
Another limitation is that this study does not provide insight in the possible progression of the adoption of home batteries or the necessary adoption. A fixed penetration rate for home batteries of 30 percent is used as a very optimistic estimate for the situation in 2030. This tells something about the possibilities at a certain point in time, but not anything about what penetration rate would have more effect. This is not necessarily of practical use, as 30 precent is already on the high side of possibilities.
In this study the total peak load reduction on the distribution transformer caused by using battery storage is used as an indicator for the total effect of battery storage on low voltage grids. This does not take into account possible effects, either positive or negative, on load on low voltage cables. This is left out of this study due to difficulties it would have imposed on the modelling and poor generalisability. It is however an important effect. Not only the transformers are subject to increasing loads, but also cables can be the limiting factor in an LV-grid. This approach taken in this study provides a general idea of the effect of different types of batteries, but for a more complete picture this should be taken into account in future research.
The generalizability of the overall results is mostly limited by the limited number of simulated grids. This selection provides a good insight. However, a much larger selection of modelled grids would provide better insight in the differences between different archetype neighbourhoods and also in the spread of impact with one archetype. However, this is not done due to computation time for the model. Each grid took around 8 hours to complete the simulation for only one scenario. Making a more resource efficient model could help in extending the number of simulated grids. This long computation time also shows that this type of modelling based on stochastic loads on an hourly basis is not practical for large scale modelling, but it does give new insights compared to other methods.
In this study only two different scenarios with batteries are actually modelled. This gives a basic understanding of the behaviour of these applications. However, this is not a definitive dismissal of LV battery storage. There are other types of control possible that could make a better impact on the grid. The setup chosen in this study aimed to outline the basic impact of storage in scenarios that are most likely to occur. Other options should be studied separately to get deeper knowledge about more specific storage applications.
This study also ignored the business case behind all the discussed battery deployments. The approach was to only look at potential effect for the DSO. This give an idea about the potential. However, this is theoretical as it not sure batteries in those applications are economically viable. Home batteries have to be bought by consumers for them to see financial gains, and a neighbourhood battery has to be run by a company that needs the business case to work.

Lastly, one assumption in the assessment of the usefulness of batteries is that no curtailment of solar energy will occur. In the data is shown that the magnitude of peak solar power is much higher in some areas than the peak power consumption. This makes it very hard and unpractical to flatten this solar peak with batteries. As in the current situation the LV grid should be able to deal with the higher power levels, the solar peak is normative for the grid capacity, and the effect of the battery is low. However, in the future changes to legislation might permit solar curtailment. This means that instead of upgrading infrastructure to be able to deal with the high solar peak, during peak times the infeed of solar power is limited at the source. This results in lower solar power peaks. In a situation like this the effects of LV batteries as presented in this study are not the same. The assumption is that in such a case batteries could be more effective, as the solar peak is less dominant. However, this should be studied more in depth to come to a better estimation of this effect.

Recommendations

Expanding on the limitations listed above, the recommendations are mostly about resolving these limitations. The most interesting follow-up research would be to include other battery storage scenarios. The most interesting one after seeing the results of the current setup is to look into home batteries that have a more advanced control algorithm. One that would be interesting to see is an advanced version of optimizing for self consumption based on forecasted load and generation profiles.This can be done based on forecasted demand and generation curves. The battery profile is then such that the self consumption is maximised but the moments of charging and discharging are shifted to minimise grid impact based on the forecasted loads and generation. This can result in the battery not charging for solar the minute energy will be exported, but that that moment is postponed until the moment the battery is forecasted to be full after the generation peak. Studies are conducted into the use and effectiveness of this strategy such as M. E. Gerards, Hurink, and Hübner (2017). This is the only way the business case for the consumer, e.g. the self consumption, is affected the least but while maintaining the lowest grid use. The success of this strategy however is fully dependant on the accuracy of the forecast. Errors is this prediction cause either sub optimal self consumption or higher than necessary grid use. However, Forecasting solar generation is something that can already be done with reasonable accuracy such that the predictions can be used in practise (M. E. T. Gerards & Hurink, 2019).

This strategy looks promising as it aims to combine both a realistic business case for the consumer with a much better grid impact compared to standard home batteries as studied here. This could unlock much more of the potential of the installed batteries compared to the scenario in this study. Therefore knowledge about that difference can help in deploying batteries more efficiently and get to other conditions for a successful battery deployment.

Based on the results of this research DSO's and policy makers can be informed about the potential of batteries on low voltage grids. They can adapt policy based on the knowledge of the limited effect these batteries can have, ideally refraining from presenting batteries as the one solution to solve all grid problems. Furthermore, DSO's can also use this study as a step to look more into the characteristics of situations in which battery storage can have a large peak reducing effect. As the reducing effect is there in certain circumstances, especially for neighbourhood batteries, the application of storage might be used to bridge a gap in time between new connections being made and grid expansions being ready. However, it should be clear that this possibility is circumstantial and very dependant on the specific grid.

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Appendix A - results

	Grid number	Baseline		Home batteries		Neighbourhood battery	
		Demand power	Supply power	Demand power	Supply power	Demand power	Supply power
Post-war terraced houses	1	195	-516	176	-507	200	-370
	2	501	-1012	491	-978	493	-844
	3	485	-1180	478	-1167	479	-998
	4	287	-321	299	-313	270	-314
	5	208	-371	186	-368	191	-250
Post-war tenements	6	493	-487	457	-460	350	-389
	7	267	-136	263	-115	129	-125
	8	328	-383	297	-373	214	-266
	9	377	-840	371	-828	388	-668
	10	278	-679	286	-690	277	-519
Detached houses	11	421	-1481	388	-1466	397	-1326
	12	609	-1019	577	-1002	601	-872
	13	272	-732	265	-733	274	-558
	14	399	-1496	395	-1504	403	-1255
	15	341	-641	334	-641	334	-490

Table 7.1: Model results in kW

	Grid number	Home batteries		Neighbourhood battery	
		Demand power	Supply power	Demand power	Supply power
Post-war terraced houses	1	-19	-9	5	-146
	2	-10	-34	-8	-168
	3	-7	-13	-6	-182
	4	12	-8	-17	-7
	5	-22	-3	-17	-121
	average	-9,2	-13,4	-8,6	-124,8
Post-war tenements	6	-36	-27	-143	-98
	7	-4	-21	-138	-11
	8	-31	-10	-114	-117
	9	-6	-12	11	-172
	10	8	11	-1	-160
	average	-13,8	-11,8	-77	-111,6
Detached houses	11	-33	-15	-24	-155
	12	-32	-17	-8	-147
	13	-7	1	2	-174
	14	-4	8	4	-241
	15	-7	0	-7	-151
	average	-16,6	-4,6	-6,6	-173,6
	Total average	-13,2	-9,9	-30,7	-136,7

Table 7.2: Absolute differences compared to baseline in kW

		Home batteries		Neighbourhood battery	
	Grid number	Demand power	Supply power	Demand power	Supply power
Post-war terraced houses	1	-9,7	-1,7	2,6	-28,3
	2	-2	-3,4	-1,6	-16,6
	3	-1,4	-1,1	-1,2	-15,4
	4	4,2	-2,5	-5,9	-2,2
	5	-10,6	-0,8	-8,2	-32,6
	average	-3,9	-1,9	-2,9	-19,0
Post-war tenements	6	-7,3	-5,5	-29	-20,1
	7	-1,5	-15,4	-51,7	-8,1
	8	-9,5	-2,6	-34,8	-30,5
	9	-1,6	-1,4	2,9	-20,5
	10	2,9	1,6	-0,4	-23,6
	average	-3,4	-4,7	-22,6	-20,6
Detached houses	11	-7,8	-1	-5,7	-10,5
	12	-5,3	-1,7	-1,3	-14,4
	13	-2,6	0,1	0,7	-23,8
	14	-1	0,5	1	-16,1
	15	-2,1	0	-2,1	-23,6
	average	-3,8	-0,4	-1,5	-17,7
	Total average	-3,7	-2,3	-9,0	-19,1

Table 7.3: Relative differences compared to baseline in percent