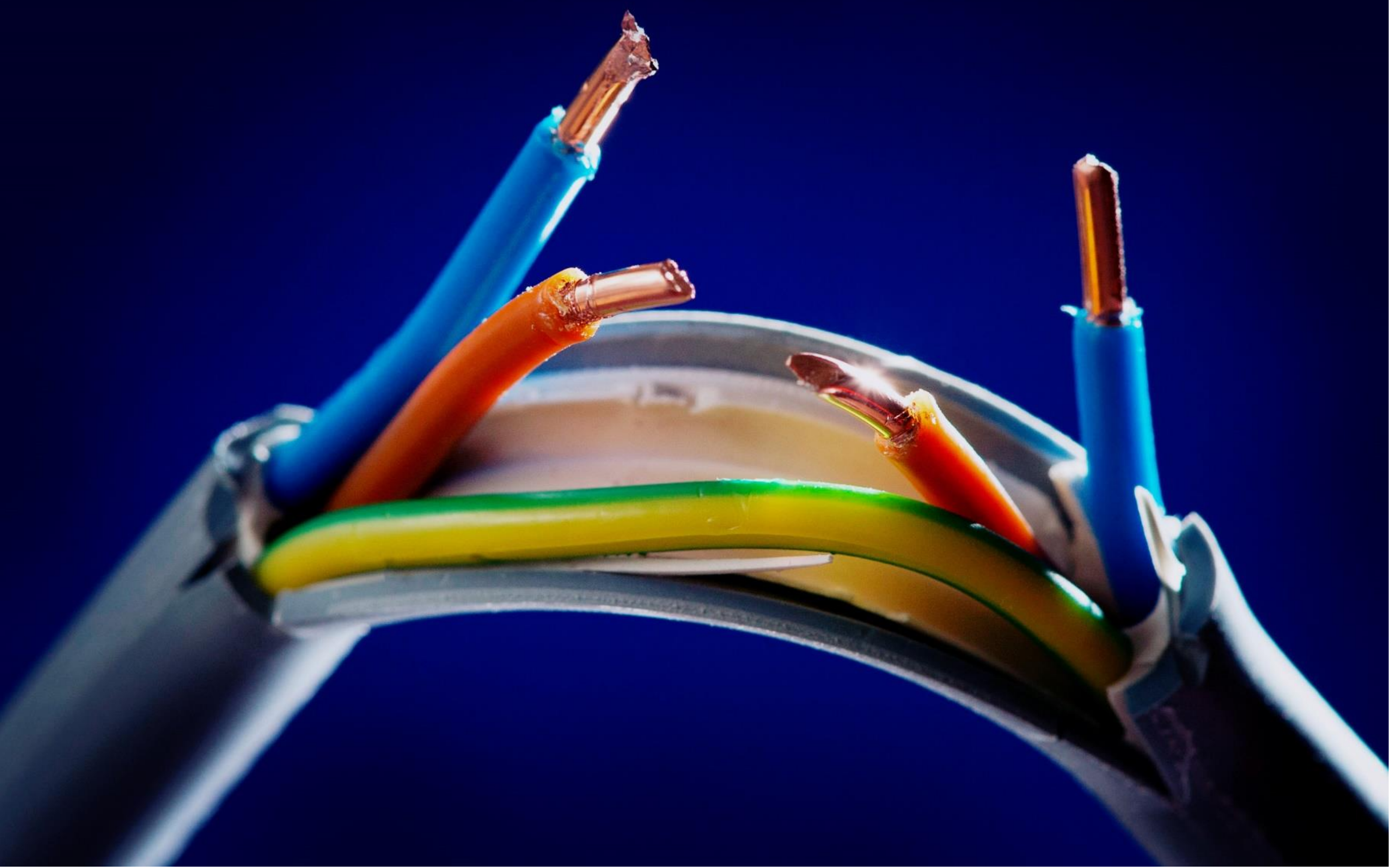
THE DISTRIBUTION SYSTEM OPERATOR AS FLEXIBILITY MANAGER OF DISTRIBUTED ENERGY RESOURCES

A spreadsheet based simulation study on the case of the Netherlands

Bob Goessen



“We have to abandon the conceit that isolated personal actions are going to solve this climate crisis. Our policies have to shift.” — Al Gore

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A spreadsheet based simulation study on the case of the Netherlands

	Author
Name	Bob Goessen
Student number	4021940
Faculty	Technology, Policy & Management, Delft University of Technology
	Graduation Committee
Chairman	Prof. dr. ir. M.P.C. Weijnen dep. Engineering Systems and Services, Faculty of Technology, Policy & Management, Delft University of Technology
First Supervisor	Dr. ir. R.A. Hakvoort dep. Engineering Systems and Services, Faculty of Technology, Policy & Management, Delft University of Technology
Second Supervisor	Dr. ir. C. van Daalen dep. Multi-Actor Systems, Faculty of Technology, Policy & Management, Delft University of Technology
Third Supervisor	C. Eid MSc dep. Engineering Systems and Services, Faculty of Technology, Policy & Management, Delft University of Technology
External Supervisor	Ir. M. Bongaerts Alliander

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Voorwoord

Toen in 2005 Al Gore zijn presentatie hield over 'The Inconvenient Truth' was de gehele wereld in shock. Ondertussen is het meer dan 10 jaar geleden, en zien we langzaam de eerste beleidsmaatregelen genomen worden om klimaatsverandering tegen te gaan. Afgelopen jaar was daar het Klimaatverdrag van Parijs, geratificeerd door bijna alle landen ter wereld, inclusief de V.S. en China. Landen beloven maatregelen te nemen om klimaatverandering tegen gaan en de wereldwijde temperatuurstijging onder de 2 graden Celcius te houden. Een van meest invloedrijke oplossingen is om meer duurzame energie op te wekken. Echter, in Nederland lopen we flink achter met de inpassing van duurzame energieopwekking: In Europa hebben alleen Malta en Luxumburg een lager aandeel duurzame energie in hun totale energieproductie.

Voor mij was het daarom duidelijk, ik wil met mijn scriptie bijdragen aan het inpassen van meer duurzame energieopwekking in Nederland. Mijn onderzoek sluit hier dan ook goed op aan. Nieuwe energie technieken, 'distributed energy resources' in het Engels, kunnen in potentie voor een groot deel bijdragen aan de terugdringing van de Nederlandse CO_2 uitstoot. De inpassing van deze nieuwe energietechnieken vraagt niet alleen om investeringen in de nieuwe energietechnieken zelf, maar ook om investeringen in de infrastructuur. In mijn scriptie heb ik onderzocht of het mogelijk is deze nieuwe energietechnieken aan te sturen, zodat de investeringen in de infrastructuur omlaag kunnen. Het resultaat ligt voor u, en mag u zelf lezen.

Ik wil graag al mijn vrienden, familie, begeleiders en collegas bedanken voor de steun en hulp die ik van jullie de afgelopen maanden heb mogen ontvangen. Graag wil ik netwerkbedrijf Alliander bedanken voor de fantastische bron aan data en informatie die ik heb mogen gebruiken voor mijn scriptie.

In het bijzonder wil ik mijn lieve vriendin Anne bedanken voor het proeflezen van mijn gehele thesis. Dit gaan we vieren met een mooie en welverdiende vakantie.

Summary

Within the Netherlands, house owners set up projects in which all houses within a neighbourhood are collectively renovated and equipped with distributed energy resources (DERs) at the same time. These projects are called 'neighbourhood distributed energy resource projects' (NDPs). As some of the equipped DERs electrify much of the heating previously generated by natural gas, and other equipped DERs produce electricity themselves, the electricity grid experiences a rise in electricity flow in these neighbourhoods. At certain times, the limits of the electricity grid will be exceeded, and black-outs will occur. Therefore, the distribution system operator (DSO) will have to invest in strengthening the electricity grid to prevent black-outs from happening. These investments are costly and because the DSO can not charge the costs directly to the NDP causing them, the DSO has to cover all the costs itself. However, as ICT-technology is advancing, an alternative solution becomes available: Steering the production and consumption of electricity of DERs, as such that the limit of the electricity grid is not exceeded, and expensive investments in strengthening the grid are not necessary. Instead of investing in strengthening the grid, the DSO could apply this 'flexibility management' option. It is however unknown how much grid limit excess would be reduced, and what the influence would be on the house owners. Therefore, the main research question this thesis seeks to answer is:

How can a distribution system operator feasibly mitigate grid limit excess in neighbourhoods with a high penetration of distributed energy resources by applying direct control flexibility management, given the current Dutch institutional context?

To answer this question, a desk study was performed on both the socio-economical side and the technical side of neighbourhood distributed energy resource projects. The obtained knowledge was used to construct a spreadsheet model which enabled for the comparison of different combinations of DERs and flexibility management options and the influence of these combinations on predefined key performance indicators (KPIs). The model incorporated the perspectives of both the DSO and the house owners, and was based on the case of the Netherlands. The following KPIs were considered: Net present value (NPV), grid limit excess and carbon emission reduction. Input data for the DERs in the spreadsheet model was based, among others, on historical data obtained from real life NDPs.

The answer to the main research question is: The possibilities for the DSO to feasibly apply flexibility management to DERs in neighbourhood with a high penetration of DERs are highly dependent on the type of DERs being applied. Results show that only rigorous peak clipping and valley filling flexibility management options are able to completely eliminate grid limit excess. Other DER combinations were found that mitigate grid limit excess, but not completely eliminate it.

Rigorous peak clipping and valley filling could feasibly be applied to DER combinations consisting of hybrid heat pumps and photovoltaics (PV). For other DER combinations, consisting of electric heat pumps and PV, flexibility management is not feasibly able to completely eliminate grid

limit excess. Furthermore, if electric vehicles (EVs) were to be introduced to the NDPs, it would become even more difficult to feasibly eliminate grid limit excess, even for DER combinations consisting of hybrid heat pumps and PV.

Future research could focus on if and how the DSO should compensate the house owners for the flexibility management applied. Other topics for future research include the way flexibility management by a DSO fits within the Dutch market environment as present, legal changes necessary for flexibility management and the costs and privacy issues occurring from developing the ICT-infrastructure needed for flexibility management should be discussed here. Furthermore, the model simulation used in the research could be further developed.

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1 Introduction: Background and focus

Since 2009, the first collectives of house owners in the Netherlands have set up local projects which equip all houses within a neighbourhood with distributed energy resources (DERs) at the same time: Neighbourhood distributed energy resource projects (NDPs) (Netbeheer Nederland, 2013a). Installing these DERs, such as photovoltaics (PV) and heat pumps, within a neighbourhood reduces carbon emissions. However, installing DERs within all houses of a single neighbourhood at the same time causes problems for the low-voltage electricity grid (Blumsack & Fernandez, 2012). The current low-voltage electricity grid was not designed to incorporate such a high penetration of DERs on a neighbourhood level. This high penetration of DERs causes electricity peaks, which the grid cannot handle. This leads to black outs: Houses being cut off from electricity supply. To prevent black-outs from happening, the low-voltage grid will have to be strengthened. In the case of the Netherlands the distribution system operator (DSO) will be responsible for the strengthening of the grid, and will have to pay for the investments needed. These investment costs are high (approx. €2k to €3k per house (Korver, 2014)) and are currently being socialized by the DSO over all its customers. As such, the house owners installing these DERs do not directly pay the costs of the grid problems they are causing.

Another potential solution to the stated problem is flexibility management (Eid, Codani, Perez, Reneses, & Hakvoort, 2016). Through recent advances in ICT-technology, the flexibility management of DERs has become possible and grid limit excess could be mitigated (Blumsack & Fernandez, 2012). Up to a certain level, the demand and production of DERs is flexible: It can be time-shifted in order to reduce electricity peaks (Eid, Codani, et al., 2016; Siano, 2014). As such, the DSO might not have to invest in strengthening the low-voltage electricity grid. However, it is unclear how the DSO could manage the flexibility of DERs, what this would mean for the DSO, and what this would mean for the house owner involved.

In this Section 1.1 the background of the problem is discussed, which is followed by an identification of the need for research on this topic. In Section 1.2 the research questions, which will be answered during the course of this thesis, are identified. Furthermore, the structure of this thesis will be explained (Section 1.3).

1.1 Problem background

In this section the problem background will be made clear. First, the phenomenon of NDPs in the Netherlands is examined. Second, relevant scientific studies are discussed which examine the case of the Netherlands. Third, more general relevant scientific studies are discussed, in which two main scientific schools of thought are identified.

1.1.1 Neighbourhood distributed energy resource projects in the Netherlands

A neighbourhood distributed energy resource project (NDP) can be defined in the following way:

A neighbourhood distributed energy resource project is a project in which all houses within a residential neighbourhood are collectively and homogenously equipped with distributed energy resources.

In neighbourhoods throughout the Netherlands NDPs are being developed (RVO, 2016b) (Energiekaart, 2016). 'Stroomversnellingswijken' for example, are practical examples of neighbourhoods in which all houses are equipped with DERs such as PV and electric heat pumps (Energiesprong, 2016a). Furthermore, the Dutch Ministry of Economic Affairs has declared that climate friendly neighbourhoods deserve priority in the national climate change combat strategy (Ministerie van Economische Zaken, 2016). Practical research is done on these NDPs, by setting up pilot projects to test various new technologies (Agentschap NL, 2012).

Initiators of NDPs in the Netherlands vary. Most projects are initiated by the house owner, which can be a housing corporation or a private house owner (Schepers, Naber, Rooijers, & Leguijt, 2015). Other initiators can be municipalities, local energy collectives or even the DSO itself (Energiesprong, 2016b) (Lemon, Pollitt, & Steer, 2015). Still, house owners are the primary investor and beneficiary of these projects.

Netbeheer Nederland (2013a) has researched the uprising of sustainable energy collectives and the need for decentralized energy markets. The collectives reach out to the DSO with all kinds of questions, expectations, wishes and wants. The study concludes that the DSO should take a more active role in approaching these collectives.

1.1.2 Studies in the Netherlands on the costs and benefits of DERs and flexibility management in neighbourhoods

Within the Netherlands, pilot projects have been launched, which research the technical applicability of combinations of various DERs within neighbourhoods (Agentschap NL, 2012). Within these pilot projects certain forms of flexibility management are researched, such as installing a local market price or lowering EVs charging rates when grid limits are exceeded (Alliander, 2015). These so-called 'smart grid pilot projects' focus on the technical side, as well as on the social acceptability of the applied flexibility management technique. As the goal of these pilot projects is solely learning from technologies, costs involved are not well documented. Also, the number of pilot projects is limited, and each focuses on a very specific topic.

Blom et al. (2012) have performed a social cost benefit analysis of 'smart grids' in the Netherlands. The study focuses on a national level of local level integration of flexibility management. The research concluded that in all researched scenarios smart grids have a positive business case for society. The results are robust for a number of different uncertain parameters, such as climate policy, DERpenetration, decentralized energy storage penetration and the amount of flexibility in DERs. Furthermore, Blom et al. (2012) concluded that the most important building block is the behavioural change of residents under variable energy tariffs.

Schepers et al. (2015) have researched the application of different heat sources for reducing carbon emissions in the built environment. In their studies, a more top-down perspective is used: Neighbourhoods can be heated with green gas, heat networks, electricity from electric sources or biomass. Green gas would be the most cost efficient way for most neighbourhoods for reducing carbon emissions. However, green gas is only limitedly available. Additionally, green gas and heat networks require the government involvement, as these cannot be applied by citizens in a neighbourhood themselves and biomass is not enough available in residential areas.

1.1.3 Scientific fields studying flexibility management

Scientific fields studying neighbourhoods with DERs and flexibility management can be divided into roughly two separate research fields. The first is a collective of social sciences including: Institutional economics, actor analysis and financial analysis. The second is a purely technical field in which the technological characteristics of DERs and the management of their flexibility is analysed.

The **socio-economical field** researches the formation, drivers and social benefits of neighbourhood distributed energy resource projects. The institutional environment is also researched within this field.

A large part of the social research field focuses on behaviour, motivations and sociology of participating citizens within NDP. Many of these studies are based on pre-project questionnaires (Goulden, Bedwell, Rennick-Egglestone, Rodden, & Spence, 2014) (Huijts, 2013) (Park, Kim, & Kim, 2014) (Pepermans, 2014) (Ponce, Polasko, & Molina, 2016). Only few studies are based on actual projects (Verbong, Beemsterboer, & Sengers, 2013). The papers found the following: There are two types of citizens; 'energy consumers', who purely have economic interests and prefer the old paradigm without DERs, and 'energy citizens', who are more interested in sustainable issues. Participants in NDPs can be identified as being 'energy citizens'. Still, project participants might be sceptical towards flexibility management integration, as they are unfamiliar with the technology (Ponce et al., 2016). Building trust between the DSO and project participants is thus key.

Another sociological field focuses on the formation of local energy projects. (Fudge, Peters, & Woodman, 2015) studied the role of local authorities and concluded that local governments play a key role in motivating citizens and facilitating projects as process manager.

Another area in the socio-economical field researches the influence of the market design on the adaptation of flexibility management. Eid, Bollinger, et al. (2016) for example concludes that either an aggregator or a locally integrated utility provider, such as a DSO, is favoured for performing flexibility management services. This market design is heavily regulated. The DSO for example, is a heavily regulated actor in the energy system, with well defined roles. These regulations currently stand in the way of certain flexibility management innovations (Hakvoort & Huygen, 2012). Ten Heuvelhof and Weijnen (2013) concluded that the wide range in smart grid market designs will likely result in the following: The first market design successfully reaching the implementation phase will likely become the new standard. For the DSO it is thus key to identify the possibilities of flexibility management and their short term influences on NDP project participants.

The **technical field** is comprised of studies about the development of DERs themselves, their application in the energy system and the managing of their flexibility.

One area in the field researches the technical integration of DERs into the energy network (de Durana, Barambones, Kremers, & Varga, 2014). Siano (2014) for example developed a new way of modelling energy networks using multiple energy carriers. The research concluded that the energy network of the future includes multiple energy carriers, advocating alternative ways of producing heat. Eltigani and Masri (2015) found that the unpredictability of many DERs makes it hard to integrate them into grids. Stacked load profiles, resulting in grid overload, may only happen once a year, but the grid should still be designed to handle these occasions.

A large area in the field researches so-called 'demand response' of DERs (Balijepalli, Pradhan, Khapard, & Shereef, 2011). Demand response is a collective of different ways of steering DERs. It can be considered analogous to the term 'flexibility management'. Many different forms of demand response exist (Hurley, Peterson, & Whited, 2013). Among others, a differentiation can be made between demand response aimed at financial gain and demand response aimed at grid stability. The first is aimed at bidding a flexible load on a market, thus gaining direct financial benefits. The latter is aimed at steering DERs to control grid stability. For the DSO, the grid stability demand response, or flexibility management, is thus the most interesting.

1.2 Research specification

1.2.1 Knowledge gap and problem statement

Pilot projects have researched specific topics, but have not covered all aspects and possibilities of flexibility management in NDPs. Also, the financial implications have not been researched. A cost benefit analysis has been performed on flexibility management, but results were measured for the Netherlands as a whole. A per-project analysis has not been performed. For different neighbourhoods an analysis has been made identifying economic optimal heat source. However, the balance between stakeholders has not been included, nor have investment costs been covered or has the influence of flexibility management been taken into account.

The following problem statement will be used in this thesis:

The DSO is the first stakeholder who experiences problems from neighbourhood distributed energy resource projects, however, no study has been performed which takes a systems perspective on the possibility of the DSO to manage the flexibility of distributed energy resources in order to mitigate grid limit excess.

1.2.2 Scope of thesis

In this thesis, ways of managing the flexibility of the DERs within NDPs is researched. The effects of managing flexibility are measured for two stakeholders: the DSO and the house owners (Figure 1).

This thesis recognizes the possibilities of flexibility management for suppliers or, as time progresses, possible aggregators, but does not include them in the analysis.

Furthermore, this research focuses on the current Dutch institutional environment. As such, Dutch rules, regulations, energy prices and technology prices are applied within the research. An exception is made for the DSO performing flexibility management, which has not been covered by the law yet. The assumption here is that the government, as the Dutch government has prioritized smart grids in its policy, will create an exception for the DSO to manage flexibility.

In this research only DERs, which are available on the Dutch market in 2016, are incorporated. Micro combined-heat-and-power (Micro CHP), photovoltaics (PV), hybrid heat pumps, solar boilers, electric vehicles (EV), and residential storage (home batteries) are incorporated.

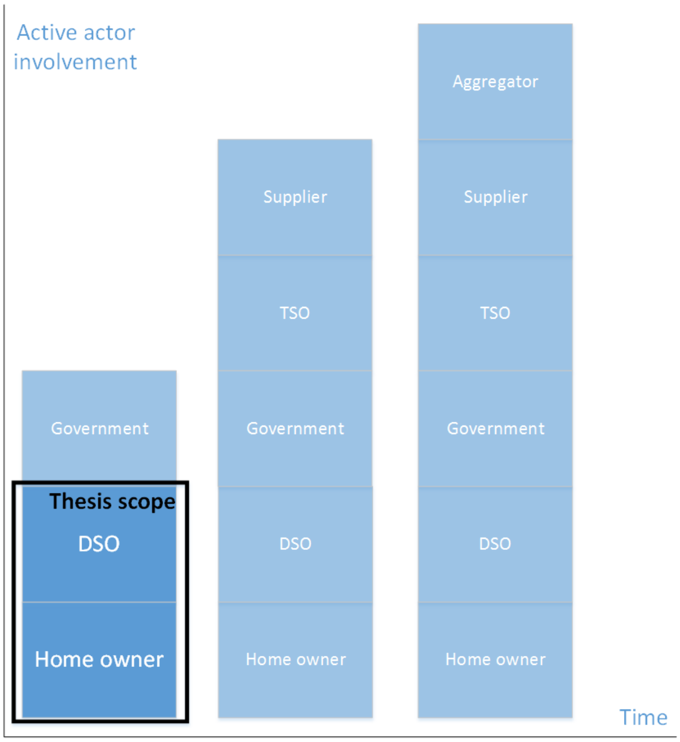

Figure 1: Stakeholder scope

In this thesis a systems perspective is taken on NDPs. This means that the analysis of the functioning of the system will take place on an aggregated level: key figures are used to represent certain DERs and flexibility management sub systems. Furthermore, the performance of the system will be measured according to the objectives of multiple involved actors: House owners and the DSO.

Flexibility management can potentially save the DSO investment costs in the grid. However, the developing of flexibility management itself costs money as well. Furthermore, these systems also have to be maintained and updated. This thesis recognizes the potential costs of flexibility management, but does not include these costs into the analysis as the costs of developing these systems is unknown.

1.2.3 Societal and scientific contribution

In NDPs in the Netherlands, DERs are now installed, based on the point of view of project participants (M. Bongaerts, personal communication, May 17th, 2016). Residents may not always take a rational decision and/or act from a biased point of view on certain aspects. A thorough analysis of the actual consequences of installing certain combinations of DERs could provide project participants with more information, and thus enable them to make a better informed decision. Additionally, the DSO is in need for information on the potential of flexibility management options for mitigating the effects of high penetration of DERs on the low-voltage electricity grid. This thesis could enable DSOs in the Netherlands to better advice NDP project participants, and also adjust its own strategy to better fulfil the social role of the DSO.

Flexibility management, or demand response, of DERs is a much researched subject in scientific literature. A lot of research is done on future market designs, community energy systems, micro grids, etc. However, the current practical side of projects is not well documented.

A systems perspective, taking into account the points of view of multiple involved actors, combined with a practical, short-term point of view, is also not researched yet. This thesis tries to add a starting point to this field which provides a basis for analysing the practical implications of applying DERs and flexibility management.

1.2.4 Research questions

The following main research question can be derived from the research problem:

How can a distribution system operator feasibly mitigate grid limit excess in neighbourhoods with a high penetration of distributed energy resources by applying direct control flexibility management, given the current Dutch institutional context?

The following sub questions will help answering the main research question:

1. What is the relationship between the distribution system operator and house owners in neighbourhood distributed energy resource projects?
2. Which distributed energy resources can currently be applied in Dutch neighbourhood distributed energy resource projects and how can their flexibility be managed by a distribution system operator?
3. What are the key performance indicators for measuring the effects of flexibility management by the distribution system operator?
4. How can a neighbourhood distributed energy resource project be represented in a model taking a systems perspective?
5. What are the combined effects of distributed energy resource and flexibility management integration for the key performance indicators?
6. What flexibility management options could the distribution system operator implement, and which distributed energy resource combinations could the distribution system operator recommend, to mitigate grid limit excess?

1.3 Methodology and structure

The research method applied consists of a modelling cycle which is described in detail in Chapter 4. The structure of this thesis follows the phases in the modelling cycle (Figure 2). The modelling cycle consists of the following four phases:

First, a desk study will be performed in order to assess the current and available knowledge on NDPs. A first overview has been given in Section 1.1: Problem background. A more in depth research is needed to get a better overview of the different aspects of the problem. This research method will be used for answering sub questions 1, 2 and 3.

Second, a model will be constructed based on the knowledge gathered in the definition phase. The model method used is a spreadsheet model, which is constructed using Microsoft Excel.

Third, the model verification and validation is performed. Afterwards, model experiments are performed based on a predefined experiments design.

Fourth, the model results are discussed and policy recommendations are given to the DSO. Furthermore, conclusions are drawn and possibilities for future research are identified.

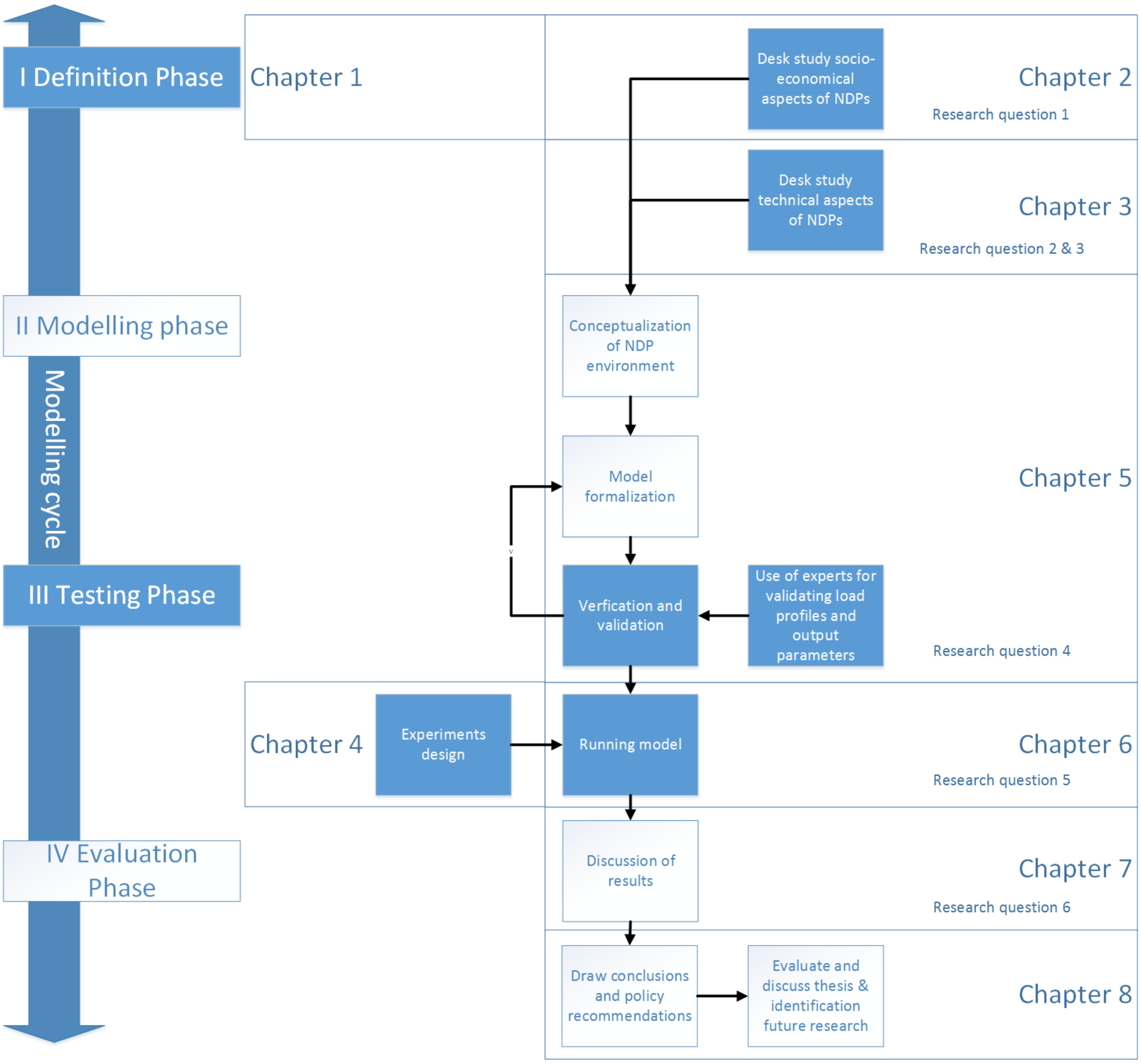

Figure 2: Thesis structure

2 Neighbourhood distributed energy resource projects and the local community

In this chapter sub question 1 will be answered:

What is the relationship between the distribution system operator and house owners in neighbourhood distributed energy resource projects?

In this chapter the social aspects of NDP will be discussed. First, the phenomenon of NDP will be analysed in detail. This will be done by presenting an example case and by comparing the concept of NDP to other forms of energy projects found in the literature. Secondly, an analysis is performed on the perspectives of both the house owner and the DSO. Thirdly, the institutional environment of NDP is discussed, in which the market environment of the Netherlands is presented and a short legal framework is given. Finally, the information is summarized and the first sub question will be answered.

2.1 The phenomenon of neighbourhood distributed energy resource projects

2.1.1 The Presikhaaf case

The neighbourhood 'Presikhaaf' is an example of a NDP. Presikhaaf is a neighbourhood in the Dutch city of Arnhem (Portaal, 2016). In this neighbourhood, 96 one-family houses have been renovated and equipped with DERs. Figure 3: Presikhaaf before and after renovation shows the houses before and after the renovation took place respectively (Bhagwandas & Dekker, 2016).

Figure 3: Presikhaaf before and after renovation

The initiator of this project was the house owner; housing corporation 'Portaal' (Portaal, 2016). Owning 56.000 total, Portaal is one of the largest housing corporations in the Netherlands

(Portaal, 2015b). The inhabitants were not directly involved in the conceptualization of the renovation as Portaal applied homogeneous DERs throughout the neighbourhood. The project not only installed DERs, but also renovated the houses in other areas. For example, the façade, kitchen, bathroom and toilet were renovated as well (Portaal, 2015a).

The goal of this project was to accomplish a 'net zero energy bill'. This can be accomplished, as the Netherlands knows a principle of 'Saldering', in which only the net energy use is billed (see further in section 2.3.2). All 96 houses within the neighbourhood were equipped with PV panels and air-to-water heat pumps with electric side heating. The PV panels produce yearly as much electricity as the household consumes and the houses were disconnected from the gas grid. Figure 4 shows a schematic of the renovation plans of this neighbourhood (Bhagwandas & Dekker, 2016).


Figure 4: Schematic of renovation of Presikhaaf house (Bhagwandas & Dekker, 2016)

After completion of the project, new insight was created of the importance of including the DSO into these kinds of projects (Stroomversnelling, 2016). It was discovered that back in 2009, the DSO just renovated the gas grid in this neighbourhood. During the project the gas grid connections have been disconnected. As such, the DSO can't earn the investments back. The DSO fulfils a public function, and as such it can be concluded that in this case a large sum of 'public money' had been lost. In addition, the project has caused high peaks in the low-voltage grid, making it necessary for the DSO to perform expensive grid investments of about €200k-€300k for the whole neighbourhood (Korver, 2014).

Presikhaaf has produced load profile data which was available for this research. Output data from the neighbourhood Presikhaaf is used later as input data for the model (Section 5.3.2).

2.1.2 Defining a NDP compared to other forms of local energy projects

In literature a number of types of collectives of house owners are described, which have various degrees of integration and value generation (Koirala, Koliou, Friege, Hakvoort, & Herder, 2016). So how do NDPs compare to these types found in literature?

Koirala et al. (2016) identified six different types of energy system integration options and their individual objectives (Table 1).

Table 1: Types of energy systems

Types	Objectives	Definition	Reference
Community micro grids	"Optimize electricity generation and demand for autarky and resiliency in	A micro grid performs all the functions of the national electricity system, only on a micro scale. Micro grids can detach from the national	(Soshinskaya, Crijns-Graus, Guerrero, & Vasquez, 2014)

	community" (Koirala et al., 2016)	electricity system and continue to fulfil consumers' electricity needs.	
Technical virtual power plants (T-VPP)	"Aggregate and manage (operate and dispatch) DERs" (Koirala et al., 2016)	A technical virtual power plant is a location bound connection of DERs in which the flexibility of DERs can be steered to benefit the technical functioning of the grid.	(Pandžić, Morales, Conejo, & Kuzle, 2013)
Commercial virtual power plant (C-VPP)	"Aggregate and manage (operate and dispatch) DERs" (Koirala et al., 2016)	A commercial virtual power plants is a non location bound connection of DERs in which the flexibility of DERs can be steered for financial gains the electricity market.	(Pandžić et al., 2013)
Energy hubs	"Multi-carrier optimization of electricity, gas, heat and cooling within a district" (Koirala et al., 2016)	An energy hub is a technical artefact which regulates the use and exchange of energy among different energy carriers	(Orehounig, Evins, & Dorer, 2015)
Prosumer community groups (PCG)	"Energy exchange among prosumers having similar goals" (Koirala et al., 2016)	"PCG is defined as a network of prosumers having relatively similar energy sharing behaviour and interests, which make an effort to pursue a mutual goal and jointly compete in the energy market" (Rathnayaka, Potdar, Dillon, & Kuruppu, 2015)	(Rathnayaka et al., 2015)
Community energy systems	"Invest and operate local energy system" (Koirala et al., 2016)	"community energy systems refer to electricity and/or heat production on a small, local scale that may be governed by or for local people or otherwise be capable of providing them with direct beneficial outcomes." (G. Walker & Simcock, 2012)	(Gordon Walker, 2008) (Gordon Walker & Devine-Wright, 2008; Gordon Walker, Devine-Wright, Hunter, High, & Evans, 2010; G. Walker & Simcock, 2012)
Integrated community energy systems	"Multi-faceted approach for supplying local communities with its energy requirements through DERs, flexible laods and storage together with different carriers" (Koirala et al., 2016)	An integrated community energy system is a combination of all above mentioned types.	(Mendes, Ioakimidis, & Ferrão, 2011; Xu, Jin, Jia, Yu, & Li, 2015)

Key for NDP is that neither the house owner, nor the inhabitant, is actively involved in the management and operation of the equipped DERs, besides daily use of the DERs. Without flexibility management by the DSO, NDP can be considered to be a form of a community energy system. The community here could either be a single house owner, a housing corporation, or a collective of private house owners. This 'community' collectively buys and applies homogenous DERs, producing electricity and/or heat on a small scale. Benefits which are provided could be lower carbon emissions, a lower energy bill and higher grid independence.

Including flexibility management by the DSO, the situation of the NDP can be compared best to a technical virtual power plant. Applying flexibility management aggregates the functioning of DERs from a house level to a neighbourhood level. While controlling for house level functionality, DERs are managed in order to higher the neighbourhood level grid performance. How this is done is further explained in section 3: Technical analysis.

The other notions are less applicable. An RESP will not be able to function independently, and as such cannot be considered a micro grid. Applying flexibility management by the DSO lowers the possibility for flexibility management for commercial use, which makes a commercial virtual power plant less applicable. Within PCGs energy exchange takes place. However, within NDP this is not the case. Although multiple carriers are possible within NDP, namely gas and electricity, a centralized optimization of electricity, gas, heat and cooling is not. As not all notions directly apply to current NDP, they can also not be considered to be integrated community energy systems. This does not mean that in the future they could not become so, but under the current notion, including flexibility management by the DSO, they are not.

2.2 Stakeholders

In this section an analysis is performed on the most important stakeholders and their relationship with each other. First, a summary is given of the complete stakeholder arena to give some more context of the situation of NDP. Secondly, the individual viewpoints of the most important stakeholder, the house owner and the DSO, are discussed. Finally, the relationship between these two stakeholders is discussed.

2.2.1 Stakeholder overview

NDP are performed by either housing corporations or collectives of private house owners. As can be concluded from the Presikhaaf case, the DSO will face the first challenges caused by these NDPs. However, other stakeholders are influencing the system as well. In this section a selection of these stakeholders and their influence on the system is highlighted. This will be done using a formal chart, which schematically depicts relationships between actors Figure 5.

NDP are influenced by various government bodies. The most direct relationship exists between the municipality and the house owner. Municipalities are often interested in NDPs for various reasons (Lemon et al., 2015). Not only do NDPs lower carbon emissions within the municipality's borders, the municipality as a whole benefits from it as well. Firstly, these projects mean a rise in job opportunities for local inhabitants. Secondly, the social cohesion within a neighbourhood is improved, and thirdly, the image of the municipality is improved. As the municipality is interested in these projects, it will help these projects as well. Building permits are issued by the municipality, and the municipality also has the power to install a local subsidy regime or give out cheap loans (H. Schneider, personal communication, May 26, 2016). Furthermore, the municipality can act as a process facilitator. For example, information evenings for inhabitants can be organized in cooperation with the municipality.

Other government bodies of interest are the provinces and a number of ministries. The Ministry of Economic Affairs decides on the national subsidy programs, which are given out by the RVO. The Ministry of Internal Affairs is involved with the building standards of houses of a housing corporation. National regulation issued by the various ministries has large effects on these NDP. More information about these regulations is given in Section 2.3. Provinces have the power to set up regional subsidy programs.

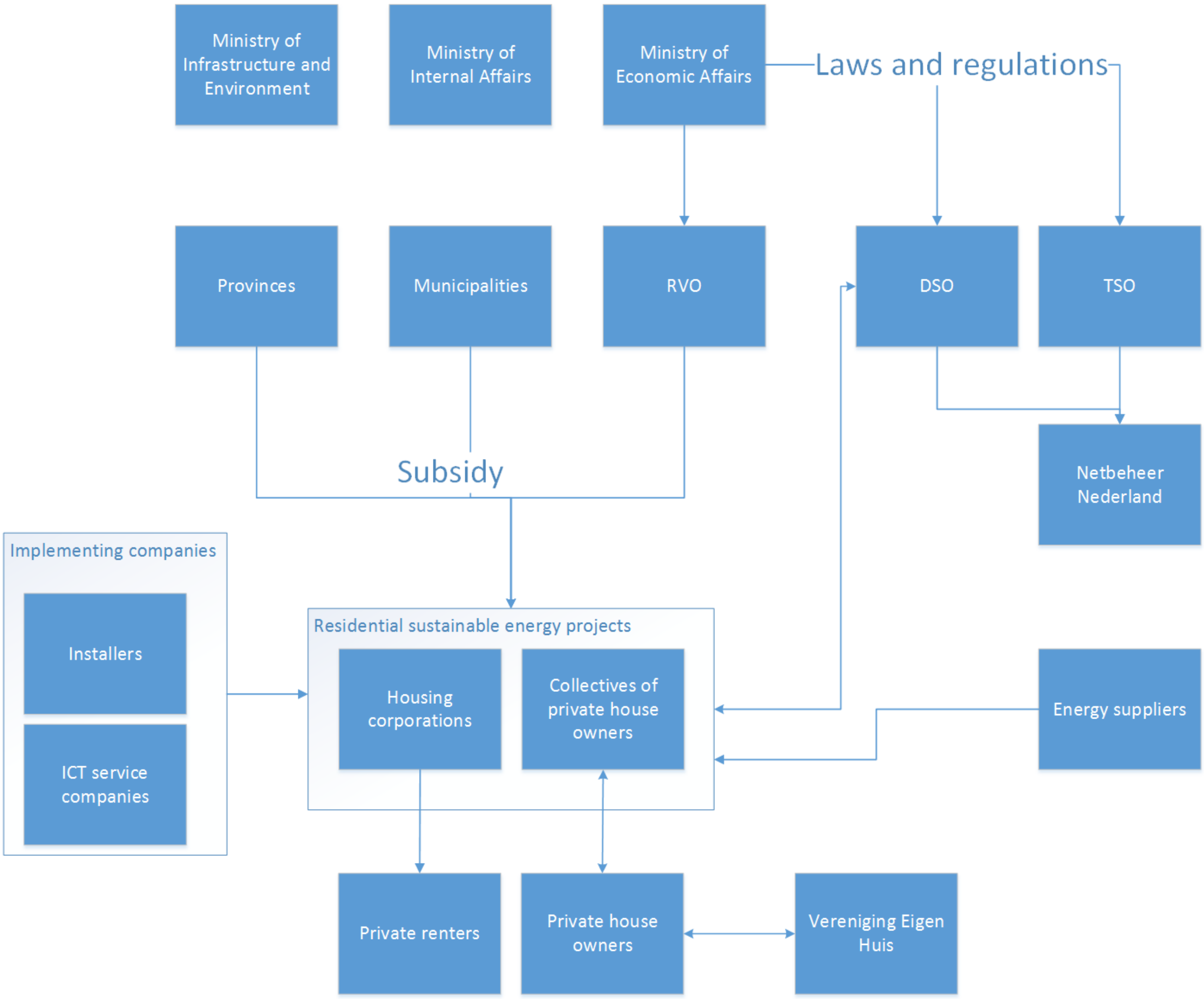

Figure 5: Formal chart of all stakeholders

There are two types of grid operators; the DSO and the Transmission System Operator (TSO). The DSO is discussed separately in Section 2.2.2. The transmission grid does not necessarily undergo grid limit excess by concentrated high penetration of DERs, as in the case of NDP, but rather the aggregated sum of all these DERs spread out over regions. The TSO might therefore be interested in the managing of flexibility of DERs in order to avoid transmission grid investments. However, this is beyond the scope of this research. Both the DSO and TSO have national monopolies and as they perform a societal function, both grid operators are heavily regulated by the Ministry of Economic Affairs. This regulation also determines the role of the DSO in NDPs, and states what can and cannot be done. More information on this aspect in Section 2.3.2. The DSO and TSO combined are represented by industry association Netbeheer Nederland (Netbeheer Nederland, 2016b).

Installers are companies which sell and install DERs. These are often specialized companies with thorough knowledge of DERs functioning and market prices of DERs. Applying flexibility management will need the involvement of specialized ICT service companies. There will have to be servers and two communication between DERs and the computer system. In the case that the concept of flexibility management by the DSO is feasible, these ICT service companies will have to be hired to develop the flexibility management options. The costs which are involved with this are unclear, and future research should be conducted to compare these costs to the costs of grid investments.

2.2.2 House owner's perspective

As shown in Figure 5, house owners can be categorized by either being a housing corporation, or a collective of private house owners. In the housing corporation case, the inhabitants of the house are the renters, while in the case of the collective of private house owners, the house owners themselves are the inhabitants. NDP like Presikhaaf consist of a housing corporation, applying highly homogenous DERs among all houses. In the case of a collective of private house owners, they will collectively purchase DERs. However, it can be expected that the homogeneity is less than with housing corporations, as the heterogeneity of private houses is higher than that of houses owned by a housing corporation. In this research however, complete homogeneity of DERs in both cases is assumed.

Although both housing corporations and collectives of private house owners initiate similar projects, small differences exist in their reasoning to install these DERs. For collectives of private house owners costs are less of an issue than for housing corporations. Housing corporations are companies which have an economic interest and their goal is continuance of the business. Private house owners participate more from an environmental point of view (Bauwens, 2016). Both stakeholders share both economic and ecological interest, but their focus is different.

A goal which is purely important for collectives of private house owners is grid independence. An example of this can be found in the Texel case (Liander, 2015a) (TexelEnergie, 2015). Although Texel is an island with a strong mentality among its citizens to become self sufficient and independent from energy from the mainland, it does illustrate the goal of some private house owner collectives to 'do it themselves', and ultimately become independent from the grid. The installation of DERs contributes to the goal to generate more energy themselves and import less from the outside world.

Important for the inhabitants of houses is that the quality of life and the comfort of the home is improved, or at least stays the same, when DERs are installed (Ponce et al., 2016). Applying flexibility management might interfere with this aspect, as flexibility management steers the production and consumption of energy of DERs. As such, DERs might not perform as how the inhabitant wants to. A related issue is that of privacy (Pepermans, 2014). Flexibility management may cause a breach in the perceived privacy of inhabitants as data is gathered about the use and energy consumption of DERs. It is assumed that housing corporations share these constraints with their tenants.

A final constraint of inhabitants is that the supply of electricity stays reliable. This constraint is not explicit currently, as the current reliability of energy supply is high in the Netherlands (Netbeheer Nederland, 2016d). As installing DERs might interfere with this reliability, this constraint becomes explicit.

The following goals and constraints are thus obtained for the stakeholder 'house owner' (Table 2). Table 2 shows no ranking between goals or constraints. These goals and constraints are translated into KPI to measure system performance in Section 3.4.

Table 2: House owner goals and constraints

House owner goal	House owner constraint
Less carbon emissions (private house owners)	Sustained comfort of living
Lower energy costs	Sustained privacy
Lower investment costs	Sustained energy supply reliability
Higher grid independence (private house owners)	

2.2.3 DSO's perspective

The DSO has three main goals: energy supply should be affordable, reliable and sustainable (Netbeheer Nederland, 2016c). Applying this to NDP it means the following:

Reliability of the grid has to do with the number of power shortages per year. Currently, the Netherlands has one of the most reliable grids in the world (Netbeheer Nederland, 2016d). On average a Dutch house is cut off from the power supply 16 minutes a year (Netbeheer Nederland, 2013b). A high penetration of DERs increases the risk of the grid limit being exceeded. When the grid limit is exceeded, the grid will fail and a black out occurs. Connected houses won't have power any more. As it is the legal responsibility of the DSO to facilitate a continuous supply of electricity, it is unwanted that any black-outs occur. As such, the goal of the DSO is to increase the reliability of the low-voltage grid. A more in depth analysis on grid limits and grid reliability is done in Section 3.1.

DSOs are actively involved in making the Dutch energy system more sustainable, and as such have developed an Action Plan Sustainable Energy Supply (Netbeheer Nederland, 2016a). This action plan recognizes the need for an increase in DERs, and the challenges which come with it for the DSO. Grids should become 'intelligent' and the DSO actively researches possibilities to integrate these DERs as best as possible. The DSO pursues a sustainable energy system. As such, its goal is that the energy system should emit less carbon emissions.

House owners in a NDP apply DERs, and pay for the investments. However, additional investments have to be made in the grid. These are paid for by the DSO. The DSO however functions as a public entity, and socializes the investment cost over all its customers (M. Bongaerts, personal communication, April 19 2016). It does this by raising its fixed grid connection prices. Ultimately, this means that everyone in the Netherlands pays for the DERs investments performed by a small group of citizens. For one NDP, this effect on the fixed grid connection price is negligible. However, as the number of NDP increases, this effect might become more apparent. Whether or not this is a bad thing is a philosophical question which is beyond the scope of this thesis. One critical note though, as it are stakeholders (either housing corporations or private house owners) with capital who perform these projects, stakeholders without capital (citizens who can't afford to participate in NDP) will relatively pay more for their electricity connection, even though they are not causing the rise in grid connection price.

NDP additionally cause a loss of public money by undoing investments made in the past. Both the electricity grid as the gas grid are subject to this. Both grids have a certain life time, and every time period new investments are being done for maintenance. This maintenance is paid back in a number of years. Usually, these periods are about 40 years. The grid limit excess caused by a NDP thus not only results in a need for new grid investments, the old investments which haven't been paid back yet have to be accounted for as well. The more recent the old investments have been made, the higher this loss of public money. The gas grid is subject to this as well. If the gas grid is not used anymore, like in the case of Presikhaaf, the public money invested in that gas grid is lost. In the case of Presikhaaf, the gas grid was only 7 years old, resulting in a loss of public money of about €600k (Westerhout, 2016).

These losses in public money could mean that the affordability of energy is threatened. Flexibility management could provide a lower loss in public money. Therefore the goal of the DSO is to both have a higher return itself, as losing less public money.

Concluding, the following DSO goals can be identified (Table 3). The table shows no ranking between goals.

Table 3: DSO goals

DSO goal
Less carbon emissions
More reliable grid
More affordable grid

2.2.4 Relationship between house owners and the DSO

In this section the difference in the relaitonship between the DSO and the house owners is explained between the situation before the commence of the NDP, and afterwards. Furthermore, the role the DSO plays in the process of NDP is discussed.

The initial relationship between the DSO and the house owners before the NDP is fairly simple. The DSO provides a connection to both the gas and the electricity grid. In return, the house owner pays a fixed price every year. Although the house owner is legally free to be disconnected from either grid, in practice all existing houses in the Netherlands have both a gas and an electricity grid connection. The DSO however is not free to disconnect the house from either the electricity or the gas grid, and has to provide them, if requested, to each house in the Netherlands.

A different relationship occurs when the DERs are installed, but before flexibility management is applied. The new relationship does not change any of the legal obligations of the two stakeholders, but does change the energy and possibly monetary flows, which is depicted in Figure 6. The amount of electricity exchange between the house owner and the DSO increases. However, the monetary flow for electricity stays the same. If the physical gas flow is abolished, as in the Presikhaaf case, this also results in an abolishment of the monetary flow of gas. This is depicted with the dotted line. If the physical flow of gas is lowered but not abolished, the monetary flow of gas stays equal.

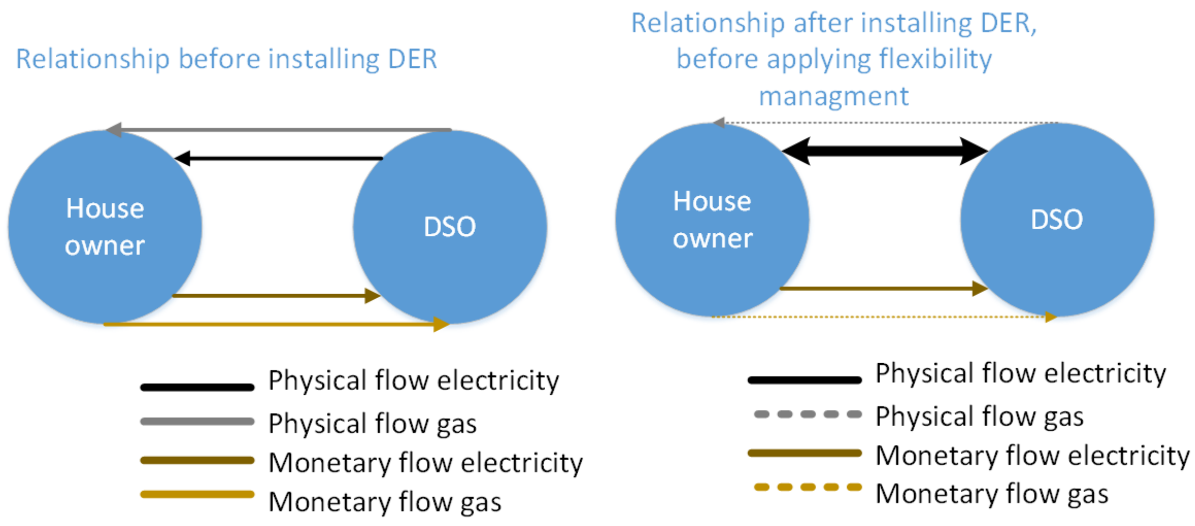

Figure 6: Relationship between DSO and house owner before and after applying DER

Outside the purely technical relationship, the DSO is involved in the NDP as an advisor. The DSO is often approached by the house owners when a NDP is initiated. This has two reasons. One fits in the role of the DSO, namely: advising on the impact of NDP on the grid. For example in the Presikhaaf case, the DSO had recently renovated the gas grid. Although the house owner is not legally obliged to take any different action because of this, moral consciousness could save public investments (Stroomversnelling, 2016). For example, the DSO could advise the housing corporation to choose other neighbourhoods. This example does not fit for collectives of private house owners though. The other reason fits less in the role of the DSO; namely the DSO as energy advisor. The DSO is sometimes approached by house owners with questions about DERs in general. Currently, the DSO is open to giving advice, but this does not fit its role as independent party. However, this provide the opportunity to bring up ideas for more societal beneficial DERs.

2.3 Institutional environment

In this section the institutional environment relevant for NDP is discussed: Rules and regulations which are enforced in the Netherlands and what the market environment looks like.

2.3.1 Market environment

As mentioned in the previous section, house owners in the Netherlands pay a fixed price per year for their connection to the gas and the electricity grid. Additionally, they are free to choose any energy supplier on the market. The energy supplier on its turn buys its energy from energy producers. The consumer price of energy in the Netherlands only for a small part consists of the actual price of generation. Most of the variable energy bill is build up by taxes and VAT (Autoriteit Consument & Markt, 2015). The consumer prices of energy varies by supplier. In Table 4 the average prices are depicted for both gas and electricity, and how they are generally build up (Milieu Centraal, 2016c).

Table 4: Gas and electricity prices for consumers in the Netherlands

	Gas	**Electricity**
Yearly grid connection price (including meter rent)	€148	€211
Variable supplier tariff	€0,28 / m³	€0,06 / kWh
Energy tax & VAT	€0,38 / m³	€0,14 / kWh

2.3.2 Regulatory environment

The 'Salderingsregeling' regulates the way decentralized production by house owners is calculated in the final electricity bill (RVO, 2016d). The regulation is stated in the Dutch Electricity Act of 2004 (Regeling vaststelling afnemerstarief Elektriciteitswet 2004). The act states that the supplier pays the same price to the house owner as the house owner pays the supplier for 'imported' electricity. This includes taxes and VAT. This act makes it possible for house owners to have a variable energy bill of zero. Even though at certain times electricity is imported from the supplier, as long as at other times the same amount of electricity is 'sold back' to the supplier, the final bill is zero. This gives an incentive for house owners to put PV on their roof, as the payback time is quicker.

The fixed energy tax payback (in Dutch: vermindering energiebelasting of heffingskorting) is a Dutch regulation in which the Dutch government pays back a fixed amount of energy tax to Dutch household (Rijksoverheid, 2016a). The idea is that energy is a base need for living. This fixed amount can be kept even though a variable energy bill is zero, as in the case of a high production of PV. The idea is that this further stimulates the implementation of PV. Currently the fixed energy tax payback amounts €310 per household (Rijksoverheid, 2016a).

To further stimulate the installation of DERs, the Dutch government has set up a number of national subsidy programs. The purchaser of certain DERs gets a fixed amount of money back on the investment cost. The following DERs are subsidized (Table 5) (Milieu Centraal, 2016j) (Milieu Centraal, 2016i).

Table 5: National subsidies on DERs in the Netherlands

DER	**Subsidy amount**
Solar boiler	€350-1100
Hybrid heat pump	€1000-1500
Electric heat pump	€1000-1500

In 2016 the Dutch government adopted a new law called the 'energieprestatievergoeding' (energy performance commission) (Rijksoverheid, 2016b). This law is aimed at stimulating housing corporations to renovate their housing stock and equip their houses with DERs. This regulation stipulates that in exchange for investing in these houses, the housing corporation may charge a surcharge from its tenants. For the tenants this means that their energy bill is reduced. However, instead of the energy bill they now pay an amount to the housing corporation. This regulation fixes the previous situation, in which the housing corporation was not allowed to charge tenants without their consent, which resulted in housing corporations not being interested in applying DERs.

Currently no legal framework exists which allows for the DSO to apply flexibility management in NDPs. The DSO is heavily regulated, as it performs a societal function and has a natural monopoly. On the short term, experimentation with flexibility management is allowed through smart grid pilot projects. The DSO gains a permit from the Ministry of Economic Affairs to experiment in these dedicated neighbourhoods with all sorts of flexibility management. On the long term however, and for applying flexibility management on a larger scale, the Electricity Act of 2004 (Regeling vaststelling afnemerstarief Elektriciteitswet 2004) will have to be changed. This is a political decision, and beyond the scope of this thesis, which only researches the potential added benefits of applying flexibility management.

2.4 Summary: Answering sub question 1

Sub question 1 can now be answered:

What is the relationship between the distribution system operator and house owners in neighbourhood distributed energy resource projects?

The relationship between the DSO and the house owners consists of two parts. First, NDPs cause a loss of public money, as grid investments made in the past cannot be earned back by the DSO. Additionally, the DSO will have to invest in new grid components. This additional investment is also paid with public money. As such, a fund allocation imbalance is created between the stakeholder creating costs (the house owner) and the one paying for it (the DSO, and indirect the public because an investment is made). The DSO is legally obliged by the government to upgrade the connection. The house owner is stimulated by the government to implement the DERs causing the need for investments. This situation might become more balanced when flexibility management is applied. However, no current legal basis is available for this, which should be resolved by the government.

Secondly, the DSO acts as an advisor within NDP. For housing corporations the DSO can advise to renovate certain neighbourhoods first. However, this does not take away the problem that eventually new investments will have to be made. Secondly the DSO is approached as a knowledge partner. This is not a legal role of the DSO, but it might create opportunities for the DSO to make advisements for socially better combinations of DERs or applying flexibility management.

3 Technological analysis

In this chapter research questions 2 and 3 will be answered:

Which distributed energy resources can currently be applied in Dutch neighbourhood distributed energy resource projects and how can their flexibility be managed by the distribution system operator?

And,

What are the key performance indicators for measuring the effects of flexibility management by the distribution system operator?

An analysis will be performed on the technical aspects of applying DERs and flexibility management options in Dutch neighbourhoods. First, an analysis is performed on the current characteristics of Dutch neighbourhoods. Second, a literature review is performed on distributed energy resources. Third, flexibility management options are identified which could be applied by the DSO. At the end, the chapter is summarized by answering the sub research questions.

3.1 Current characteristics of Dutch neighbourhoods

3.1.1 Energy performance of Dutch houses in NDP

In the Netherlands natural gas is the most used form of energy carrier for heating houses. In NDP, existing houses are being renovated. This changes the amount of heat needed, and as such the gas consumption is lowered. For houses in the Netherlands an energy performance index exists, called 'energy label'. The range of this energy label is from A to G, with A being awarded to houses with the best energy performance and G to houses with the worst energy performance. Houses within a NDP typically have energy label E/F/G before they are being renovated (V. Dekker, personal communication, 22-8-2016). After the renovation they typically have energy label A. Table 1Table 6 shows the average gas consumption per energy label (Rijksoverheid, 2012). Throughout the years the national average gas consumption has been declining from about 2000 m^3 per year to 1500 now m^3 per year (Milieu Centraal, 2016d). This is the result of more efficient boilers and better insulated houses.

Table 6: Average gas consumption per energy label

Energy label	**Gas consumption [m^3 / year]**
A	1379
B	1399
C	1500
D	1627
E	1746
F	1924
G	1883

The electricity consumption is less dependent on the energy label (Rijksoverheid, 2012), and depends more on the amount of people living in a house as well as their behaviour and the amount of electric devices (Milieu Centraal, 2016d). The average electricity consumption per household is 3300 kWh per year. The average electricity consumption has stayed relatively stable in the past few years.

Another Dutch metric for determining the energy performance of a houses is the EPC index (RVO, 2016c). EPC stands for energy performance coefficient (in Dutch: energie prestatie coëfficiënt). Where the energy label is designed for consumers, the EPC is mostly used in a professional context. The EPC is used for determining the energy efficiency of new buildings. Additionally, it is also used in the context of the Energieprestatievergoeding law. An EPC of 1,0 corresponds with a newly build house in 1990. From 2015 onward the EPC requirement for newly build houses is 0,4.

3.1.2 Characteristics of the gas grid and low-voltage electricity grid in Dutch neighbourhoods

The distribution gas grid usually stretches out over multiple neighbourhoods (M. Bongaerts, personal communication, April 23, 2016). It is therefore difficult to shut off if all house owners in a neighbourhood decide to collectively abandon their gas grid connection.

Calculating the exact costs of abandoning the gas grid is difficult, as it depends much on the local situation. Depending whether or not the gas grid is used by neighbouring neighbourhoods, the grid will have to be dug up and removed. Known is what households pay per year to the grid operator for a gas grid connection. Assuming this is an indicator for the costs of the gas grid, the DSO loses €148 per household per year on abandoning the grid.

The low-voltage electricity grid in the Netherlands consists of two main parts, a transformer and cables. The transformer connects a low-voltage grid part with the rest of the electricity grid. Such a low-voltage electricity grid has a life time of about 40 years (M. Bongaerts, personal communication, April 23, 2016). The low-voltage electricity grid as a system was designed to withstand a capacity of about 1 kW per connected house. A low-voltage electricity grid system with 100 houses thus has a capacity of about 100kW. However, in practice this could be more. Often a cable has been laid down, but the not the maximum number of houses has been connected to it, thus giving more capacity to the other houses. This gives the DSO room to advice the housing corporations to renovate certain neighbourhoods first, as less investments have to be made.

The costs of upgrading the low-voltage electricity grid in a neighbourhood dependent on the local situation. A rule of thumb used within Dutch DSOs is that it costs around €2000 to €3000 per house (M. Bongaerts, personal communication, April 23, 2016). This is further confirmed by an internal study done by Dutch DSO Alliander on the costs of upgrading the low-voltage grid in neighbourhood Presikhaaf (Korver, 2014). The costs of strengthening the grid are mostly dependent on the excavation activities needed to replace the cable. As such, the costs of applying a cable which strengthens the grid limit with +200% instead of a cable which strengthens the grid limit with 100% do not proportionally increase, as the excavation activity costs are similar in both cases.

3.2 Distributed energy resources

In this section the technical details of DERs are discussed. The following definition of DERs is used: "Distributed energy resources (DER) refers to electric power generation resources that are directly connected to medium voltage (MV) or low-voltage (LV) distribution systems, rather than to the bulk power transmission systems. DERs includes both generation and energy storage technologies" (Akorede, Hizam, & Pouresmaeil, 2010)

3.2.1 What types of DERs can be applied in NDP?

In the Presikhaaf case, photovoltaics and heat pumps have been applied. However, also other types of DERs exist which could be applied within a NDP. For example, the introduction of electric vehicles (EV) is investigated, as the introduction of EVs may influence the working of flexibility management on other DERs.

DER that are taken into account in this paper are photovoltaics (PV), heat pumps, micro CHP, solar boilers and EVs (Tuballa & Abundo, 2016). These can be categorized to the function they perform (Figure 7). For electricity production, PV and micro CHP can be applied. For electricity storage home batteries can be used. Heat production can be performed by either micro CHP, all electric heat pumps or heat pumps, with an addition of solar boilers. In the upcoming sections each DERs is analyzed.

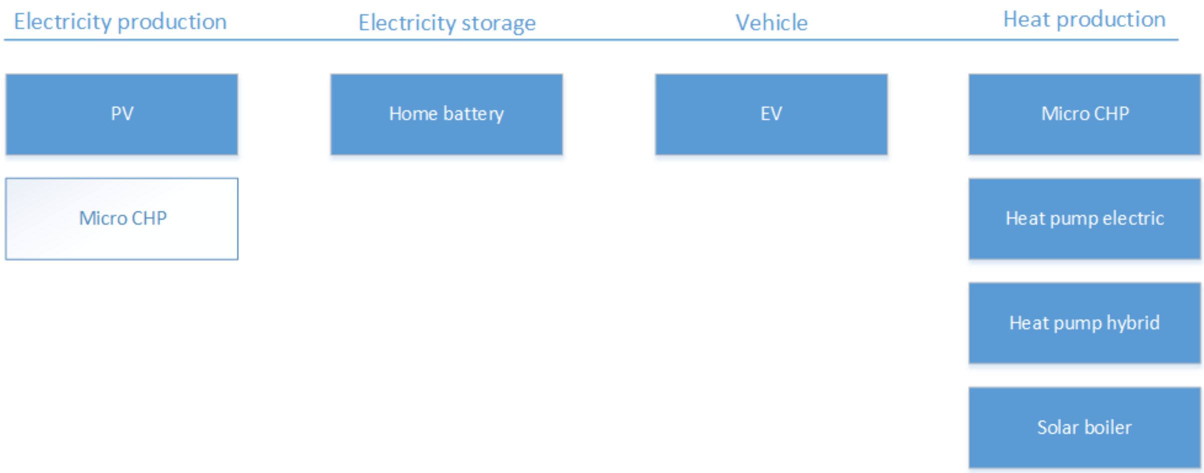

Figure 7: Considered DER

3.2.1 PV

Of all available DERs, PV is applied the most in the Netherlands. Compared to neighbouring countries the Netherlands is lagging behind, although the growth percentage has been increasing every year (Eurostat, 2016). The current total capacity is about 1088MW. The capacity has doubled every year since 2010 (Van Sark, Muizebelt, Cace, de Vries, & de Rijk, 2014).

PV is installed on the roof of a house. A PV installation consists of multiple panels connected to an invertor (Milieu Centraal, 2016e). The invertor connects the panels to the electricity system of the house. The peak capacity of the invertor is usually equal to the peak capacity of the combined panels. The higher the capacity for the invertor, the more expensive it is (Kop & Laagland, 2016). This information is important to for the functioning of the static curtailment flexibility management option described in Section 3.3.

Figure 8: PV on a rooftop

The yearly production of PV is dependent on the capacity of the installation and the weather conditions. On average though a new panel has maximum capacity of 0,26 kW (Milieu Centraal, 2016h). Assuming average weather conditions, this panel produces 225 kWh of electricity a year.

The price of PV has decreased by almost 25% in the past 5 years, and by more than 60% in the past 9 years (Milieu Centraal, 2016h). The current price of PV panels depends the size of the installation. PV gets relatively cheaper when the installation is bigger. Table 7 shows the price per peak capacity for different sizes of PV installation. This price includes the cost of installation. The average lifetime of a PV panel is 25 years (Van Sark et al., 2014). The average payback time is about 10 years (Zonnepanelen-info, 2016a).

Table 7: Costs of PV panels

Size (number of panels)	Price (€ / Wp)
6	1,94
10	1,78
19	1,62

3.2.2 Heat pumps

Heat pumps are a relatively new technology in the Netherlands. In 2013 about 100.000 heat pumps have been installed across the Netherlands (DHPA, 2015). It is estimated that in 2020 around half a million heat pumps will be installed. Heat pumps are therefore still in the starting phase. Heat pumps are not spread evenly over the country, but are concentrated in certain neighbourhoods. A heat pump could, depending on the type, double the amount of electricity consumption of a household. This will have a large impact on the grid if no flexibility management is applied.

Figure 9: An air-based heat pump

There a number of different types of heat pumps available. Table 8 shows the main types of heat pumps (Liander, 2015b). Each main type has a number of different variations, which differ depending on the manufacturer. For existing houses it is more interesting to make use of either a hybrid heat pump, or an air heat pump (Milieu Centraal, 2016k). Heat pumps which make use of ground heat storage are more interesting for houses which are newly build, as they can immediately be integrated into the design of the house.

Table 8: Heat pump types

Heat pump type	**Characteristics**	**House type suitability**
Hybrid heat pump	For normal days, uses electricity to heat air to heat water. When a peak in heating is required, additional heat is produced with natural gas with a normal boiler.	Existing New
Air to water heat pump	Uses electricity to heat air to heat water. When a peak in heating is required, an electric 'after heater' is used.	Existing New
Ground heat pump	Uses electricity to pump water which is stored below ground.	New

The cost of heat pumps in the Netherlands are hard to define. It depends on the specific situation, for example the size of the house, the insulation applied and the requirements of inhabitants all play a role in defining the approximated cost of a heat pump. For this thesis, average costs are used. Table 9 shows the total cost of a heat pump, including installation and changes to the house, excluding extra insulation measures. These average costs exist in a 'cost range'. Different sources report different average costs.

Table 9: Heat pump costs

Heat pump type	**Cost low**	**Cost medium**	**Cost high**
Hybrid heat pump	€3600 (Milieu Centraal, 2016k)	€6500 (Milieu Centraal, 2016k)	€7200 (Frenaij, 2016)
Air heat pump	€4000 (Warmtepomp-info, 2016)	€11400 (Frenaij, 2016)	€14500 (Milieu Centraal, 2016k)
Ground heat pump	€12000 (Milieu Centraal, 2016k)	€15000 (Warmtepomp-info, 2016)	€22200 (Frenaij, 2016)

The payback time and the cost effectiveness of heat pumps are unclear. The cost depend on the COP (Coefficient of Performance) of a heat pump, which defines its efficiency. A COP of 4 means that for every kW of electricity consumed, the heat pump 'produces' 4 kW of heat. The COP depends much on the weather conditions and the amount of insulation applied. The amount of insulation required for a heat pump to be efficient differs among various sources. COP estimates range between 2.5 in the very low cases, to 5 in the best cases (Kalkman & Van den Berg, 2015).

An analysis performed by Frenaij (2016) for DSO Alliander states that in order for heat pumps to have a 'positive business case', an EPC (see Section 3.1.1) of 0.0 is necessary. Frenaij based his conclusion on a number of interviews with industry experts. Newly build houses currently have an EPC requirement of 0.4. Therefore even new houses should be further insulated before heat pumps can be applied according to this source. A range of estimated payback times for heat pumps in general is found in Table 10. From this table, one of two conclusions can be drawn. Either, there is much uncertainty regarding the payback time of heat pumps, or the methods for calculating payback time differ.

Table 10: Heat pump payback times

Source	Payback time low	Payback time high
(Warmtepomp-info, 2016)	7 years	15 years
(Warmtepompforum, 2010)	17 years	40 years
(Frenaij, 2016)	24 years	38 years

The energy prices, cost of the heat pump, etc. are all uncertain. But this shouldn't result in a payback time period of 7 to 40 years. A more plausible answer would be that the methods for calculating payback times differ. Certain sources, like (Frenaij, 2016), take into account high cost for insulation, while others (Warmtepomp-info, 2016) do not. The payback time furthermore depends on whether the 'zero alternative' is included or not. The assumption is made that a household cannot be without heat. As such, the minimal investment needed is a 'standard' high efficiency boiler. As such, when calculating the payback time of a heat pump, the cost of a conventional high efficiency boiler can be subtracted. Also of influence is the inclusion or exclusion of grid costs for gas. As concluded in Section 1, these fixed cost are about €200 per year. Making a house 'all electric' raises the possibility for quitting the gas grid connection, saving additional yearly costs which can be subtracted in the payback time calculation. The life expectancy of a heat pump is around 15 to 20 years.

3.2.3 Micro combined heat and power

A micro combined heat and power (micro CHP) makes use of a sterling engine (Milieu Centraal, 2016f). A micro CHP installation uses gas in an efficient way: The gas is first used for heat production, and produces electricity as a by-product. Comparative to final gas consumption, the efficiency of heating is about 88% and the efficiency of electricity production about 12% (Milieu Centraal, 2016f). For example, if a household consumes 1650 m^3 gas with a traditional boiler, this household will consume 1890 m^3 with a micro CHP gas, but with added production of on average 2300 kWh electricity. As 1 m^3 holds 9,76 kWh of energy, the added gas consumption (1890 m^3 – 1650 m^3= 240 m^3) results in an efficient use of energy.

Figure 10: A micro CHP

The cost of a micro CHP are dependent on its capacity. A typical micro CHP with a capacity of 1kW costs €10000 to €11500 (Milieu Centraal, 2016f) (Mank, 2016). This is about €9000 more than a traditional boiler, which costs about €2100 (Section 3.2.7) (Milieu Centraal, 2016g). A micro CHP saves about €300 on a household's energy bill per year. A household has to needs a relatively large gas consumption of more than 1600 m^3 for a micro CHP to become cost effective. The life expectancy of a micro CHP is about 15 years.

3.2.4 Solar boiler

A solar boiler uses solar power to heat water. Through small tubes in a panel water is conducted which gets heated by the suns power. A solar boiler with a collector of 3,5 m^2 can save a 4 person household about 200 m^3 gas per year (Milieu Centraal, 2016m). Solar boiler scan be applied in NDP to produce heat without producing any carbon emissions.

Figure 11: A solar boiler on a rooftop

A solar boiler will cost about €3300, depending on the size (Milieu Centraal, 2016m). This saves a household about €110 per year. A subsidy is possible of €350 to €1100, depending on the size of the boiler (Milieu Centraal, 2016j). The expected lifetime of a solar boiler is 20 years.

3.2.5 Electric vehicles

Electric vehicles (EV) are not part of the renovation of neighbourhoods in NDP. As such, taking into account a 'high penetration' of EVs seems to be not necessary. EVs are not collectively bought, and will be purchased individually by households. Still, a high penetration of EVs in a neighbourhood will alter the aggregated load profile of the neighbourhood significantly (see further in this section). This influences on its turn the functioning of the flexibility management of other DERs. The situation might occur that the DSO is advised to implement certain types of flexibility management for PV and heat pumps, but that the added benefits of them are nullified by the introduction of EV. Therefore, a hypothetical high penetration of EVs is included in this thesis, to counter for this possible scenario. This hypothetical high penetration is than assumed to be caused by households wanting to become environmental friendlier.

Figure 12: Example of an EV: Renault Zoe

There are 97036 EVs in the Netherlands in July 2016 (RVO, 2016a). This number includes battery electric vehicles, hybrid electric vehicles, busses and motorcycles. This number has been growing steadily since the introduction of the first electric vehicles in 2010. Battery electric vehicles have a higher battery capacity than hybrid electric vehicles. The charging of their battery thus results in a higher peak in the electricity grid. As such, this thesis will focus on the battery electric vehicle only, to research a 'worst case scenario'. Battery electric vehicles will be called 'electric vehicles (EV)' for the remainder of the thesis.

EV are charged at home. EVs often have batteries with a capacity of 20kWh and more (Bhatti, Salam, Aziz, Yee, & Ashique, 2016). As the charging rate at home can reach capacities of up to 3,5 kW, the grid limit of 1 kW will be exceeded. The aggregated charging profile of EVs has a peak in the evening, when inhabitants get home from work (V. Dekker, 2014).

The cost presented here should be taken as indicative. Most are based on assumptions and best guesses, as the car market is complex and vastly changes. However, for the goal of this thesis this is sufficient, as the research questions are about the comparative results of applying flexibility management versus no flexibility management.

Defining an average price for one EVs is hard to do, as the costs and specifications of a car depend much on the brand of the car. For this thesis, the choice is made to consider the EVs with the lowest purchasing price. In the Netherlands this is the 'Renault Zoe', which costs around €24000 (ANWB, 2016). An electric car is free of 'Belasting voor personenauto's en motorrijwielen' (BPM) (English: Tax on cars and motorcycles), which is the tax one pays when purchasing a new car. A gasoline fired car of similar size costs around €15000 (RVO, 2010). However, such a car is not free of BPM. The BPM of a car similar to the Renault Zoe would be around €3500.

Assuming an average 13500 km yearly traveled, the yearly consumption of electricity is about 2750 kWh (Milieu Centraal, 2016b). The electricity costs thus amount to €550 per year assuming an electricity price of €0,2 / kWh (Autoriteit Consument & Markt, 2015). The fuel cost of a conventional car would be around €1350, assuming a car efficiency of 15 km per liter, and a gasoline price of €1,5 per liter. Furthermore, an electric needs less maintenance (RVO, 2010). The estimated payback time of an EV compared to a conventional car is about 8 years (ANWB, 2016).

3.2.6 Home batteries

Figure 13: An example of a home battery: Tesla Powerwall

Home batteries, like EVs, are not a standard option when renovating houses in NDP. However, their potential of mitigating grid congestion and the recent interest in becoming more grid independent (section x), makes them interesting to consider in this thesis.

Home batteries are batteries which allow a household to store electricity. For example, when a house is equipped with PV, the surplus can be stored in the home battery. Home batteries are relatively new in the Netherlands (Milieu Centraal, 2016n). In neighboring countries like Germany they are more popular, as the 'salderingsregeling' (Section 2.3) only partially refunds the electricity send back to the grid, while in the Netherlands electricity given back is fully refunded. A popular home battery in Germany is the Samsung SDI MW (Zonnepanelen.net, 2016). However, the newly introduced Tesla Powerwall is cheaper and has a higher capacity. As such, this thesis will base the characteristics of a home battery on the basis of this Tesla Powerwall.

The capacity of the Tesla Powerwall amounts to 6,4 kWh (Tesla, 2016). The system charging efficiency is about 85%, as losses occur when converting between direct current and alternating current (M. Bongaerts, personal communication, May 14 2016). The power output is 3,3 kW. In the Netherlands the Tesla Powerwall is distributed by energy supplier Eneco (Eneco, 2016). The purchasing price including installation and software amounts between €7000 and €7500.

3.2.7 Reference technologies

When houses in a neighbourhood are renovated during a NDP, the alternative of not applying DERs to produce heat is installing a 'traditional' boiler. As heat is a basic need, a house can not be without a heat source. As such, the application of traditional boilers can be regarded as 'sunk costs', which have to be made regardless. A traditional boiler costs on average €2100 (Milieu Centraal, 2016g). When calculating the payback time of DERs providing heat, such as electric heat pumps, these 'sunk costs' of traditional boilers can be subtracted from the investment costs of electric heat pumps.

The same logic can be applied to EVs. When buying an EV, a household is committed to invest a certain amount into a new car. As such, the costs of a 'traditional' car can be subtracted when calculating the payback time of an EV. As concluded in Section 3.2.5 a traditional car costs about €15000 (RVO, 2010).

3.3 Flexibility management

In this section the concept of flexibility management is discussed. First, an explanation is given of flexibility and why it is necessary.

3.3.1 The definition of flexibility and why it is necessary

DER are potential providers of flexibility. So what is meant with 'flexibility'? An example: An electric heat pump produces heat while consuming electricity. Through the day, the production of heat differs, and so does the consumption of electricity. As such, an electricity consumption pattern is created. This pattern is called a 'load profile'. In this example, the heat pump produces most heat when the inhabitants are at home. It is assumed that the inhabitants get home around 18:00. So, the production of heat rises around 18:00, and so does the consumption of electricity. Additionally, the consumption of electricity of other devices also gets higher when the inhabitants get home (Figure 14: red line). The television is turned on, the oven is put to work, or someone is charging their phone. The electricity consumption of the heat pump gets 'stacked' on top of the consumption of the other electric devices (Figure 14: blue line). A high 'peak' is created in the electricity consumption. This peak causes the grid to 'congest', or in other words, a 'grid imbalance' occurs: the balance between local supply and demand is not even anymore. This balance can exist within a certain range, defined by the maximum capacity of the grid: the grid limit. This is the maximum amount of electricity the grid can handle. To increase this maximum amount, the DSO has to upgrade the grid.

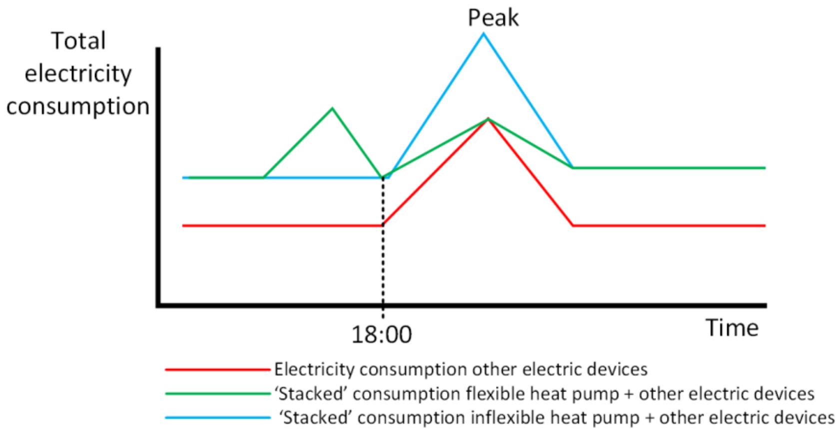

Figure 14: Example of flexibility management

This peak is a problem for the grid. The grid can only transport so much electricity, and grid congestion occurs, possibly resulting in a black out. Now comes the flexibility into the picture. Imagine that, instead of heating the house when the inhabitants get home, the heat pump heats the house during the afternoon. The house is well insulated, so heat is sufficiently kept inside. During the peak of other electric devices from 18:00 till 21:00, the heat pump is turned off or heat production is significantly lowered (Figure 14: green line). This reduces the 'stacked' peak of both the heat pump and the other electric devices. The load profile of the heat pump itself has now changed. It has become 'flexible'. Flexibility management is about changing the load profiles of all kinds of DERs, and it has the potential to lower 'stacked peaks' in the grid.

Another example of flexibility management is controlling electricity production, instead of consumption. PV for example, can produce too much electricity. Again, the grid can not transport this amount of electricity. By lowering the production, the grid limit is potentially not exceeded.

Flexibility management is also called 'demand response' in literature (Eid, Codani, et al., 2016). An overall definition of demand response (DR) is given by (Balijepalli et al., 2011): "Changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized." Whereas (Hurley et al., 2013) define DR as: "Demand response refers to the intentional modification of electricity usage by end-use customers during system imbalances or in response to market prices."

3.3.2 Applying flexibility management as a DSO

Flexibility management can be organized into four different categories. First, a division is made between the consumer controlling the flexibility, or an external entity controlling the flexibility (for example, the DSO). The latter is called 'direct control', as the external entity 'directly' controls the DERs. Secondly, a division is made on the goal behind flexibility management. This can either be gaining economic benefit on the electricity market, or maintaining grid balance.

Table 11 shows the four different categories which are obtained, applied on the case of NDP. A user controlled DERs is dependent on the behaviour of the household. As such, the predictability is low, compared to direct control by the DSO. A market oriented flexibility management option has a relatively low impact on low-voltage grid balancing, as the coupling between one neighbourhood and the national electricity market is low. For the DSO, only the combination of direct control and grid oriented is interesting: as it has both a high predictability and a high impact. Note, that this table does not take into account the possibility of a decentralized electricity market (Deconinck, Craemer, & Claessens, 2015; Eid, Koliou, Valles, Reneses, & Hakvoort, 2016).

Table 11: Types of flexibility management

	User control	**Direct control**
Market oriented	Low predictability / Low impact	High predictability / Low impact
Grid oriented	Low predictability / High impact	High predictability / High impact

3.3.3 Types of direct control flexibility management

There are a number of general ways of applying flexibility management (The World Bank, 2005). These can be seen in Figure 15. Peak clipping 'cuts off' the electricity consumption of a DERs at a given moment. Valley filling temporarily decreases electricity production. Load shifting 'shifts' the electricity consumption to another moment, this is what happened in the example of the heat pump in the previous section. Energy efficiency is increasing the overall efficiency of a DERs, thereby decreasing electricity consumption. Electrification is the increasing of electric consumption, which could for example be used to compensate for a 'valley peak' caused by a high production of electricity by PV.

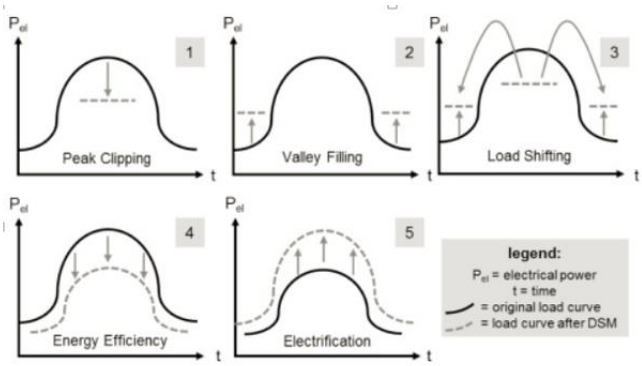

Figure 15: Flexibility management principles (The World Bank, 2005)

Furthermore, a distinction can be made between unidirectional and bidirectional flexibility within DERs (Eid, Codani, et al., 2016). With unidirectional flexibility the load profile of a DERs can either be increased or decreased. With bidirectional flexibility the load profile of a DERs can both be increased and decreased. Sometimes this difference is a bit ambiguous, such as in the example of the heat pump in the previous section. The heat pump both increases the production, but also decreases the production at another point in time.

3.3.4 Grid oriented direct control flexibility management

As concluded in the section 3.3.3, only direct control grid oriented flexibility management is interesting for the DSO. This section identifies which forms of flexibility management will be researched in this thesis. An overview of considered flexibility management options can be seen in Figure 16: Considered flexibility management optionsFigure 16.

Eid, Codani, et al. (2016) identify the theoretical flexibility potential of different DERs. All DERs considered in this thesis have a flexibility potential, with the exception of solar boilers. Translating the theoretical flexibility potential into practical flexibility management options is done by assessing information available within a Dutch DSO (Alliander). Figure 16 shows the overview of considered flexibility management options in this thesis, based on this assessment. Flexibility management options are considered for PV, home battery, EV, electric heat pumps and hybrid heat pumps. The flexibility potential of two-way charging of EVs (using EV's battery as a home battery), as well as the flexibility potential of micro CHP is not taken into account in this thesis. Although they are interesting, time constraints of this research did not allow for the inclusion of these. Micro CHP is still taken into account for its base influence on the grid.

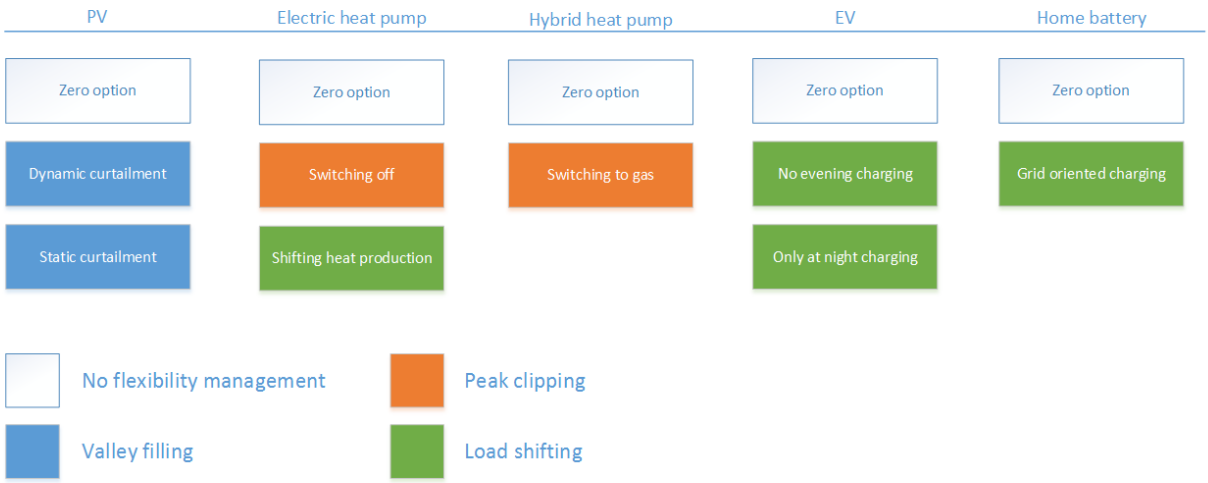

Figure 16: Considered flexibility management options

For PV two flexibility management options are considered: Dynamic curtailment and static curtailment. Static curtailment is an already applied technology (Bird et al., 2016). It involves peak clipping the maximum output a PV installation can give, thus 'valley filling' the load profile. Usually, the convertor is used for this. For example, a PV installation has panels totalling a capacity of 3 kWp, but the convertor only puts out a maximum of 2 kWp. The idea is that the 'peaks' are cut off, while keeping the 'body' of the generation. Only a few times a year will the panels actually put out more than 2 kWp. Additionally, a convertor with a smaller capacity can be about €500 cheaper than one with the same capacity as the panels (Laagland & Hartman, 2016). Dynamic curtailment also uses valley filling. However, dynamic curtailment makes use of a convertor which adapts its output to the grid limit. For example, if the base load is 1 kW, a solar PV puts out 3 kW and the grid limit is 1 kW, the convertor will limit the output to 2 kW. As the convertor in theory can still put out the maximum of 3kW, no money is saved on a cheaper convertor by the house owner.

For electric heat pumps two flexibility management options are considered: Switching off and shifting heat production. Switching off is a peak clipping option for electric heat pumps, where the heat pumps are switched off when grid limits are exceeded by the stacked electricity load. A heat pump would than be switched of by a certain percentage, lowering the electricity consumption. This might be beneficial for the DSO, and could be accepted by house owners if this would only be required a few times a year for al limited percentage. More switching off would interfere too much with the house owner constraints of sustained comfort of living as defined in Section 2.2 Shifting of heat production is like the example in section 3.3.2 and can be considered load shifting. The production of heat is shifted to other time periods, and the thermic mass of the house is used to temporarily 'store' heat energy.

For hybrid heat pumps one flexibility management option is considered: Switching to gas. A hybrid heat pump already uses to gas for peaks in heat demand. With this flexibility management option the electricity consumption is peak clipped. The heat pump is now forced to switch to gas when grid limits are met.

For EVs two flexibility management options are considered: No evening charging and At night only charging. No evening charging is a load shifting measure, in which the charging of EVs is not allowed between 17:00 and 20:00. EVs will be charged afterwards. At night only charging does not allow charging at home during the day, but only allows charging between 00:00 and 07:00. Charging a car during the day should then be done at the office or at a designated charging station.

For home batteries one flexibility option is considered: Grid oriented charging. The home battery will, on the basis of historical data of the household, predict when a peak and a valley occurs in the aggregated load profile. The home battery will discharge and charge at the moments, thereby both 'valley filling' and 'peak clipping' peaks. It is unknown what the 'zero option' behaviour is of the home battery. It is assumed that the home battery will charge as soon as there is a net outflow of electricity, and discharge as soon that a net inflow of electricity is detected.

3.4 Identifying KPI as a means to measure systems performance

On the basis of goals and constraints of the house owners and the DSO, in combination with this technical analysis, key performance indicators (KPI) can be identified. These KPI will be used in the model analysis to measure system performance. Thereby they form the basis on which to draw conclusions.

KPI are identified in two ways: (i) KPI are identified based on the goals and constraints of the house owners and the DSO. (ii) KPI are identified on the basis of a technical analysis and whether or not they can be objectively 'measured'. The following goals and constraints were identified in section 2.2 (Table 12). Based on these goals, the following KPI were identified.

Table 12: Goals and constraints of house owners and the DSO

	House owners	**DSO**
Goal	Less carbon emissions	Less carbon emissions
	Lower energy costs	More reliable grid
	Lower investment costs	More affordable grid
	Higher grid independence	
Constraint	Sustained comfort of living	
	Sustained privacy	
	Sustained energy supply reliability	

Looking at the constraints of the house owner, two constraints are difficult to measure from a technical standpoint, these are 'sustained comfort of living' and 'sustained energy supply reliability'. As such, these will not be taken into account during the modelling phase. However, they are still used as qualitative constraints in the discussion of results in Chapter 7.

Looking at the remaining goals and constraints, some are shared between the two stakeholders. That means that the DSO and the house owner both have these goals. These are 'less carbon emissions' and the 'affordability of the grid'. For the house owners, this translates into lower energy costs. For the DSO, both the investments in the grid, as the public affordability which is linked to it are important. Furthermore, it can be argued that for both stakeholders the grid reliability is important. However, for the DSO it is a much more 'active' goal than it is for the house owner, which takes the reliability of the grid for granted.

Besides these common goals, both stakeholders also have stakeholder specific goals. For example, the house owner is interested in lower investment costs of DERs, while the DSO is interested in lower grid limit excess. Furthermore, some house owners pursue grid independence, which goal is not shared by the DSO. The DSO on its turn wants to reduce its investments, which might not be shared by the stakeholders, as they are usually the ones initiating them.

The goals can be translated into KPI, which can be seen in Table 13. A division is made between house owner specific KPI, DSO specific KPI and 'Shared KPI'. The KPI are not ranked in any particular order, the numbers shown on the left are for identification purposes only.

For all KPI a time horizon of 15 years is chosen, which is the minimal life time of any of the considered DERs. The reference scenario is the situation before applying DERs and flexibility management, but after insulation. This is important for calculating KPI like net yearly carbon emissions saved.

Table 13: Key performance indicators

#	KPI	Unit
	House owner specific KPI	
1	House owner NPV	[€ / household]
2	House owner payback time	[year]
3	House owner grid independence	[%]
	DSO specific KPI	
1	DSO NPV	[€ / household]
2	Grid limit excess	[%]
	Shared KPI	
1	Shared NPV	[€ / household]
2	Net yearly carbon emissions saved	[ton CO_2 / household]
3	Percentage yearly carbon emissions saved	[%]
4	NPV per net total carbon emissions saved	[€ / ton CO_2]

House owner net present value (NPV), represents the value of the investment done over a given amount of time. It takes both the investment costs and the benefits of the house owner into account. This KPI represents the goal of the house owner to have lower energy costs and lower investment costs. It is calculated in Euros per household.

The **payback time** is another KPI which represents the goal of the house owner to have both lower energy costs and lower investment costs. The payback time is the amount of time it takes for the cumulative energy savings to equal the investment costs. It can be used in addition to the house owner NPV to get insight into the change in attractiveness of the investment when flexibility management is added.

The **house owner grid independence** represents the measured percentage of energy consumption being produced by the house in a given year. This does not take energy production being exported, such as excess PV production, into account. The reasoning behind not taking into account energy being exported, is that the house owner is not really grid independent when electricity is exported, although through the Dutch 'salderingsregeling' (Section 2.3) net electricity costs can be zero. This KPI represents the goal of the house owner to become more grid independent.

DSO net present value (NPV), represents the value of the investment done over a given amount of time. It takes into account both the investment costs and the benefits of the DSO. This KPI represents the goal of the DSO to have a more affordable grid. It is calculated in Euro per household, in a way that it can be compared to the NPV of the house owner.

The **grid limit excess** is the maximum peak in a load profile in a given year, minus the grid limit, divided by the grid limit. As such, it is a percentage that represents how much the grid limit is exceeded. As a KPI grid limit excess represents the goal of the DSO to become more reliable. While reliability is usually measured in minutes of black out per year. This is difficult to measure on a small scale, and hard to mimic in a model. Therefore grid limit excess shows with what percentage the maximum peak exceeds the grid limit, as the grid should be capable of handling the peak.

Shared NPV represents the goal of both the house owner and the DSO to have a more affordable energy system. It is calculated by adding up the house owner NPV and the DSO NPV.

The **net yearly carbon emissions** show how much carbon emissions per house are saved per year. This represents both the house owner's goal as the DSO's goal to have less carbon emissions. The **percentage yearly carbon emissions** saved puts the net yearly carbon emission saved into perspective. Now it can be seen how much of a percentage of a household carbon emissions are saved, compared to their original carbon emission output.

The **NPV per net total carbon emissions saved** is used to put a price on the carbon emissions saved. It can be used to gain insight into the economic efficiency of two different solutions when it comes to saving carbon emissions. It is calculated by dividing the Shared NPV through the net yearly carbon emissions saved.

3.5 Summary: Answering sub questions 2 and 3

Based on the information in this chapter, sub questions 2 and 3 can be answered:

Which distributed energy resources can currently be applied in Dutch neighbourhood distributed energy resource projects and how can their flexibility be managed by the distribution system operator?* And, *what are the key performance indicators for measuring the effects of flexibility management by the distribution system operator?

The following DERs can be applied in Dutch NDP (Figure 17):

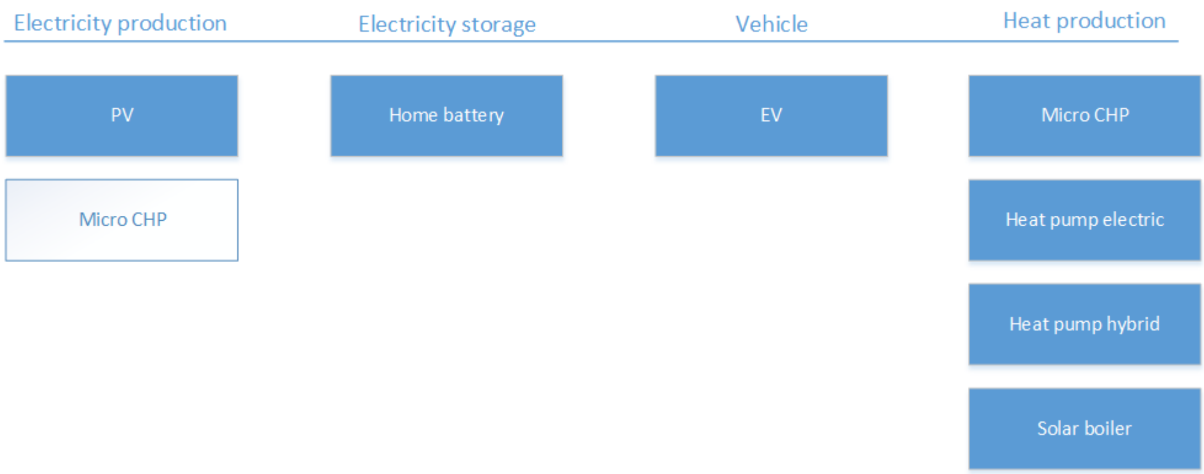

Figure 17: Considered DER

The following flexibility management options for a DSO are considered (Figure 18):

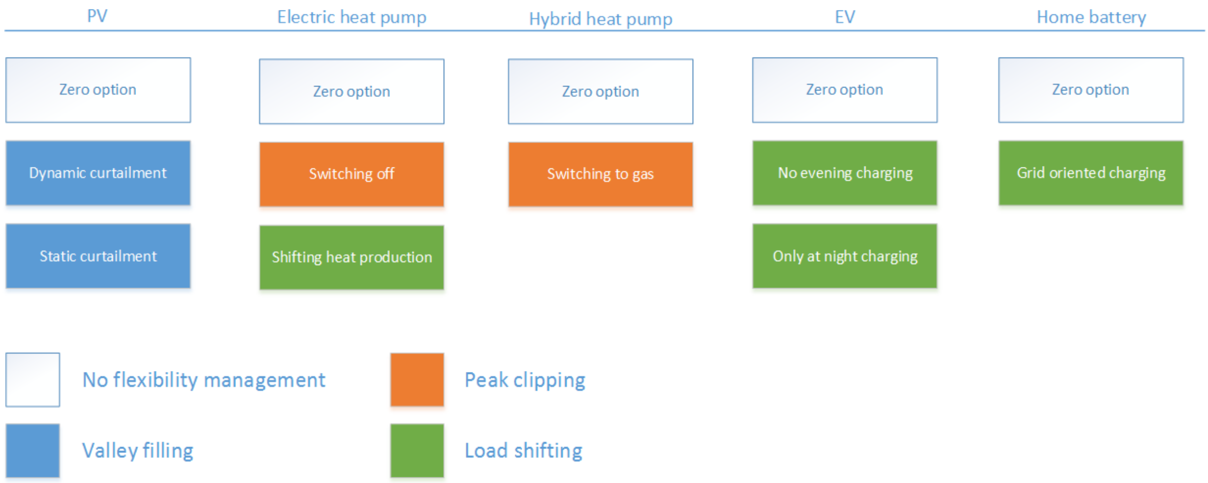

Figure 18: Considered flexibility management options

The following KPI are used to measure system performance (Table 14):

Table 14: Key performance indicators

#	KPI	Unit
	House owner specific KPI	
1	House owner NPV	[€ / household]
2	House owner payback time	[year]
3	House owner grid independence	[%]
	DSO specific KPI	
4	DSO NPV	[€ / household]
5	Grid limit excess	[%]
	Shared KPI	
6	Shared NPV	[€ / household]
7	Net yearly carbon emissions saved	[ton CO_2 / household]
8	Percentage yearly carbon emissions saved	[%]
9	NPV per net total carbon emissions saved	[€ / ton CO_2]

4 Methodological framework

In this chapter the methodological framework is explained of this thesis is explained. It is first explained *why* a modelling method was chosen for this research and second the modelling method is explained into further detail. Second, the modelling cycle is explained. Third and final, the experimental design of thesis is further discussed.

4.1 Model simulation: Getting insight into usefulness of flexibility management

In this section the choice for model method is explained. The reasons why a simulation study is performed are explained and the spreadsheet modelling paradigm is discussed.

4.1.1 Research method choice

In order to answer the main research question, the outcome of different DERs and flexibility management combinations have to be analysed. There are roughly three research methods which could be used to answer the main research question:

1. Literature review
2. Empirical research
3. Model simulation

The desk study performed at the beginning of this study showed that a knowledge gap exists on the effects of various combinations of DERs and DSO flexibility management options on the systems performance of NDP. It is doubtful that performing an additional literature review would result in new insight which could be applied on current Dutch NDP. Furthermore, the question arises if the results from different studies could be compared. Studies performed in different countries for example are not directly comparable as base energy system characteristics differ.

Empirical research would be a great way to test the actual implications of DERs in neighbourhoods. Actual empirical research is being performed by the DSOs in the Netherlands in smart grid pilot projects. Accessing this data could potentially form a good basis for conducting an empirical research study. Still, the number of these pilot projects is limited, and each project focuses on a very specific combination of DERs. For example, pilot project 'Texel', has installed PV in a neighbourhood combined with a display device in the living room (Liander, 2012). The pilot project researched the effect of the information given on the device on the energy consumption of households. Although this information is interesting for the DSO, it is not sufficient for answering the research question. Additionally, as concluded in Section 1.1.2, costs are not well documented in these smart grid pilot projects. For drawing conclusions on KPI like 'Shared NPV', a more detailed analysis is needed.

In order to simulate the interactions between different combinations of DERs and flexibility management options, a model needs to be constructed. This research uses the following definition for a model: "A model is a set of mathematical relationships and logical assumptions implemented in a computer as a representation of some real-world object, decision problem or phenomenon" (Ragsdale, 2010). There are a number of benefits that arise from the use of a model simulation. First, model simulation allows for analysing a large number of different combinations of system configurations. Second, using a model to analyse decision problems is less expensive than actually testing them in real life. Third, models deliver information on a timelier basis, as constructing all combinations of DERs and flexibility management options would be very time evasive. Fourth, models can test things that are not yet developed in reality. This is useful for testing the concept of flexibility management, before time and resources are put into the actual implementation. Fifth and final, models can bring new insight and understanding of an object or decision problem under investigation.

There are also downsides to using a model. First, a model results' usability is based on the validity of the data in the model. As the data is often based on certain assumptions, the validity of the model itself is based on the quality of the assumptions. Second, model construction can still be time consuming, especially if the initial problem or research boundaries are ill defined.

As using a simulation model of a NDP will probably generate the largest amount of useable data in the shortest amount of time, the choice is made to construct a simulation model. To correct for the possible downside of creating an invalid model, the model will undergo a thorough verification and validation process.

4.1.2 Spreadsheet modelling paradigm and functionality of the model

Spreadsheet modelling allows for a flexible way of constructing a prescriptive and mathematical model. Spreadsheet modelling is beneficial for the modelling of electricity utilities, as it allows for the accommodation of range values of load profiles (Mumford, Schultz, & Troutt, 1991). Spreadsheet modelling is flexible, and allows for high level of customization. The model will be a so-called 'prescriptive spreadsheet model' (Ragsdale, 2010). In a prescriptive spreadsheet model, the relationships between variables are known, and the values of independent variables are also known. As can be concluded from Chapter 3, the values of independent variables (in this case, the parameters of DERs like efficiency or cost) are either known or known within a certain range. The relationships between variables are known as well. For example, the variable payback time can be calculated from knowing the 'investment costs' and the 'savings per year'. An unknown relationship occurs in statistical modelling, when a researcher does not know the relationship between two variables. A possible unknown in this relationship is the relationship of variables calculating the effects of flexibility management options. Not all flexibility management options have been applied in real life yet. As such, assumptions will have to be made regarding the mathematical translation of the concept of a flexibility management option to a spreadsheet model variable.

There are multiple ways of constructing a spreadsheet model. However, the most commonly used tool for spreadsheet modelling is Microsoft Excel (Ragsdale, 2010). Excel combines a user-friendly model building environment combined with a higher number of features. The constructed model is thus built using Excel.

The model will need a number of functionalities in order to be able to answer the research question. The model will be able to:

- include various DERs, include various flexibility management options and include the KPI of both the house owner as the DSO;
- include detailed pre-defined load profiles of various DERs, accounting for various seasons and include minimum and maximum peaks;
- perform calculations on these load profiles to account for an increase in the amount of DERs of a specific type;
- perform calculations on combining these load profiles into a single aggregated or 'stacked' load profile;
- include mathematical equations which represent flexibility management options and their effect on the load profiles of various DERs;
- make financial calculations on net present value and payback time;
- calculate the electricity and gas consumption based on the area under a load profile;
- measure the effects of various combinations of DERs and flexibility management on the predefined KPI.

4.2 Modelling cycle

The model was constructed using the modelling cycle research method (Bertrand & Fransoo, 2002). As can be seen in Figure 19, there are 4 phases in this modelling cycle research method. The first phase is the **definition phase**. In the definition phase the model background is defined: It explains why the model is needed, what the model should do and on what data the model is based. This phase is based on 'desk research', in which data is gathered from various sources such as scientific literature, internal documents of a DSO, internet based information and interviews with experts. Websites used for internet based are mostly websites which give advice on DERs to the general public. An example is milieucentraal.nl, which is much used in this thesis. Milieucentraal gathers information about DERs and is fact checked by a board of members of the scientific community (Milieu Centraal, 2016l). The second phase is the **modelling phase**. This phase consists of conceptualization and model formalization. During the conceptualization step the base functionalities of the model are defined. During the formalization step the model is actually constructed, by defining input parameters, load profiles and parameter relationships. The third phase is the **testing phase**. This phase consists of the verification and validation of the model as well as performing experiments and running the model. Verification and validation is needed to see if the model is correctly coded and behaves realistically. Experts are used to perform a part of the validation process. A direct feedback loop exists between the verification and validation step, and the model formalization step: The modeller makes adjustments on the basis of the functioning of the model. The experimental design of the model is performed separately, and is based on the need for information for answering the research questions. The fourth phase is the **evaluation phase**. In this phase the results of the previously performed experiments are discussed. Furthermore, conclusions are drawn and topic for future research are identified. The whole process of all four phases is an iterative process, in which the researcher adjusts previous steps based on information gained in later steps: Thereby completing the modelling cycle.

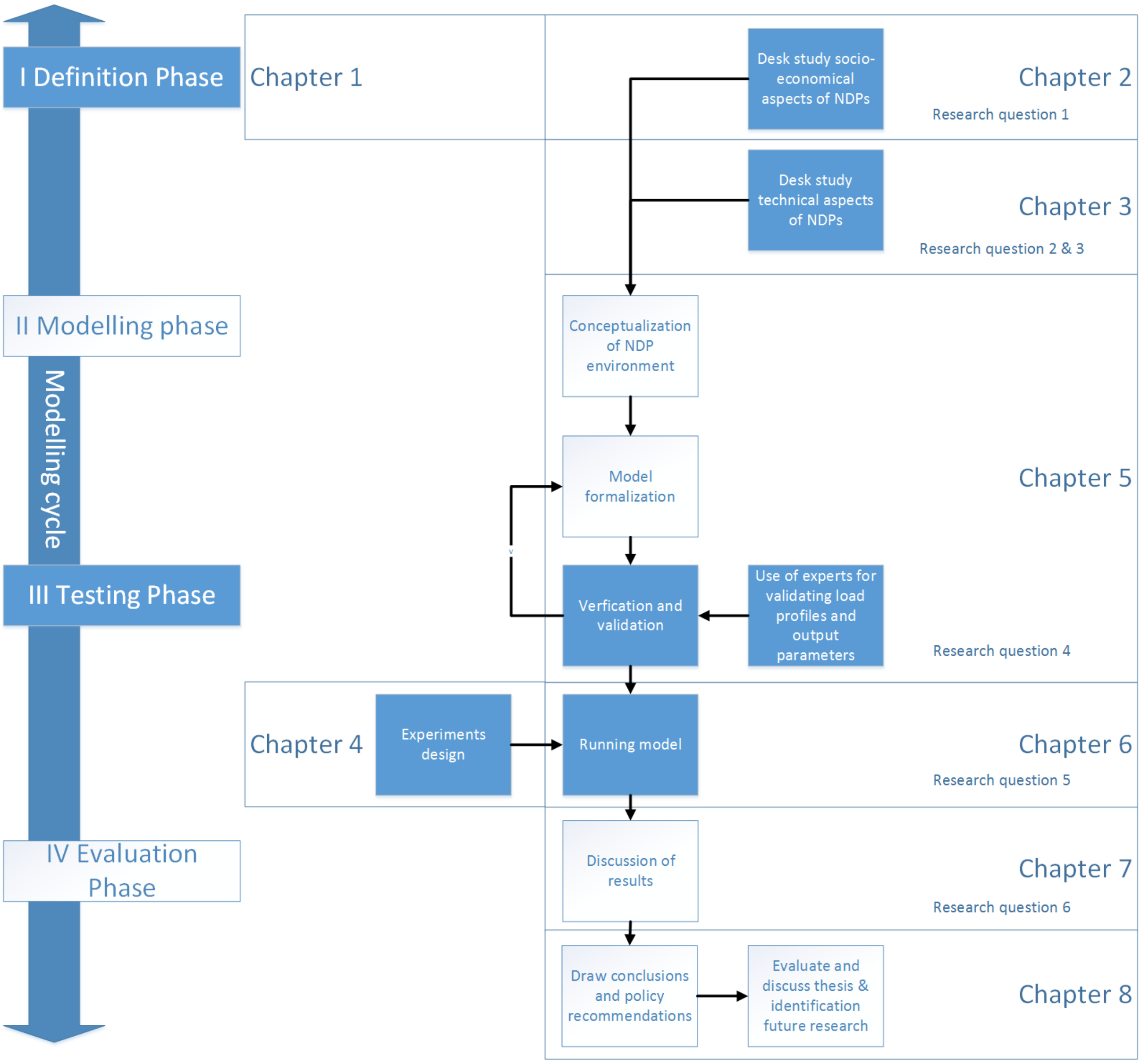

Figure 19: Thesis structure

4.3 Experimental design

In this section the experimental design of the model is further explained. In Appendix VI a detailed table can be found of all performed experiments.

4.3.1 How experiments are designed

The results of the experiments should be able to show the effects of various combinations of DERs and flexibility management options. The results of the experiments should also form a basis on which policy recommendations can be given to Dutch DSOs.

Translating these goals to the spreadsheet model means the following for performing experiments: Each experiment consists of a unique combination of DERs and flexibility management options. These DERs and flexibility management options are used as 'input parameters' (Chapter 5). By changing the input variables different experiments will be created, from which different results can be obtained. There are seven different DERs for house owners, and 10 different flexibility management options for the DSO (Chapter 3). As not all combinations are mutually exclusive, a high number of possible combinations is possible. The researcher thus has two options. (i) A factorial analysis can be performed, obtaining results for every possible combination. (ii) A 'smart design' can be made, where the experiments are constructed based on logical combinations of DERs and flexibility management options.

The first option, a factorial analysis, would make use of either a full factorial or a partial factorial design. Either one would produce a large amount of data. In order to draw conclusions from the analysis, a statistical model needs to be constructed. The data obtained from the statistical model could show trends of the influence of certain DERs or flexibility management options on grid limit excess. However, drawing conclusions based on specific situations could be difficult. The alternative analysis, a smart design, would make logical combinations of DERs and flexibility management options. For example, PV is the most applied DERs, and it can thus be assumed that PV is applied first in NDP. One of the goals of this thesis is to give practical policy recommendations to the DSO about applying flexibility management. It is therefore unnecessary to analyse all DERs and flexibility management combinations, as this is not in line with the goal of the thesis. The practical use of this analysis would be higher and more situation specific policy recommendations can be given to the DSO. As such, the latter possibility of a smart design is chosen.

4.3.2 How the smart design experiments are designed

This smart design represents logical combinations of DERs. Figure 20 shows how these logical combinations are constructed. Each experiment consists of a unique combination of DERs and flexibility management options. An overview of all combinations can be found in Appendix VI.

First, every DERs for which flexibility management is considered, is researched individually (with the exception for home batteries, as they are not logical to implement without any other DERs present). Example: Experiment 1 considers a neighbourhood with PV but no flexibility management, experiment 2 considers a neighbourhood with PV and dynamic curtailment. This analyses resulted in 11 unique experiments with singular DERs and flexibility management options.

Secondly, experiments are designed with combinations of DERs for which flexibility management is considered. These follow the structure shown in Figure 20. First, experiments are constructed with a DER combination of PV and either one of the two heat pumps (hybrid heat pumps or electric heat pumps). Then, home batteries are added to this DER combination. Then EVs is added to this DER combination. For combinations which include electric heat pumps, 21 experiments are designed in total. For combinations which include hybrid heat pumps, 16 experiments are designed in total.

Thirdly, experiments are designed which include combinations of DERs for which no flexibility management is considered. For these experiments, no flexibility management option is added. No home batteries are included, because they can be considered a form of flexibility management as well (even the zero option home battery). As such, combinations are obtained which have a base of PV, solar boilers and either one of: Hybrid heat pumps, electric heat pumps or micro CHP. For every combination EVs is added as well. In the end, a combination is made of 50% heat pump and 50% micro CHP, to investigate the possibility of synergy between these two technologies. This category consists of 8 experiments in total.

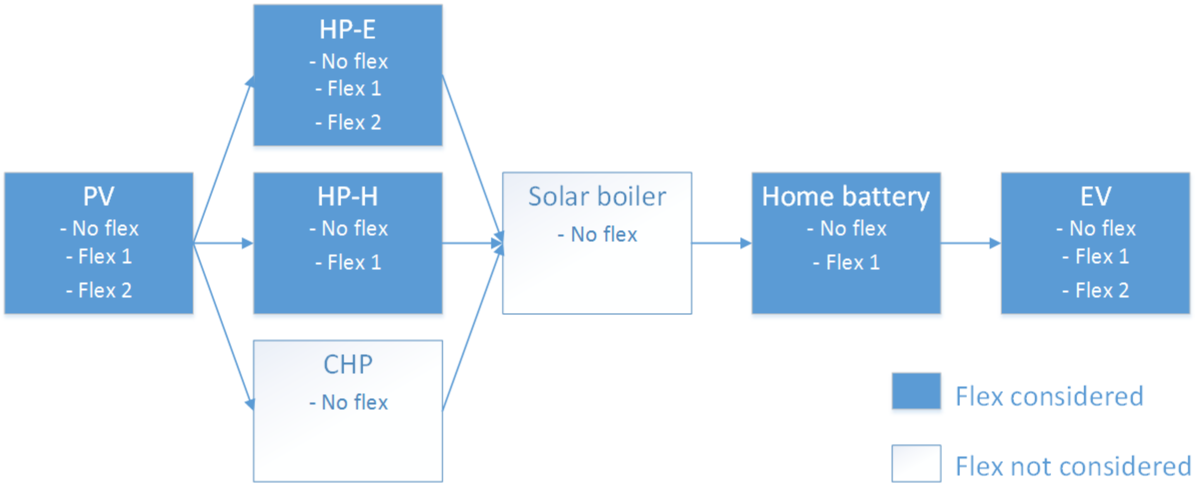

Figure 20: 'Logical' experimental design

4.3.3 Experiment base settings

All experiments use the same base settings, because within NDP, all houses in a neighbourhood are equipped with the same DERs at the same time. As such, the base design chosen for the experiments is a neighbourhood with 100 houses with energy label A, in which certain DERs are installed in all houses at time zero. In order to measure the influence of different DERs and flexibility management combinations on grid limit excess, the DSO has the option to apply certain flexibility management options at time zero as well.

The time horizon of the model will be 15 years, as this is the minimum life expectancy of certain DERs (Section 3.2). The time step used is 1 year for general calculations, 15 minutes for the calculation of electricity load profiles, and 1 hour for the calculation of gas consumption profiles. The latter two are explained further in Chapter 5.

4.3.4 KPI used in the experiments

As concluded in Section 3.4, there are nine KPI for which experiment results will be recorded, which can be found in Table 15. In the Chapter 6: Results 3 of these are used for safeguarding readability. Results on all KPI can be found in Appendix VII.

Table 15: Key performance indicators

#	KPI	Unit
	House owners specific KPI	
1	House owners NPV	[€ / house owner]
2	House owners payback time	[year]
3	House owners grid independence	[%]
	DSO specific KPI	
1	DSO NPV	[€ / house owner]
2	Grid limit excess	[%]
	Shared KPI	
1	Shared NPV	[€ / house owner]
2	Net yearly carbon emissions saved	[ton CO_2 / house owner]
3	Percentage yearly carbon emissions saved	[%]
4	NPV per net total carbon emissions saved	[€ / ton CO_2]

5 Model description: From reality to spreadsheet model

In this chapter the translation from reality to a spreadsheet model is discussed. The fourth sub question will be answered in this chapter:

How can a neighbourhood distributed energy resource project be represented in a model taking a systems perspective?

First, the conceptualization of the model is discussed, in which the 'blue print' for the model is laid out. Second, the model is formalized, by defining the values and formulas for every aspect of the model. Third, an overview of the entire model in Excel is shown. Fourth, the model verification is discussed, to show that the model has been sufficiently correctly coded. Fifth, the model validation is discussed, to show that the model accurately enough depicts reality. Finally, the fourth research question is answered.

5.1 Conceptualization

The conceptualization phase defines the first step in the modelling progress (Albin & Forrester, 1997). The conceptualization phase puts bounds on the model, it defines the purpose of the model and it describes the main model components.

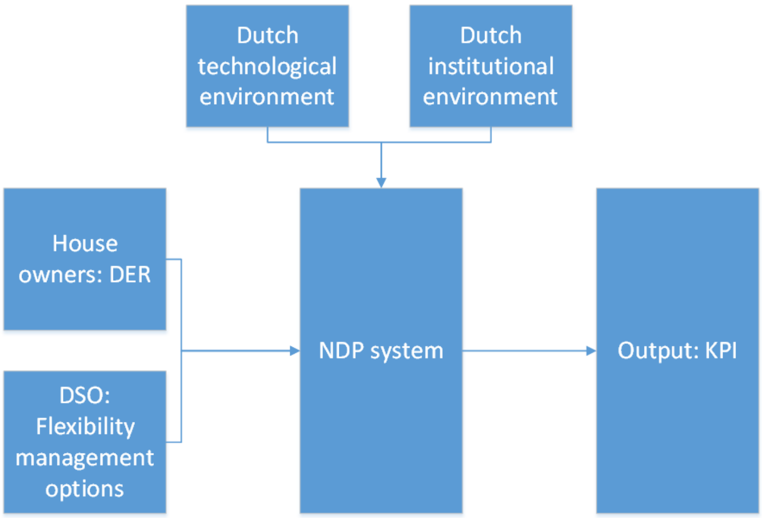

Figure 21: Conceptual model

Much of the bounds and purpose of the model has already implicitly been described in previous chapters. For example, Chapter 1: Introduction for example describes what the bounds of this study are, and Chapter 2 and Chapter 3 further define which DERs and flexibility management options are included. The purpose of the model is already stated in Section 1: Introduction: A model which provides insight into the influence of flexibility management of DERs in NDP on the stakeholders' KPI which provides ways of analysing this system via simulation.

The model contains 6 different sub-models (Figure 21). The **main sub-model** is the 'NDP system'. This sub-model includes the calculations and makes the connections between all other sub-models.

There are two **input sub-models**: The first one, **House owners: DERs** consists of policy options for house owners, and includes the technical characteristics of different DERs. The second sub-model, **DSO: Flexibility management options** consists of flexibility management options for the DSO, and includes the technical characteristics of different flexibility management options. These sub-models include the input variables for the model.

There are two environmental sub-models. The first one, **Dutch technological environment**, includes Dutch gas and electricity consumption details as well as Dutch grid constraints among others. The second sub-model, **Dutch institutional environment,** includes current Dutch energy prices as well as tax and netting regulations. Also Dutch subsidiary settings are included in this sub-model.

The last sub-model is the output sub-model **Output: KPI**. This sub-model calculates the different KPI and stores experiments and their outcomes. It does this on the basis of information 'gathered' by the **Neighbourhood distributed energy resource project system** sub-model.

5.2 Model formalization

The model formalization phase specifies the values and formulas behind the different variables. It explains how the necessary data is obtained and how this data is used in the model. The formalization is shown in the following order: First, parameter values are shown for sub-models DERs, Dutch technological environment and Dutch institutional environment. Secondly, the load profiles used in sub-model DERs are discussed. Thirdly, the sub-model flexibility management options are discussed. Fourthly, the relationships between variables in the sub-model Neighbourhood distributed energy resource project system are presented. Finally, the output sub-model is discussed.

5.2.1 Parameter values

This section shows the parameter values in the various sub-models. The choice is made to keep this parameter values constant during all experiments, as in NDP the same DERs is installed for all houses at he same time.

Table 16 shows the time settings of the model. As concluded in Section 4.3, the chosen time horizon is 15 years, as this is the minimum life time of certain DERs. DERs and flexibility management will both by implemented at the beginning of the starting year 2016.

Table 16: Model time settings

Model time settings	
Model time step	1 year
Model time horizon	15 years
Starting year	2016
Load profile time setting	1 week
Load profile time step – Electricity	15 minutes
Load profile time step – Gas	1 hour
Average load profile calculation	1 season
Season separation for average load profile calculation	Winter: December 1st – February 28th Spring: March 1st – May 31st Summer: June 1st – August 31st Autumn: September 1st – October 31st

Table 17 shows the DER parameter settings. The parameters are based on the data gathered in Chapter 3. The DERs produce electricity and heat in order to suffice the base case scenario. For example, a house needs 12900 kWh of heat per year. Therefore, the chosen heat pump needs to produce (at least) 12900 kWh in order to meet the standard requirements of the base case scenario. As in the experiments only the combination of DERs is changed, this means that that this 'zero electricity bill', might not be obtained. The choice for set parameters makes it easier to compare the results. However, the zero electricity bill will have to be kept in mind when translating the modelling results to policy recommendations.

Table 17: DER parameter settings

Parameter	**Setting**	***Parameter***	**Setting**
PV parameters		**Hybrid heat pump parameters**	
Solar panel size	1,65 m2	*COP*	3,75
Solar panel capacity	0,26 kW	*Cost price*	€6500
Cost price	€1,7 / W	*Max electric consumption*	0,65 kW
Yearly average production	220 kWh / panel	*Gas boiler efficiency*	95%
Static curtailment convertor cost reduction	€500	**Electric heat pump parameters**	
Panels per installation	15	*COP*	3,75
Micro CHP parameters		*Cost price*	€12000
Cost price	€10500	*Max electric consumption*	1,6 kW
Electricity production per gas consumption	12%	**EV parameters**	
Heat production per has consumption	88%	*Cost price*	€24000
Solar boiler parameters		*Car efficiency*	0,2 kWh / km
Panel size	3,5 m2	*Average daily distance drive*	37 km
Cost price	€3300	*Charging efficiency*	80%
Yearly average output	2280 kWh / panel	*Battery capacity*	22 kWh
Panels per installation	1	*Battery lease cost*	€1200
Home battery parameters		*Relative maintenance cost advantage*	€350
Cost price	€7250	*Relative yearly tax advantage*	€950
Capacity	6,4 kWh	*Relative purchase tax advantage*	€3500
Power	3,3 kW		
Charging loss	15%		

Table 18 shows the reference technology parameter settings. Reference technologies are technologies which would be the alternative in the case that DERs are not implemented. For example, a household can not be without heat. Therefore the cost of a traditional boiler can be subtracted when calculating the cost of heat generating DERs. These parameters are based on information gathered in Section 3.2.

Table 18: Reference technologies parameters

Parameter	**Setting**
Boiler parameters	
Cost price	€2200
Efficiency	95%
Gasoline car parameters	
Cost price	€15000
Efficiency	15 km / liter

Table 19 shows the parameters of the Dutch technological environment. These are based on information gathered in Section 3.1. The cost of strengthening the grid with 100% capacity amounts €2000 per house, and the cost of strengthening the grid with 200% capacity amounts €3000 per house. This is the result of the base cost of excavation activities, which are applicable in either case (M. Bongaerts, personal communication, April 23, 2016).

Table 19: Dutch technological environment parameters

Parameter	**Setting**	**Parameter**	**Setting**
House parameters		**Grid parameters**	
Heat demand	12900 kWh	*Grid limit*	1 kW / house
Electricity demand	3300 kWh	*Cost of new capacity > 1x grid limit < 2x grid limit*	€2000 / house
		Cost of new capacity > 2x grid limit	€3000 / house

Table 20 shows the parameters of the Dutch institutional environment. These are based on information gathered in Chapter 2.

Table 20: Dutch institutional environment parameters

Parameter	**Setting**	***Parameter***	**Setting**
Subsidy parameters		**Misc. parameters**	
PV subsidy	€0 / PV	*Saldering*	Fully
Micro CHP subsidy	€0 / CHP	*Fixed energy tax payback*	€310
Solar boiler subsidy	€650 / SB	**Energy price parameters**	
Hybrid heat pump subsidy	€1250 / HHP	*Fixed gas grid costs*	€148
Electric heat pump subsidy	€1250 / EHP	*Variable gas costs*	€0,66 / m3
Home battery subsidy	€0 / HB	*Fixed electricity grid costs*	€211
		Variable electricity costs	€0,2 / kWh
		Gasoline price	€1,5 / liter

5.2.2 Input load profiles of DER

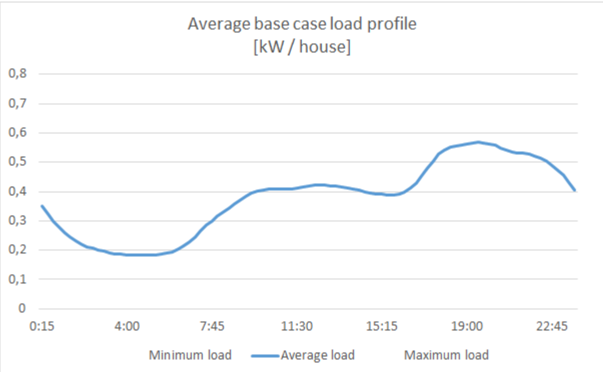

Figure 22: Base case load profile

The core of the model consists of a number of load profiles of different technologies. Load profiles are the collective of electricity loads over a given time period. Every 15 minutes the 'load' is given, measured in kW. Over a week this collection forms a load profile. Figure 22 shows the average load profile of a neighbourhood without any DER; the so-called 'base case' load profile. A number of different load profiles are used in the model, which can be seen in Table 21. From every load profile a 'relative' load profile is constructed. A relative load profile is a load profile in which the different data points are fractions instead of loads. These cumulative of these fractions add up to 1. As such, the load profile can be multiplied by any yearly production or consumption amount, measured in kWh, from which real time production and consumption are derived, measured in kWh / quarter hour.

Table 21: Load profile sources

Load profile needed	Input data used	Source
Base electricity consumption load profile	EDSN standard electricity consumption load profile	(Van Langen, Van Tol, Quak, & van Bruggen, 2016)
Base gas consumption load profile	Zonnedael – slimme meter dataset gas load profile	(Kaas, 2013)
Solar PV production load profile	Zonnedael – slimme meter dataset PV load profile	(Kaas, 2013)
Micro CHP	Zonnedael – slimme meter dataset gas load profile	(Kaas, 2013)
Solar boiler	Zonnedael – slimme meter dataset PV load profile	(Kaas, 2013)
Electric heat pump	Dagprofiel stroomversnellingswijk	(Bhagwandas, 2016)
Hybrid heat pump	Dagprofiel stroomversnellingswijk	(Bhagwandas, 2016)
EV charging load profile	KMProfiles – EVs charging load profile	(V. Dekker, 2014)

Because of the limited availability of data sources, certain load profiles are used for multiple DERs. In order to be able to use certain load profiles for DERs for which it was not originally designed, assumptions have to be made. For example, a micro CHP is assumed to follow the load profile of gas consumption of a regular household, a solar boiler is assumed to use a modified load profile of a PV installation and a hybrid heat pump is assumed to use a modified version of a load profile of an electric heat pump.

Every load profile consists of 4 average weeks, each representing a different season. For certain DERs, for which the data was available, also a minimum and maximum week are used. These are PV and heat pumps.

5.2.3 Flexibility management options

The flexibility management options identified in Section 3.3 are translated into Excel formulas. For understanding purposes, these formulas are translated into text shown in Table 22. In Appendix III, the actual Excel formulas can be found. The formulas are used to calculate new load profiles. As such, the formula refers to a cell in which the amount of electricity consumed or produced over a 15 minute period is calculated.

Table 22: Flexibility management options text equations

Flexibility management option	Text equation
PV – Dynamic curtailment	Take the minimum of: "the usual PV production" and "the grid constraint plus the amount of electricity being transported without PV"
PV – Static curtailment	Take the minimum of: "the usual PV production" and "Maximum PV capacity multiplied with the static curtailment percentage"
Hybrid heat pump – Switching to gas	Take the minimum of: "the usual electricity consumption for heat production" and "the grid constraint minus the amount of electricity being transported without the hybrid heat pump load profile" Furthermore: "Take the difference between this amount and the usual electricity consumption, and add it up with the amount of heat needed to be produced by gas."

Electric heat pump – Switching off	Take the minimum of: "the usual electricity consumption for heat production" and "the grid constraint minus the amount of electricity being transported without the electric heat pump load profile"
Electric heat pump - Shifting heat production	Makes use of a heat buffer, and assumes no losses in buffer. First identifies the period when a peak or valley occurs. Then, if a valley occurs: "Fill up the heat buffer" Then, if a peak occurs: "Use heat buffer to lower heat production". If the buffer is empty, the peak clipping stops.
EV – No evening charging	Between 17:00 and 20:00 "equals zero". Then, "Distribute this 'saved charging' over the time after 20:00"
EV – Only at night charging	Between 06:00 and 00:00 "equals zero". Then, "Distributed this 'saved charging' between 00:00 and 06:00, filling up the lowest point in the base load profile first"
Home battery – Grid oriented charging	Makes use of an electricity storage, and assumes losses of 15% when charging. First, identifies the period when a peak or valley occurs. Then, if a valley occurs: "Fill up electricity storage" Then, if a peak occurs: "Use electricity storage to lower peak". If the electricity storage is empty, the peak lowering stops.

The following figures show the effect of each flexibility management option on the load profile of a DERs. Included in each situation is the base electricity profile of a household. Each example compares the flexibility management load profile with the zero case load profile for 1 day, starting at 00:00, and ending at 23:59.

In Figure 23, the graph shows the zero option **PV load profile** during a sunny summer day. It can be seen that during the day the load profile has a 'valley'. This valley is caused by the increased production of PV, which is highest when the sun is highest as well. In Figure 24, the graph at the left shows the dynamic curtailment PV load profile. The production of PV is now 'cut off' when the grid limit (of 1 kW) is obtained. It can be seen that the load profiles stays horizontal at the -1 kW line, which is the result of the Dynamic curtailment. In Figure 24, the graph at the right shows the Static curtailment PV load profile. Here, the production of PV is cut off at a fixed maximum. As it is not dynamically adjusted to the grid limit, and the underlying base load profile changes during the day, the load profile is not perfectly horizontal.

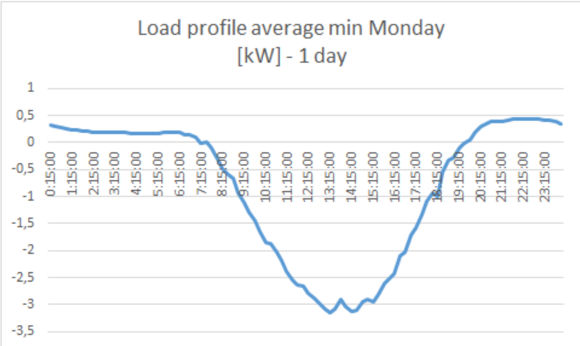

Figure 23: PV load profile with no flexibility management

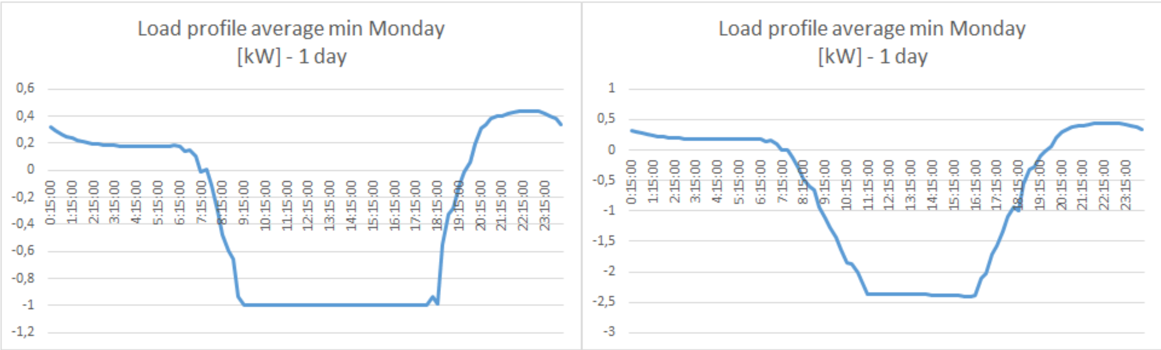

Figure 24: PV load profiles; Dynamic curtailment (left); Static curtailment (right)

The graph below (Figure 25) on the left shows the **hybrid heat pump load profile** without flexibility management during a cold winter day. It can be seen that the load profile follows the shape of the base case load profile, found in Figure 22. However, the load profile is 'lifted up' by the maximum electric capacity of the hybrid heat pump. During this winter day, the hybrid heat pump is producing much heat, and is at constant maximum electric capacity. The remaining heat required is produced using the gas fired boiler. The graph below on the right shows the Switching to gas hybrid heat pump load profile. The hybrid heat pump now switches to gas when the grid limit of 1 kW is reached.

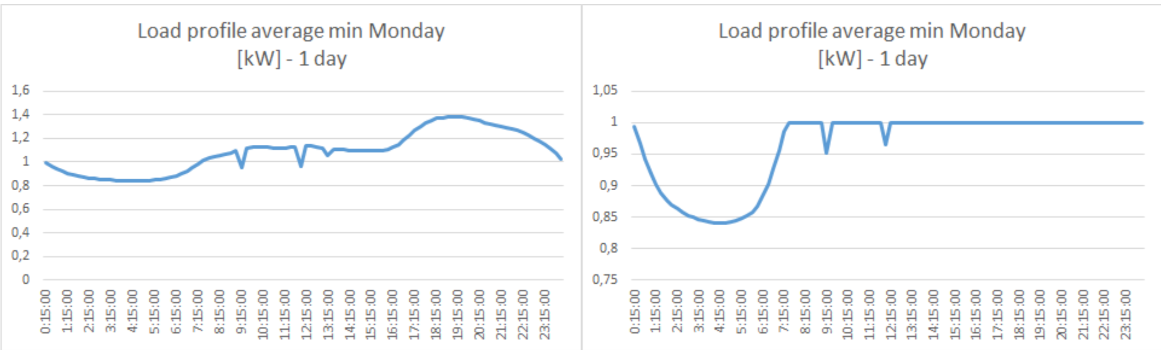

Figure 25: Hybrid heat pump load profile; No flexibility management (left); Switching to gas (right)

In Figure 26, the graph shows the **electric heat pump load profile** without flexibility management during a cold winter day. It can be seen that through the day, the production of heat varies, depending on the need for heat of the household. In Figure 27, the graph at the left shows the Switching off load profile. It can be seen that the electric heat pump is switched off when the 1 kW grid limit is reached. The graph at the bottom shows the Shifting heat production load profile. It can be seen that the load profile has lower peaks and valleys then the zero option load profile at the right (Figure 27). This is caused by the 'load shifting' mechanism taking place: heat is generated at other times and is stored using the thermal capacity of the house.

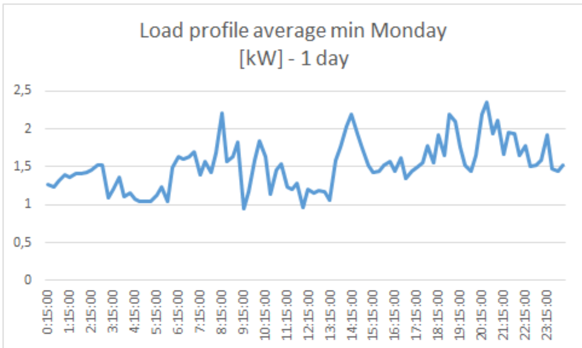

Figure 26: Electric heat pump load profile with no flexibility management

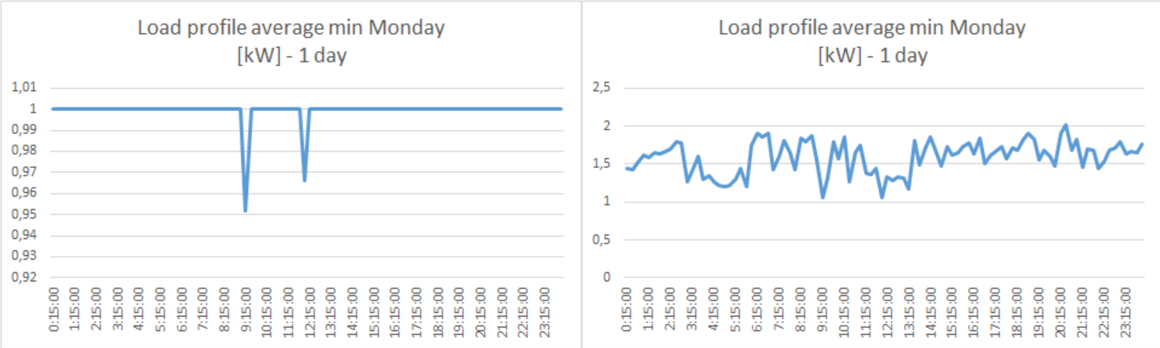

Figure 27: Electric heat pump load profile; Switching off (left); Shifting heat production (right)

In Figure 28, the graph on the left shows the zero option **home battery load profile** when combined with PV. It can be seen that, compared to Figure 23, the PV valley is less 'deep', until around 14:30. Before this time, the home battery stored part of the electricity generated by the PV. Around 14:30, the home battery is full, and the battery stops charging. At this point, the full PV output is exported to the grid, leading to the steep drop in the load profile. The graph on the right shows the Grid oriented charging home battery load profile when combined with PV. In this load profile can be seen that the home battery starts charging when the valley is around its lowest point. As such, it refrains from being 'full' before the peak has ended.

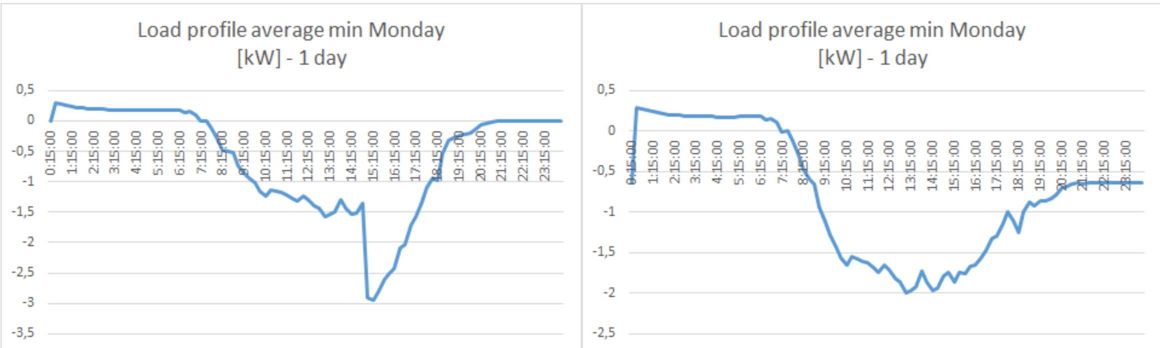

Figure 28: Home batteries and PV load profile; Zero option charging (left); Grid oriented charging (right)

In Figure 29, the graph shows the **EV charging load profile** without flexibility management. It can be seen that households charge their vehicle during the whole day, with a peak in the evening hours. This can be explained from the fact that people come home from work around this time, and then are done using their vehicle for the day. In Figure 30, the graph at the left shows the No evening charging load profile. With this flexibility management option, EVs are not allowed to charge during the evening hours. Between 17:00 and 20:00 no charging is allowed, resulting in a steep drop. Afterwards, the 'lost'

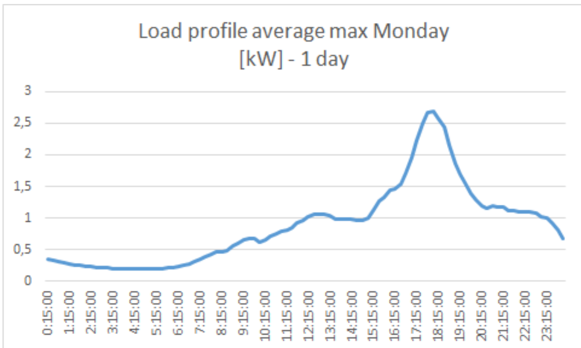

Figure 29: EV charging load profile without flexibility management

charging is spread out over the remainder of the late evening. In Figure 30, the graph at the right shows the At night only charging load profile. In this load profile the only times charging is allowed are between 00:00 and 07:00. As such, an increase is seen during the night. Not that the maximum peak with At night only charging (around 1,6 kW) is lower than the peak during the zero option (around 2,6 kW)

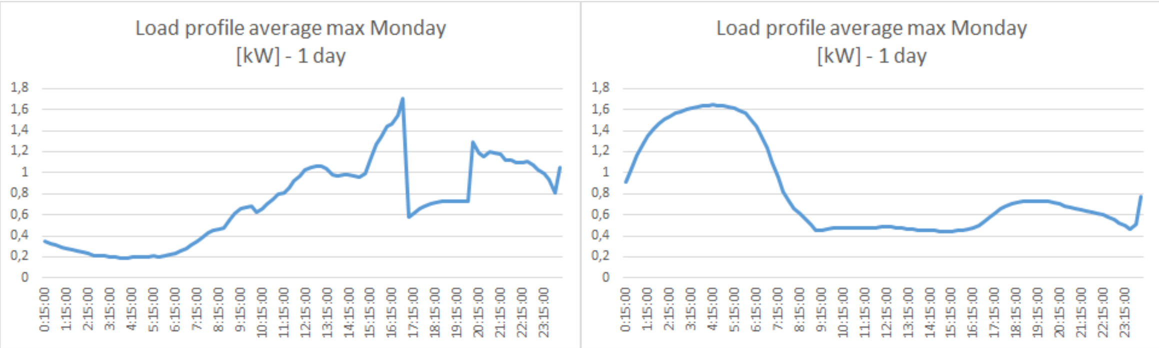

Figure 30: EV charging load profile; No evening charging (left); At night only charging (right)

5.2.4 Relationships in the NDP system sub-model

The NDP system sub-model connects all input variables. The main tasks performed by this sub-model are adding up the load profiles of different DERs and performing calculation steps for the output variables. In this section the main functionalities of this sub-model are discussed.

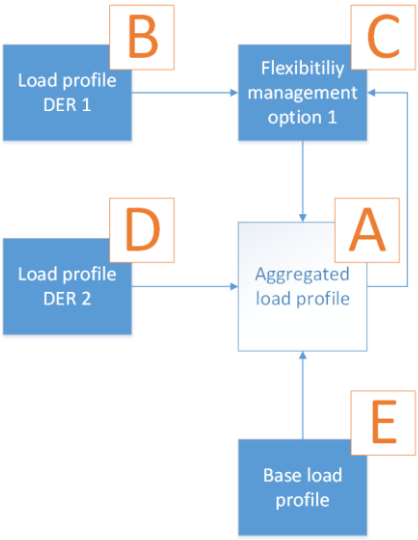

Figure 31: Relationships in the NDP system sub-model explanation

Figure 31 shows the working of the sub-model. Within the model an aggregated load profile (A) is used to connect all individual load profiles. The aggregated load profile consists of all other load profiles combined. A load profile of DERs 2 (D) is combined with the base load profile (E) and a flexibility management option profile (C). This flexibility management profile is based on the load profile of DERs 1 (B), but also on information given by the aggregated load profile (A). As such, a 'feedback loop' is created.

However, Excel is not able to deal with feedback loops. As such, an alternative method is used to mimic this effect (Figure

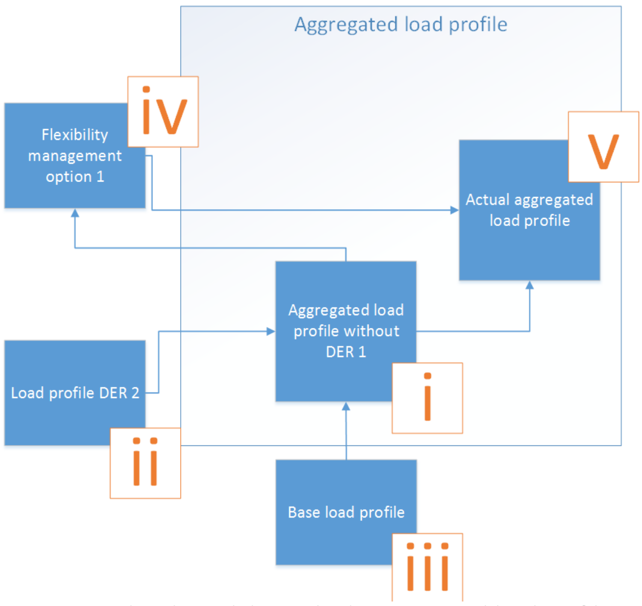

Figure 32: Sub-sub-models inside the aggregated load profile

32). First, an aggregated load profile (i) is generated which combines the load profiles of all other DERs being applied, such as the load profile of DERs 2 (ii) and the base load profile (iii). This Aggregated load profile without DERs 1 (i) is than 'send' to Flexibility management option 1 (iv), which adjusts the load profile if DERs 1 (not depicted) based on the information given by the Aggregated load profile without DERs 1 (i). The Actual aggregated load profile (v) then combines the Flexibility management option (iv) and the Aggregated load profile without DERs 1 (i). The Actual aggregated load profile (v) is then used for the calculation of KPI.

The main information needed for the output sub-model is the effect of applying flexibility management on the load profile. The output sub-model then uses the information obtained from the 'Relationships in the NDP system' sub-model to calculate KPI. Most of these KPI use the amount of electricity and gas being consumed as a base. Within the model this is done as follows: First, calculate the area under a load profile by summing up all entries in the Excel model. Every season has a different load profile, which should be added up. The result should then be divided by 4 (representing the number of weeks), and multiplied by 52 (number of weeks in one year). This results in the yearly output being calculated. Note that only the average weeks are used here and that the minimum and/or maximum week is not incorporated in this calculation.

5.2.5 Output sub-model

The output sub-model calculates the output variables. The output variables are direct translations from the KPI identified in section 3.4. The following KPI were identified (Figure 33). As stated in the previous section 5.2.4, the KPI are calculated using the areas under the aggregated load profile. A change in load profile could thus result in a change in KPI. A detailed explanation of how the KPI are calculated in the model can found in Appendix III.

	A	B	C	D	E
4		Key Performance Indicators			
5			Unit	Active experiment:	Custom scenario
6		**Home owners specific KPI**			
7		Home owners NPV	[€]	€ 5.406,50	
8		Home owners payback time	[year]	7,56	
9		Home owners grid independence	[%]	0,00	
10		**DSO specific KPI**			
11		DSO NPV	[€]	€ -2.250,00	
12		Grid limit exceedance	[%]	64%	
13		**System KPI**			
14		Social NPV	[€]	€ 3.156,50	
15		Net yearly carbon emissions saved	[ton CO2]	0,97	
16		Percentage yearly carbon emissions saved	[%]	0,15	
17		NPV per net total carbon emissions saved	[€ / ton CO2]	216,73	

Figure 33: Key performance indicators in the spreadsheet model

5.3 Model overview

This section provides a summary of how the Excel model works. The Excel model consists of 21 sheets. Appendix I shows a detailed overview of every sheet's functionality. The input sheet is shown in Figure 34 and is discussed further in this section. There are two output sheets which give detailed the effect of different experiments on the KPI (Appendix VI). The Settings sheet specifies the model settings. There are four experimental sheets. (1) 'Design of experiments' gives an overview of the experimental designs, (2) 'Experiment overview' stores and compares output variables (KPI) of experiments, (3) 'Verification test' is used to perform sensitivity tests and (4) 'Validation test' is used to perform historical data tests. The other sheets contain the load profiles, formulas and other data of the different model aspects respectively.

	A	B	C	D	E	F	G	H	I	J	
1		**Input neighborhood**									
2		**Experiment loaded**		**Custom scenario**			**Experiments**				
3		Index number		1					**Inidividual DER experime**		
4		**Neighborhood type**						**Custom scenario**	1	2	
5			Unit						A00	A01	A
6		Construction date	[Age]	Energy label A/B			Construction date	Energy label A/B	Energy labe	Energy labe	E
7		Total number of houses	[house]	1			Total number of houses	1	100	100	
8		**Production and storage**									
9		**Energy production**	Unit	Amount	Standard size		House owners DER				
10		PV		0	15 Panels		PV [A]	0	100	100	
11		Micro CHP		0	1 ...		Micro CHP [B]	0	0	0	
12		Solar boiler		0	1 ...		Solar boiler [C]	0	0	0	
13		Hybrid heat pump		0	4 ...		Hybrid heat pump [D]	0	0	0	
14		Electric heat pump		0	4 ...		Electric heat pump [E]	0	0	0	
15		**Energy storage**	Unit	Amount							
16		EV		1	0		EV [F]	1	0	0	
17		Home battery		0	0		Home battery [G]	0	0	0	
18		**Flex options**									
19		PV Flex					Flexibility management options DSO				
20				Option	Standard		**PV**				
21		Dynamic curtailment		No	No		Dynamic curtailment [A01]	No	No	Yes	N
22		Static curtailment		No	No		Static curtailment [A02]	No	No	No	Y
23		Heat pump flex					**Heat pump**				
24				Option	Standard		Switching off [E01]	No	No	No	N
25		Switching off [E01]		No	No		Shifting heat production [E02]	No	No	No	N
26		Shifting heat production [E02]		No	No		Switching to gas[D01]	No	No	No	N
27		Switching to gas[D01]		No	No		**EV**				
28		EV Flex					EV charging [F00,01,02]	At night only	When comi	When comi	W
29				Option	Standard		**Home battery**				
30		EV charging		At night only	When coming home		Charging [G00,01]	Smart	Dumb	Dumb	D
31		Home battery flex									
32				Option			No flex [00]				
33		Charging [G00,01]		Smart							
34				Smart							

Figure 34: Spreadsheet model input sheet

Figure 34 shows the input sheet can be seen of the model. On the left, in column B and D, input variables for DERs and flexibility management options can be seen. These are generated by the input variables for DERs and flexibility management options on the right, in columns G and H. This is done by changing the 'experiment loaded' at the top left corner (cell D2). The experimental design is stored on the far right (columns I and J). The researcher can load any of the predefined scenarios, of which 2 can be seen.

5.4 Verification

In this section the verification of the model is discussed. A definition of model verification is given by (Altiok & Melamed, 2007): "Verification assesses the correctness of the formal representation of the intended model (in our case, a computer simulation program), by inspecting computer code and test runs, and performing consistency checks on their statistics."

5.4.1 Types of verification tests

Verification consists of the following 3 activities (Altiok & Melamed, 2007):

1. Checking the code for errors
2. Inspecting model output for the correctness of the code
3. Performing consistency checks among different experiments

The first activity is performed by the researcher during and after the construction of the model. This activity is difficult to document and relies on the researcher's expertise.

The second activity easier to document. One of way of checking the correctness of the code is by performing a sensitivity analysis. In a sensitivity analysis a large number of input variables is systematically altered by a set percentage. The output variables are then checked for expected behavior. For example, the 'Cost of electric vehicles' is raised by 20%, controlling for all other variables. It is expected that the output variable 'House owner NPV' will alter by 20% as well. However, 'carbon emissions' should not be altered, as it is not dependent on the cost of electric vehicles.

The third activity is performed by comparing different experiment set ups. If two experiment set ups show different results on certain output variables where the same results are expected, this can be an indication that the code of the model is not working properly. The researcher should look for the mistake, change the code accordingly and run the test again.

5.4.2 Example

An example of a test performed for the second activity is the sensitivity analysis, which is documented in Appendix IV. The extreme value test is documented in Appendix IV as well. Experiment 23 is used as a verification test subject in this example (Table 23). Experiment 23 includes three DER: PV, electric heat pumps and EV. The output variable being checked here is the house owners NPV. The input variable being varied is the EVs cost price. The table shows how the House owner's NPV changes when the EVs cost price is lowered by 20%, when the EVs cost price remains the same and when the EVs cost price is raised by 20% respectively. The table shows that when the EVs cost price is lowered by 20% the House owner's NPV is lowered by 83%. As such, the model performs as expected: The house owners NPV raises by €4800, which is the exact the difference in price for the EV. This confirms that this calculation is performed correctly.

Table 23: Example verification test; sensitivity analysis

	Output:	**House owners NPV**		
Input:	Input change	-20%	0	+20%
EV cost price	Input value	€19200 (24000 - 4800)	€24000	€28800 (24000 + 4800)
	Output value	€10587 (5787 + 4800)	€5787	€987 (5787-4800)
	Output change	+83%	0	-83%

The third verification activity is comparing results of experiments to check for inconsistencies. An example of such a test is comparing the results of three different ways of charging EVs. Table 24 shows the results of the singular EVs experiments, including the Zero option, Only at night charging and No evening charging respectively. As can be seen, the different charging profiles all result in the same house owners NPV. This shows that the amount of electricity charged by an EV is shifted, and not altered in amount. Additionally table shows that, as expected, the same percentage yearly carbon emissions are saved. As such, it can be concluded that his part of the model has been coded correctly. Using this method, also the other parts of the model are checked for. If a mistake is detected, the model code is altered and the test is run again.

Table 24: Example verification test; comparing results

KPI	Unit	Zero option	Only at night charging	No evening charging
House owner specific KPI				
Home owners NPV	[€ / house]	€ 5406,50	€ 5406,50	€ 5406,50
Home owners payback time	[year]	7,56	7,56	7,56
Home owners grid independence	[%]	0%	0%	0%
DSO specific KPI				
DSO NPV	[€ / house]	€ -3.000,00	€ -2.000,00	€ -2.000,00
Grid limit exceedance	[%]	170%	71%	64%
Shared KPI				
Shared NPV	[€ / house]	€ 2406,50	€ 3406,50	€ 3406,50
Net yearly carbon emissions saved	[ton / year / house]	0,97	0,97	0,97
Percentage yearly carbon emissions saved	[%]	15%	15%	15%
NPV per net yearly carbon emissions saved	[€ / ton / year]	165,23	233,90	233,90

5.5 Validation

A definition of validation is given by (Altiok & Melamed, 2007):"Validation assesses how realistic the modelling assumptions are, by comparing model performance metrics (predictions), obtained from model test runs, to their counterparts in the system under study (obviously, validation is possible only if the latter exists)." In this research three validation methods are applied: Comparing results with historical data, comparing results with previous research and using expert knowledge to validate model assumptions.

For validating model correctness certain scenarios can be simulated in the model and compared with sample data, a so called historical data test (Irannajad, Farzanegan, & Razavian, 2006). This method relies on the availability of historical sample data. For NDP this data is limitedly available and most of the available data has been used as input data for the spreadsheet model itself, making it unfit for validation purposes. Still, there is some data available to make a comparison between model results and historic data. This comparison is shown in Appendix V. Figure 35 shows a part of this test. The data shown in the figure represents a neighbourhood with PV and electric heat pumps in spring. The blue line represents the historical data (T. Dekker et al., 2016) and the orange line represents model data. As can be seen, the similarity is high. The average difference between the model and historical data is 7%. The variance of the difference is 11%.

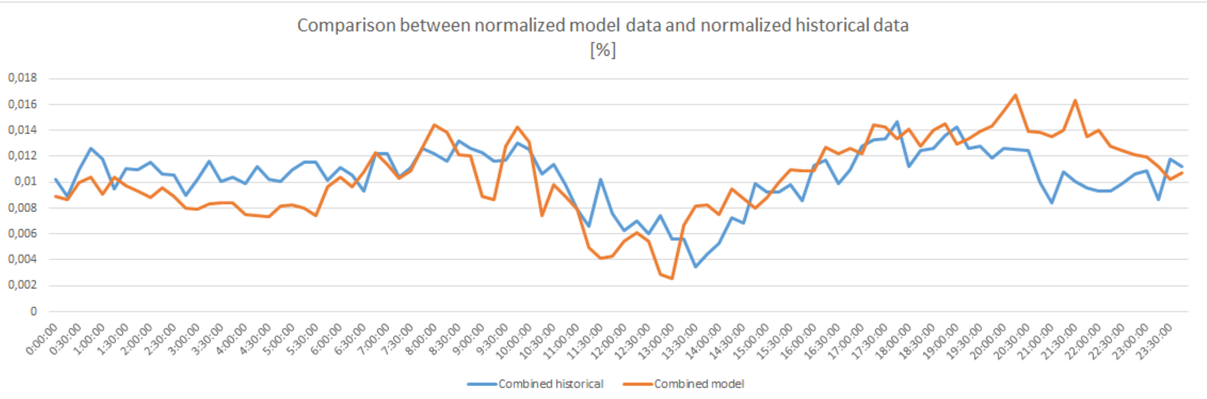

Figure 35: Comparison of normalized historical load profile and normalized model load profile

A second method applied is comparing the simulation results with previous research. A difficulty of this method is that research itself is not consistent in its results. For example as concluded in Section 3.2, the payback time of heat pumps differs in literature between 7 and 39 years. As this represents the difference for a single DERs, the difference for combinations of DERs are expected to be even more ambiguous. Furthermore, the payback time of specific combinations of DERs used in this research is not available. Performing a literature comparison on combinations of DERs is thus difficult. As such, for the validity of results of combinations of DERs, the internal verification of the model as performed in Chapter 5 is used. Individual technologies are tested to the best of means in Appendix V.

Table 25 shows the parameters with the highest difference between the model data and the data found in previous research. All other used parameters stay within the 25% limit. For these six parameters the difference between the literature and the model data is explained below.

Table 25: Validation; Parameters with the highest difference

Parameter	Unit	Model data	A	Difference A	B	Difference B	Source A	Source B
Electric heat pump energy bill reduction	[€]	427	300	42%	208	109%	(Milieu Centraal, 2016k)	(Warmtepompforum, 2010)
PV energy bill reduction	[€]	660	440	50%	782	-16%	(Milieu Centraal, 2016h)	(Zonnepanelen-info, 2016b)
CHP energy bill reduction	[€]	209	300	-30%	400	-48%	(Milieu Centraal, 2016f)	(Mank, 2016)
CHP payback time	[year]	39,7	38	4%	27,5	44%	(Milieu Centraal, 2016f)	(Mank, 2016)
Hybrid heat pump payback time	[year]	15	14,16	6%	24,69	-39%	(Milieu Centraal, 2016k)	(Frenaij, 2016)
Hybrid heat pump energy bill reduction	[€]	203	300	-32%	195	4%	(Milieu Centraal, 2016k)	(Frenaij, 2016)

The **electric heat pump energy bill reduction** model results are significantly higher than those of the sources. This difference can be explained by the choice the model provides to households to disconnect from the gas grid. A fixed tariff of €148 is paid every year for a gas grid connection (Autoriteit Consument & Markt, 2015). This tariff can be saved when the household chooses to disconnect from the gas grid. This option is not incorporated in the two sources. If €148 is not incorporated, the yearly energy savings are €279 instead of €427. This is within 25% difference of the two sources.

The **PV energy bill reduction** lies in between two the two sources. These sources differ 80% from each other. As stated before, the model produces an average for each DERs, and much depends on the specific situation. The model results is in the right order of magnitude.

The **CHP energy bill reduction** and **CHP payback time** differ from the sources. They are both lower. This can be explained by the base amount of gas consumed by the household. As stated by (Milieu Centraal, 2016f), micro CHP becomes interesting at a yearly gas consumption of 1600m3.

The households in the model have a gas consumption of only 1390 m^3 per year. Thus lower energy bill reduction and longer payback time were expected. The data does however lay in the right order of magnitude of the sources.

The **Hybrid heat pump payback time** and **Hybrid heat pump energy bill reduction** both differ from one source, but are almost identical to the other source. The Hybrid heat pump payback time is 39% lower than one source states. This can be explained, as this source uses higher investment costs for hybrid heat pumps, including the costs for insulation, whereas the model does not. The Hybrid heat pump energy bill reduction differs 32% from one source. This difference is difficult to explain, but might have to do with the assumed efficiency of the hybrid heat pump. If the source uses a higher efficiency the energy bill reduction is higher.

A third method applied is expert validation. The model was shown in a presentation to three NDP experts from DSO Alliander. The presentation showed both the model assumptions regarding DERs and the considered flexibility management options. After the presentations and the following general discussion, they concluded that the DERs input variables and load profiles were correctly used (V. Dekker, personal communication, August 22, 2016). Appendix V shows the questions asked and the answers given at the end of the discussion. The two experts have the following two remarks:

First, in real life NDP, the valley caused by PV is much lower, going as low as 7 kW, while in the model results only a valley of 3,5 kW is obtained (Section 6.2). The difference can be explained by the model choice to keep parameter values constant during the experiments, and to only change the combination of DERs. In real life a NDP consists of at least 30 PV panels per house, while the model considers only 15 panels per house. The reason why the model considers only 15 panels, as this covers the base electricity demand per house (3300 kWh per year), as all DERs parameter values are chosen to cover 'base energy' needs. Comparing results becomes easier when the parameter values between experiments remain constant. When the number of panels was changed to 30, the model also showed a valley of 7 kW. Second, a remark was made that in the case of DSO Alliander, recently (August 2016) Alliander made the decision to charge house €600 if they want to disconnect from the gas grid. However, it is not known if other DSOs charge this removal fee as well. It would however make the difference between the DSO NPV and the House owner NPV smaller

5.6 Summary: Answering sub question 4

Sub question 4 can now be answered:

How can a neighbourhood distributed energy resource project be represented in a model taking a systems perspective?

A model was designed and verified to investigate the effects of various combinations of DERs and flexibility management options on grid limit excess. The model uses model parameters that are based on previous literature and uses the load profiles of historical data of existing NDP. Flexibility management options are based on equations, altering the load profiles of DERs. Output variables are calculated mostly on the basis of the calculation of the area under the four seasons of the load profiles.

6 Results

This chapter presents the model results. This chapter answers sub question 5:

What are the combined effects of distributed energy resource and flexibility management integration for the key performance indicators?

This chapter is built up following the experimental design in Chapter 5. The complete experimental design can be found in Appendix VI. In the first section, the characteristics of the base case are discussed, in which the load profile of a neighbourhood without DERs is presented. In the following sections the results are discussed. The results are summarized using load profiles and tables. In these tables three KPI are shown: Grid limit excess, Shared NPV and Percentage yearly carbon emissions saved. In the text, sometimes additional results are stated. These are all based on the results found in Appendix VII. The results are discussed as follows:

First, the results of the experiments are shown in which only 1 DERs is being installed. The results show the effect of different flexibility management options on the grid limit excess which is caused by the simultaneous installation of one form of DERs. A comparison is made between the case in which no flexibility management is applied (the 'zero case'), and cases in which different flexibility management options are applied.

Second, the results of experiments are shown in which multiple DERs are installed simultaneously for which flexibility management options are considered. The results show the effect of different flexibility management options on the gird limit excess which is caused by the simultaneous installation of multiple forms of DERs. A comparison is made between the case in which no flexibility management is applied (the 'zero case'), and cases in which different flexibility management options are applied.

Third, the results of experiments are shown in which multiple DERs are installed simultaneously, also including DERs for which no flexibility management options are considered. The results show the effect of combining different DERs on the gird limit excess which is caused by the simultaneous installation of multiple forms of DERs. A comparison is made between combinations of different DERs.

6.1 Base case

In this chapter a number of load profiles will be presented, which represent the effect of various flexibility management options on the load profiles of different DER combinations. In order to place these into perspective, the 'base case' is presented. Figure 36 shows the load profile of a base case neighbourhood, in which no DERs are applied. Every other load profile in this chapter uses the same structure as this one. The figure shows a 1 day time period of three load profiles. The graph shows the minimum load profile representing a summer day (green line), the average load profile (orange line) and the maximum load profile representing a winter day (blue line). The differences between the maximum and minimum are explained by seasonal variety. During winter households consume more electricity than during summer. This seasonal variety will also explain the differences between maximum and minimum for all other load profiles in this chapter. In Appendix VII some examples are given which show the seasonal averages, instead of the yearly ones used in this chapter. A yearly average is used in this chapter for clarity and readability purposes.

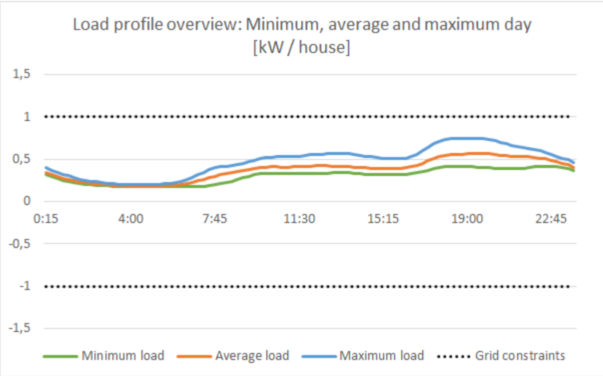

Figure 36: Base case load profile

The dotted lines represent the grid constraints, which are set on -1 kW and +1 kW (Section 3.1). In the 'base case' situation the electric load is at a minimum during the night, and is at a maximum during the evening. It can be seen that the grid limits are not exceeded in the normal situation.

6.2 Singular DERs and flexibility management options results

In this section the results of the first set of experiments are presented: **Singular DERs and flexibility management options** (Section 4.3.2). The load profiles of singular DERs and flexibility management options are shown in Section 5.2.3, and therefore are not repeated in this section.

It was found that **PV** causes the highest grid limit excess of all DER: 234% (Table 26: PV resultsTable 26). The grid limit excess can be fully eliminated when applying Dynamic curtailment. When applying Dynamic curtailment, the PV installation is shut-off when grid limits are exceeded. The DSO thus does not have to invest in the low-voltage grid anymore, resulting in an increased Shared NPV. It is thus solely the DSO who benefits fro this flexibility management option. The House owner NPV even decreases when Dynamic curtailment is applied, because: As the PV installation is shut off when the grid limit is exceeded, the house owner produces less electricity, which results in a payback time which is 1.5 years longer (11.7 years instead of 10 years). Still, the Shared NPV is €1625 per house higher than when no flexibility management is applied. Additionally, as less electricity is produced with Dynamic curtailment, slightly less carbon emissions are saved (5% less). Static curtailment also increases Shared NPV, being €495 per house higher. However, here the benefits go purely to the house owner, which benefits from the cheaper convertor. Static curtailment reduces grid limit excess compared to the Zero option, but is still high with 141%. The 70% peak clipping simply is not enough to fully eliminate grid limit excess. The DSO thus still has to invest in the low-voltage grid.

Table 26: PV results

PV	Unit	Zero option	Dynamic curtailment	Static curtailment
Grid limit excess	[%]	234 %	0 %	141 %
Shared NPV	[€ / house]	€ 270	€ 1895	€ 765
Percentage yearly carbon emissions saved	[%]	37 %	32 %	37 %

It was found that **electric heat pumps** cause the second highest grid limit excess: 184% (Table 27). The grid limit excess can be fully eliminated when applying the Switching off flexibility management option. Electric heat pumps will now be switched off when the grid limits are reached. This increases the Shared NPV from €-7734 per house to €-2757 per house. This increase can be explained by two things: First, the DSO does not have to invest in the grid, and second, the house owner which consumes less electricity. The latter is caused by the heat pumps being switched off regularly during winter. During the most extreme week, at certain times 83% of the heat pumps will have to be switched off to maintain the low-voltage grid balance. This is undesirable, and is further discussed in Chapter 7. Shifting heat production decreases the grid limit excess from 184% to 127%. In this case the production of heat is shifted to other time periods and the heat is 'stored'. As the losses for this storage are assumed zero, the Shared NPV remains equal.

Table 27: Electric heat pump results

Electric heat pump	Unit	Zero option	Switching off	Shifting heat production
Grid limit excess	[%]	184 %	0 %	127 %
Shared NPV	[€ / house]	€ -7734	€ -2757	€ -7734
Percentage yearly carbon emissions saved	[%]	24 %	29 %	24 %

The installation of **hybrid heat pumps** without flexibility management results in a grid limit excess of 40%, which is lower than that of other DERs (Table 28). Forced switching to gas eliminates this grid excess completely. The heat pump now switches to gas when the grid limit is reached. As such, the DSO does not have to invest in the strengthening of the electricity grid. However, the house owner will have to pay for a higher gas consumption: €197 more at the end of 15 years, which results in a longer payback time of 1 year (16 years instead of 15 years). The carbon emissions of hybrid heat pumps without flexibility management are marginally lower than electric heat pumps: 22% carbon emission reduction instead of 24% when using electric heat pumps. Switching to gas lowers the percentage carbon emissions saved by 1% point.

Table 28: Hybrid heat pump results

Hybrid heat pump	Unit	Zero option	Switching to gas
Grid limit excess	[%]	40 %	0 %
Shared NPV	[€ / house]	€ -2000	€ -197
Percentage yearly carbon emissions saved	[%]	22 %	21 %

EVs have a high grid limit excess of 170% (Table 29). The Shared NPV is the highest compared to other DERs, with €2407 per house. The reason for this is because it only takes around 8 years more to pay back an electric vehicle compared to a conventional car. As a standard 15 year time period is considered in the model, a high NPV for the house owner is thus obtained, raising the Shared NPV. The DSO though has to perform costly grid investments of €3000 per house. The Shared NVP might be high but the NPV balance between the DSO and house owner is low. A change in the charging behaviour of EVs lowers grid limit excess and thereby lowers the need for grid investments (Table 29). Applying No evening charging lowers grid limit excess to 70%, and Only at night charging to 64%. The DSO still has to do grid investments, but these are now €2000 per house instead of €3000 per house. The percentage yearly carbon emissions saved is 15%, meaning that the net carbon emissions saved is 1 ton/year/house. This is a result from the fact that EVs use electricity, which has a net lower carbon emission than gasoline. However, natural gas is used to heat the house, and therefore the relative carbon emissions saved are lower than for other DERs (electric heat pumps (24%) or PV (37%)).

Table 29: EV results

EV	Unit	Zero option	No evening charging	Only at night charging
Grid limit excess	[%]	170 %	70 %	64 %
Shared NPV	[€ / house]	€ 2407	€ 3407	€ 3407
Percentage yearly carbon emissions saved	[%]	15 %	15 %	15 %

6.3 Combinations of DERs results

In this section the results of the **DER combination experiments** will be presented (Section 4.3). Being presented are only the best and the worst scoring experiments. Complete results can be found in Appendix VII.

6.3.1 PV and electric heat pumps

In this sub section the results are presented from the experiments which are include a DER combination **of PV and electric heat pumps**. The impact of various combinations of flexibility management options on the two DERs are compared to each other.

The zero option of a **combination of electric heat pumps and PV** without flexibility management produces a grid limit excess of 224% (Table 30). Figure 37 shows that both the maximum load profile and the minimum load profile result in grid limit excess. The maximum load profile represents a cold winter day when the electric heat pump has a high load and the PV production is minimal. The minimum load profile on the other hand, represents a sunny summer day when maximum PV production

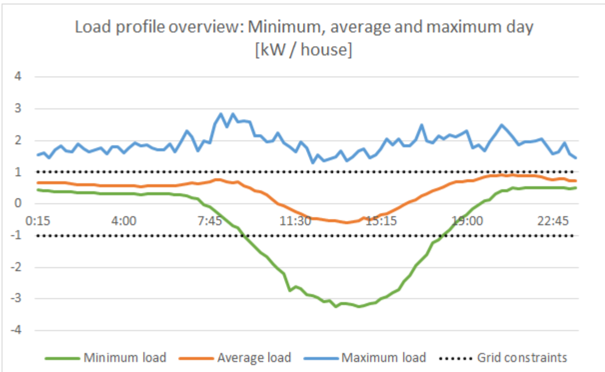

Figure 37: PV and electric heat pumps load profile with no flexibility management

occurs and heat production by the heat pump is minimal. The Shared NPV is negative with €-3964 per house. This is caused by a negative DSO NPV as the DSO has to invest in the grid, and additionally, because the DSO will lose the yearly gas grid connection fee from the households. The NPV of the house owner is slightly positive being €380 per house. The reduction in carbon emissions is however high, being 61%, which is caused by the combination of carbon free electricity generation and relative low carbon emission as electricity is being used for heating the house instead of natural gas.

Looking at the combinations of flexibility management options, results show that grid limit excess is difficult to eliminate for this combination of DERs. Table 30 shows the two most effective combinations of flexibility management. A combination of Dynamic curtailment for PV, and Switching off for the electric heat pumps is the only possibility for eliminating grid limit excess. Figure 38 (left) represents the load profile of the Dynamic curtailment / Switching off combination. The figure shows how both loads are cut off at the grid limit. In this case, in order to eliminate grid limit excess 83% of the heat pumps have to be switched off at cert times. This is undesirable (see Chapter 7).

The next best option to mitigate grid limit excess is a combination of Dynamic curtailment and Shifting heat production. Grid limit excess is reduced from 224% tot 126%. However, this is not enough to reduce grid investments. Figure 38 (right) shows the load profile of this combination. It can be seen that the 'valley' caused by PV is mitigated (green line), but that the electric heat pump still causes grid limit excess (blue line).

Table 30: PV and electric heat pumps results

PV and electric heat pumps	Unit	Zero option	Dynamic curtailment and Switching off	Dynamic curtailment and Shifting heat production
Grid limit excess	[%]	224 %	0 %	126 %
Shared NPV	[€ / house]	€ -4464	€ -1354	€ -5289
Percentage yearly carbon emissions saved	[%]	61 %	62 %	58 %

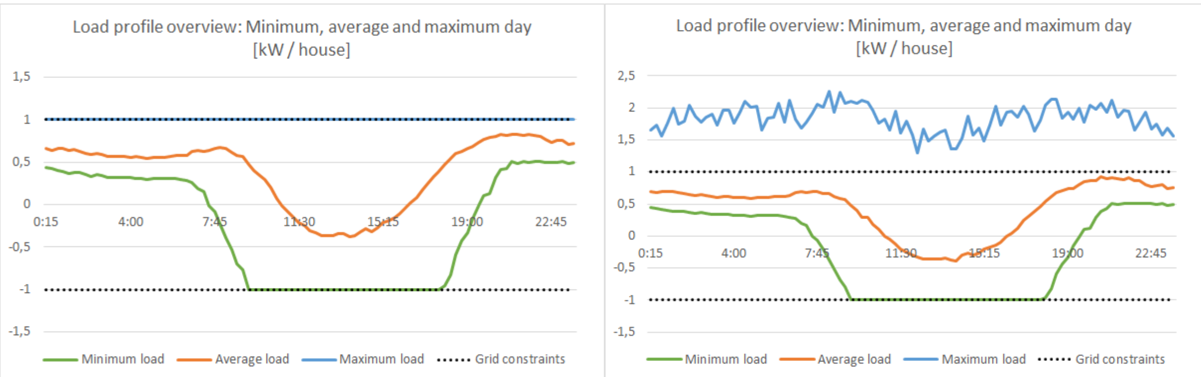

Figure 38: PV and electric heat pumps load profile; Dynamic curtailment and Switching off (left); Dynamic curtailment and Shifting heat production (right)

6.3.2 PV, electric heat pumps and EV

In this sub section the results from the experiments which include a **DER combination of PV, electric heat pumps and EVs** are presented. The impact on grid limit excess of applying various combinations of flexibility management options on the installation of the three types of DERs in NDP are compared to each other.

The zero option, when all three types of DERs are installed but when no flexibility management options are applied, results in an even higher grid limit excess than the zero option of the previous showed combination (of only PV and electric heat pumps): 313% instead of 224% (Table 31). This rise is caused by the stacked load profiles of the base load profile, the heat pumps and the EVs charging (Figure 39). EVs are getting charged when inhabitants get home. This charging peak occurs at the same time as the traditional evening peak takes place, and as such results in a high grid limit excess. As the installation of EVs results in a high positive NPV for the home owner, the Shared NPV is positive, even though the DSO NPV is negative. However, the DSO has to invest in the grid, and adding this up to the lost gas grid connection fees results in a negative DSO NPV of €-4850 per house. The percentage of yearly carbon emissions saved is lower than for the combination of these three DERs without EVs (53% instead of 61%, compare Table 31 with Table 30). However, the absolute carbon emissions saved is higher, as carbon emissions from a traditional car are not incorporated when no EVs is present in the experiment (3.44 ton per year per house instead of 2.47 ton per year per house).

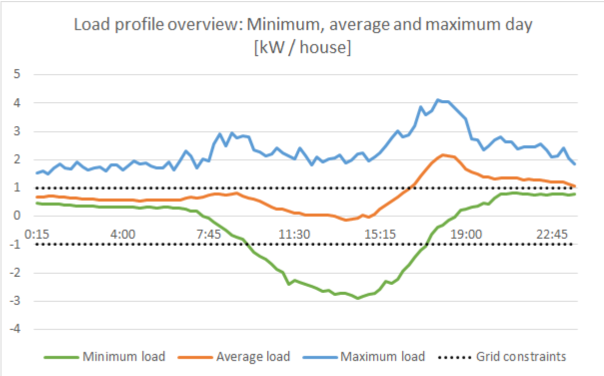

Figure 39: PV, electric heat pumps and EVs load profile with no flexibility management

None of the flexibility management options are able to completely eliminate grid limit excess. However, some are able to reduce it significantly. The combination of Dynamic curtailment of PV and Switching off of electric heat pumps is the most grid effective option, when combined with either Only at night charging or No evening charging of EVs (Figure 40). These combinations reduce grid limit excess the most, from 313% to 64% for the including Only at night charging, and 70% for including No evening charging. However, this time as many as 99,8% of the heat pumps will have to be shut off at certain times. This is undesirable. The next best option to reduce grid limit excess is Static curtailment of PV combined with Shifting heat production of electric heat pumps and No evening charging of EVs (Figure 40). The combination of these flexibility management options on the three forms of DERs reduces grid limit excess from 313% to 220%. The Shared NPV only improves slightly, as the DSO still has to invest a lot in the low-voltage electricity grid. All other combinations of flexibility management options performed worse on grid limit excess.

Table 31: PV, electric heat pumps and EVs results

PV, electric heat pumps and EVs	Unit	Zero option	Dynamic curtailment, Switching off and At night only charging	Static curtailment, Shifting heat production and No evening charging
Grid limit excess	[%]	313 %	64 %	220 %
Shared NPV	[€ / house]	€ 942	€ 5192	€ 1437
Percentage yearly carbon emissions saved	[%]	53 %	60 %	53 %

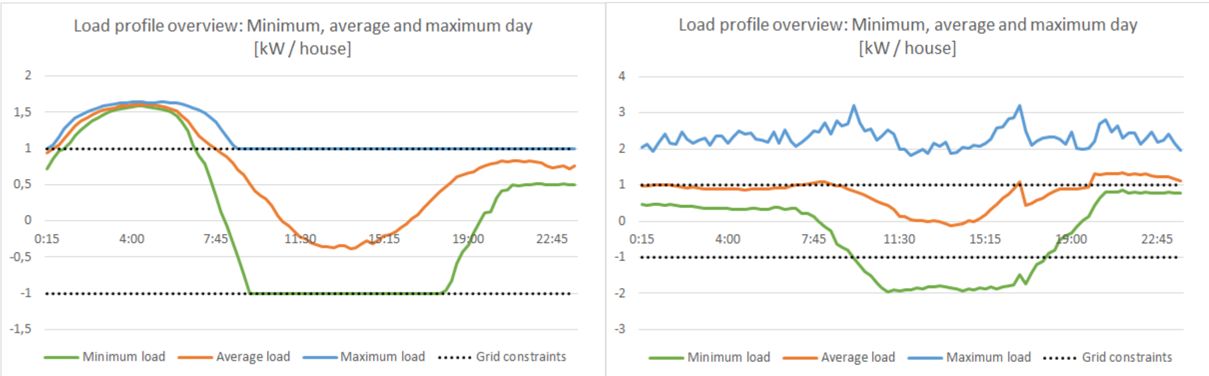

Figure 40: PV, electric heat pumps and EVs; Dynamic curtailment, Switching off and At night only charging (left); Static curtailment, Shifting heat production and No evening charging (right)

6.3.3 PV and hybrid heat pumps

In this sub section the results are presented from the experiments which are built up around a **DER combination of PV and hybrid heat pumps**. The impact of various combinations of flexibility management options are compared to each other.

The zero option **combination of PV and hybrid heat pumps** causes a grid limit excess of 224% (Table 32). As can be seen in Figure 41, this is mainly the result of the valley caused by PV. The Shared NPV is slightly positive (€270 per house) and 59% of carbon emissions are saved yearly. Looking at the results in Appendix VII, it becomes clear that even though the Shared NPV is slightly positive, a big difference exists between the NPV of house owners (€3270 per house) and the NPV of the DSO (€-3000 per house).

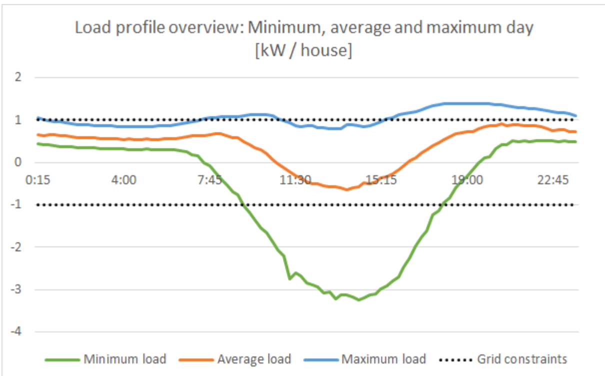

Figure 41: PV and hybrid heat pumps with no flexibility management

There are multiple flexibility management options which reduce grid limit excess drastically (Appendix VII). Only applying Dynamic curtailment of PV already reduces grid limit excess to 40% (Table 32). This effect can be seen in Figure 42 on the left, in which the remaining grid limit excess is caused by the hybrid heat pump. The combination of Dynamic curtailment of PV and Switching to gas of hybrid heat pump eliminates the remaining grid limit excess (Figure 42 (right)). Compared to the zero option, a combination of Dynamic curtailment and Switching to gas results in 5% less carbon emission reduction. This is caused by more gas being consumed than in the zero option case. Further more, the Shared NPV raises from €270 per house to €2302 per house. This rise is caused by the €3000 per house which the DSO saves, because it does not have to invest in the grid anymore. However, the house owner will have to use relatively more expensive gas instead of electricity, and as such his NPV drops from €3270 per house to €2302 per house. The household payback time thereby becomes 12 years instead of 11 years. Combinations which include Static curtailment reduce grid limit excess to 127%, even if not combined with the flexibility management option Switching to gas. Combinations with Static curtailment raise house owner NPV. For example, applying only Static curtailment reduces grid limit excess to 127%, while raising house owner NPV from €3270 per house to €3765 per house (Appendix VII). The rise is caused by the cheaper convertor applied in Static curtailment. The implications of Static curtailment are further discussed in Chapter 7.

Table 32: PV and hybrid heat pumps results

PV and hybrid heat pumps	Unit	Zero option	Switching to gas and Dynamic curtailment	Dynamic curtailment
Grid limit excess	[%]	224 %	0 %	40 %
Shared NPV	[€ / house]	€ 270	€ 2302	€ 451
Percentage yearly carbon emissions saved	[%]	60 %	55 %	57 %

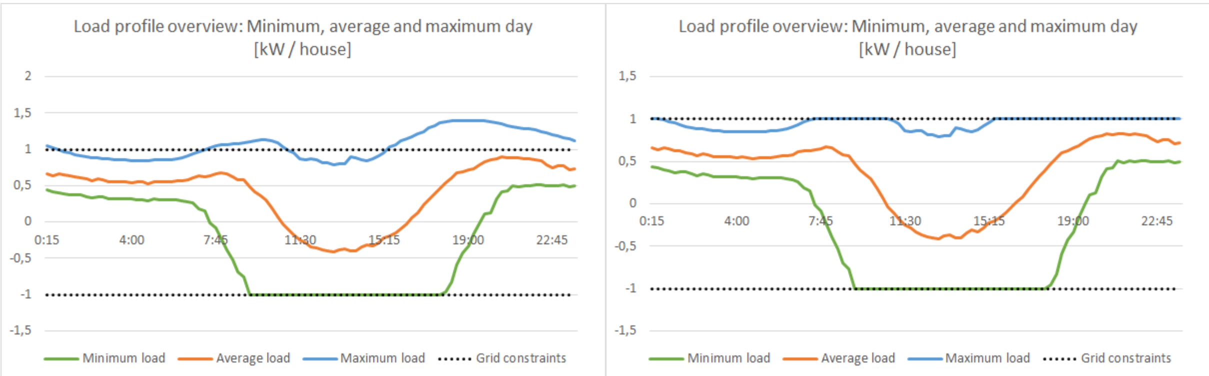

Figure 42: PV and hybrid heat pumps; Dynamic curtailment (left); Dynamic curtailment and Switching to gas (right)

6.3.4 PV, hybrid heat pumps and EVs

In this sub section the results from the experiments which include a **DER combination of PV, hybrid heat pumps and EVs** are presented. The impact of various combinations of flexibility management options are compared to each other.

The zero option of a combination of PV, hybrid heat pumps and EVs results in a grid limit excess of 235% (Table 33). This is 11% higher than the same combination without EVs (Table 32). This slight increase can be explained by the 'room' left in the peak of the aggregated load profile, as the peak of hybrid heat pumps is relatively not so high, as concluded in the previous sub section. Looking at the load profile (Figure 43), the high evening peak is caused by the fact that house owners normally charge their EVs when they get home. The Shared NPV amounts to €5426 per house. Again, an imbalance occurs between the house owner NPV (€8677 per house) and the DSO NPV (€-3000 per house). The percentage yearly carbon emissions saved is 51%, and the absolute yearly carbon emissions saved is 3.38 ton per year per house.

The lowest grid limit excess (64%) can be obtained by a flexibility management combination of Dynamic curtailment of PV, Switching to gas of hybrid heat pumps and At night only charging of EVs (Table 33). The Shared NPV however is lower than without flexibility management. The difference between the NPV of house owners and the DSO shrinks from €8677 per house to €6711 per house. In addition, less carbon emissions are saved with this flexibility option combination than without flexibility management (45% instead of 52%). Changing the night only charging for EVs in this combination to no evening charging for EVs only slightly raises grid limit excess (70% instead of 64%). Applying this latter option will result in a higher NPV for house owners: €7515 instead of €6710. The higher house owner NPV for the No evening charging option compared to At night only charging option can be explained by the amount of electricity produced by the PV needing to be curtailed. The installation of PV results in an electricity peak during the day, as at that time the most energy is produced. When the EVs are charged during the night they take less of the PV peak away during the day. This results in a higher need for dynamic curtailment, and thus in a higher electricity bill and lower NPV. The next best flexibility management combination for the grid is applying a single flexibility management option of not charging EVs in the evening. This reduces grid limit excess from 235% to 190% (Table 33). The peak in the evening is now reduced, however, the valley caused by PV still remains (Figure 44).

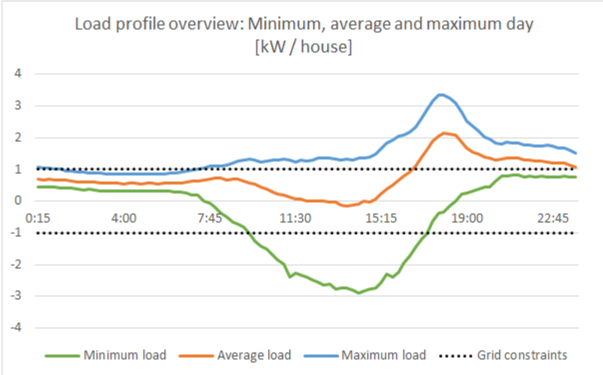

Figure 43: PV, hybrid heat pumps and EVs with no flexibility management

Table 33: PV, hybrid heat pumps and EVs results

PV , hybrid heat pumps and EVs	Unit	Zero option	No evening charging	Dynamic curtailment, Switching to gas and At night only charging
Grid limit excess	[%]	235 %	191 %	64 %
Shared NPV	[€ / house]	€ 5677	€ 5677	€ 4711
Percentage yearly carbon emissions saved	[%]	52 %	52 %	45 %

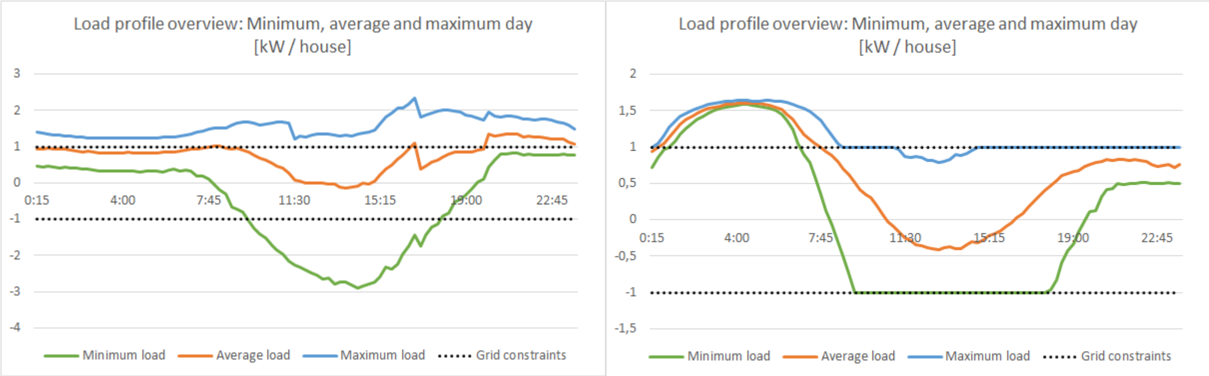

Figure 44: PV, hybrid heat pumps and EVs; No evening charging (left); Dynamic curtailment, Switching to gas and At night only charging (right)

6.3.5 Adding home batteries

In this sub section the results from the experiments which include **home batteries** are presented. Home batteries are applied to either a combination of PV and hybrid heat pumps, or PV and electric heat pumps. Additionally, EVs is added to both DER combinations as well.

Home batteries can be seen as an additional flexibility management option. When they are used with a 'zero option' algorithm for charging and discharging, this does not reduce the grid limit excess of either the combination of hybrid heat pumps and PV or the combination of electric heat pumps and PV (Appendix VII). This can be explained by the fact that a single home battery does not have enough storage capacity to handle the influx of PV generated electricity. The battery is fully charged before the actual PV peak in electricity production occurs. However, a 'grid oriented' algorithm for charging and discharging reduces grid limit excess for the combination of electric heat pumps and PV from 224% to 150%, and for the combination of hybrid heat pumps and PV from 224% to 136%. Figure 45 shows the difference between the zero option load profile (left) and the grid oriented load profile (right). The figure on the left shows a sudden drop around 14:00. This drop is the result of the home battery starting to charge too early and being 'full' when the valley is lowest. The figure on the right shows a much smoother load profile.

Although the adding of home batteries reduces the grid limit excess when the grid oriented algorithm is used, the Shared NPV reduces when compared with the experiments where no home batteries were used. When home batteries are added to the combination of PV and electric heat pumps the Shared NPV reduces from €-4464 per house to €-11903 per house (Compare Table 30 with Table 34). When home batteries are added to the combination of PV and hybrid heat pumps the Shared NPV reduces €270 per house to €-7074 per house (Compare Table 32 with Table 34). The reason for this is that home batteries are expensive (€7250 per home battery). A benefit for the house owner is the higher grid independence. For both combinations the grid independence increases from 28% without home batteries to 43% with home batteries. Still, the house owner's payback time increases significantly, from 15 to 22 years for the electric heat pump combination, and from 11 to 20 years for the hybrid heat pump combination.

When adding EVs to both the DER combinations, similar results are obtained (Appendix VII). Home batteries using grid oriented charging lower grid limit excess, but not enough to save grid investments. Again, the Shared NPV is much lower compared to not implementing home batteries.

Table 34: Home batteries results

PV, home batteries with Grid oriented charging and heat pumps (hybrid or electric)	Unit	Electric heat pumps	Hybrid heat pumps
Grid limit excess	[%]	150 %	224 %
Shared NPV	[€ / house]	€ -11903	€ 270
Percentage yearly carbon emissions saved	[%]	61 %	60 %

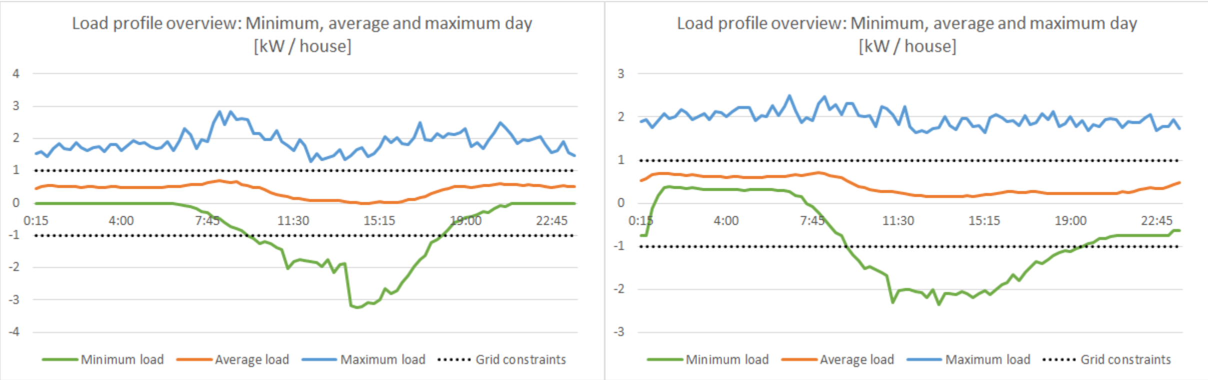

Figure 45: PV, electric heat pumps and home batteries; Zero option charging (left); Grid oriented charging (right)

6.3.6 Electric heat pump experiments and hybrid heat pump experiments comparison

In this sub section the results of the experiments including either **electric heat pumps or hybrid heat pumps are compared**. This comparison is made because both DERs can be applied to NDP, and the results for both the house owner and for the DSO differ. The comparison forms the basis for the policy recommendations on the preferred heat source (see Chapter 7). Two ways of comparing electric heat pumps and hybrid heat pumps are used. First, by comparing the results of the zero options of the combinations of PV and heat pumps. Secondly, by comparing the averages of electric heat pump experiments with hybrid heat pump experiments. Both experiment sets have different flexibility management options. Still, the 'range' of possibilities for these DER combinations can be compared.

Table 35 shows the results on all KPI of both the zero option of PV and electric heat pumps combination and PV and hybrid heat pumps combination. The **grid limit excess** is the same for both the electric heat pump combination (224%) and for the hybrid heat pump combination (224%). This is caused by PV having a higher absolute peak than that of either electric heat pump or hybrid heat pump. Hybrid heat pumps are more affordable than electric heat pumps, which results in a higher **house owner NPV**, being €3270 per house instead of €381 per house for electric heat pumps. The grid investments needed to be made are the same for both options, being: €-3000 per house.

However, when applying electric heat pumps, the gas grid connection is terminated, resulting in additional losses for the DSO and additional profits for the house owner. Electric heat pumps result in slightly higher **house owner grid independence** (28% compared to 25%). This is caused by the electric heat pumps consume more of the electricity generated by PV than the hybrid heat pump. The **carbon emissions saved** are slightly higher for electric heat pumps as well, both in percentage (61% instead of 59%), as absolute (2,57 instead of 2,41 ton per house per year). The small percentage shows that the 'bulk' of the heat of a hybrid heat pumps is generated using electricity. Looking at the cost to obtain this carbon emission reduction, from a systems perspective the hybrid heat pumps are much more cost effective (€7 per ton per year) than the electric heat pumps (€-120 per ton per year).

Table 35: Comparing zero option results of electric heat pumps and hybrid heat pumps

PV and heat pumps (hybrid or electric) zero option	Unit	Electric heat pumps	Hybrid heat pumps
Grid limit excess	[%]	224 %	224 %
Shared NPV	[€ / house]	€ -4464	€ -270
Percentage yearly carbon emissions saved	[%]	61 %	60 %
House owner NPV	[€ / house]	€ 381	€3270
DSO NPV	[€ / house]	€ -4850	€ -3000
House owner grid independence	[%]	28 %	25 %
Shared NPV per net yearly carbon emissions saved	[€ / ton / year]	€ -120	€ 7
Net yearly carbon emissions saved	[ton / house / year]	2,47	2,41

In Table 36 the various combinations of flexibility management options are compared. Combinations with hybrid heat pumps on average result in lower grid limit excess than combinations with electric heat pumps. The average Shared NPV difference is about €2400 higher for hybrid heat pumps than for electric heat pumps. The yearly carbon emission reduction is slightly lower for hybrid heat pump combinations.

Table 36: Comparing aggregated results of electric heat pumps and hybrid heat pumps

Shared NPV	Electric heat pumps	Hybrid heat pumps	**Grid limit excess**	Electric heat pumps	Hybrid heat pumps	**Yearly carbon emission reduction**	Electric heat pumps	Hybrid heat pumps
Min	€ -11903	€ -7156	*Min*	0 %	0 %	*Min*	52 %	45 %
Average	€ -2297	€ 1423	*Average*	223 %	191 %	*Average*	57 %	54 %
Max	€ 5401	€ 5677	*Max*	313 %	235 %	*Max*	65 %	60 %

6.4 Combinations of zero option DER

In this section the results of the **combinations of zero option DERs** experiments are presented. First, the possibilities for integrating Micro CHP and solar boilers are presented. Secondly, the possibility of equipping half the houses in a NDP with micro CHP and either one of the heat pump options is presented. Complete results can be found in Appendix VII.

6.4.1 Integrating solar boilers and micro CHP

In this sub section the results from the experiment which include a DER combination of PV, micro CHP and solar boilers are presented. Additionally, EVs is added as well.

A **DER combination of PV, micro CHP and solar boilers** results in a grid limit excess of 234% (Table 37). This excess is caused by mostly the high electricity production of PV during summer. However, during summer the micro CHP also has a small electricity output which further lowers the valley, and as such increases the grid limit excess. The Shared NPV is low, being: €-6077 per house. This is because the micro CHP cannot be paid back within the 15-year time horizon.

Furthermore, the average house in a NDP has energy label A and therefore only has a base gas demand of 1390 m^3. A micro CHP becomes 'cost effective' around 1600 m^3 gas consumption (Milieu Centraal, 2016f). The percentage yearly carbon emissions saved is however high, being: 60%. This is caused by both the PV, as by the more energy efficient micro CHP compared to a regular boiler.

Including EVs in this DER combination lowers grid limit excess to 201%. The EVs uses some of the electricity produced by the PV during the summer, this can be seen by comparing the two load profiles in Figure 46. The figure on the left shows the load profile of PV and micro CHP without EV, and the figure on the right shows the load profiles including EV.

Table 37: PV, micro CHP and solar boilers results

PV, micro CHP and solar boilers

	Unit	Excluding EV	Including EV
Grid limit excess	[%]	234 %	201 %
Shared NPV	[€ / house]	€ -6077	€ -670
Percentage yearly carbon emissions saved	[%]	60 %	52 %

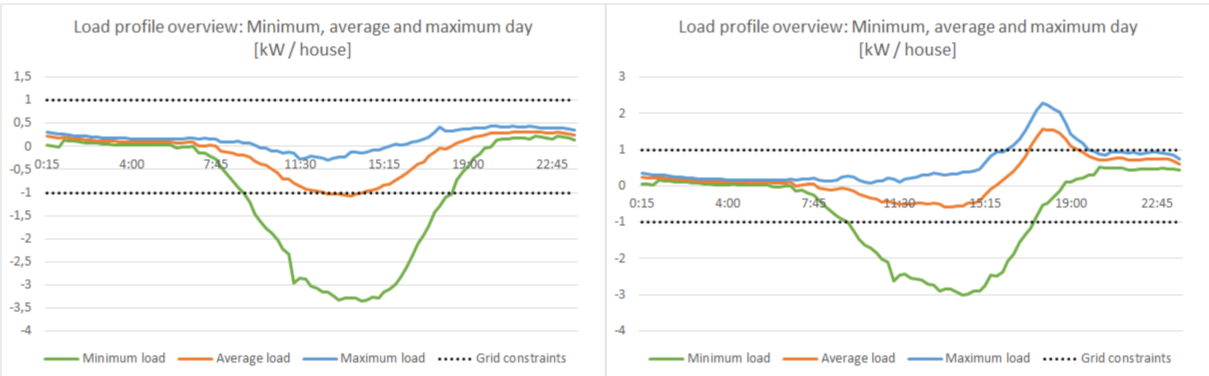

Figure 46: PV and micro CHP; without EVs (left); including EVs (right)

Adding **solar boilers to the combination of PV and heat pumps** (hybrid or electric) raises grid limit excess by a few percent: 227% compared to 224% (Compare Table 38 with Table 30). During summer, the solar boiler produces most heat. As such, the heat pump produces less heat, and thus consumes less electricity. As the production of electricity by the PV remains the same, less of this electricity is 'consumed' by the electric heat pump. This results in the valley of the aggregated load profile to be lowered. The shared NPV is lower than without the same DER combination without solar boilers. This is caused by solar boilers not being paid back within the time horizon of the model. The yearly carbon emissions saved raises a few percent. The solar boiler follows the same production profile as the PV. As such, most of the heat produced during the summer is already being produced with emission free electricity. Adding solar boilers to this combination does not help much more for carbon emission reduction.

Table 38: PV, heat pumps and solar boilers results

PV, heat pumps and solar boilers	Unit	Electric heat pumps	Hybrid heat pumps
Grid limit excess	[%]	227 %	225 %
Shared NPV	[€ / house]	€ -6500	€ -2080
Percentage yearly carbon emissions saved	[%]	64 %	61 %

6.4.2 Mixing a project with half heat pumps and half CHP

In this sub section the results from the experiment which includes a **DER combination of PV, solar boilers, 50% micro CHP and 50% heat pump** (hybrid or electric) are presented. The idea behind this DER combination is that the micro CHP produces most electricity during winter, when gas consumption is highest, which could compensate for the higher electricity need of heat pumps during winter.

This DER combination does not result in lower grid limit excess compared to a neighbourhood with heat pumps only (Table 39). Looking at the load profiles in Figure 47, it can be seen that this is the result of the PV valley not being reduced. However, it does reduce the peak caused by the heat pumps. Adding EVs to this combination would nullify the usefulness of this possibility (Appendix VII). EVs cause a high peak in grid limit excess which can not be 'mixed away' by applying a mix of heat pumps and micro CHP.

Table 39: PV, micro CHP and heat pumps mixed results

PV , micro CHP and heat pumps mixed (Hybrid or electric)	Unit	Hybrid heat pump mix	Electric heat pump mix
Grid limit excess	[%]	234 %	234 %
Shared NPV	[€ / house]	€ -3621	€ -6202
Percentage yearly carbon emissions saved	[%]	63 %	64 %

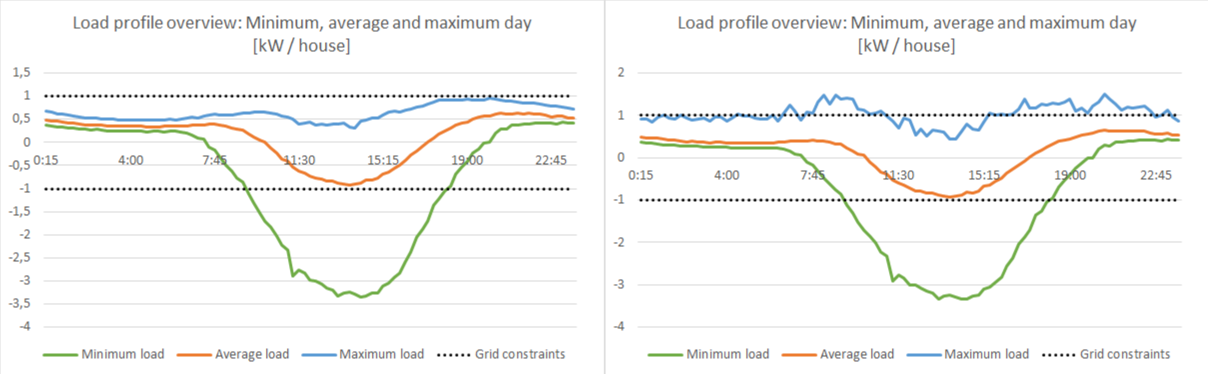

Figure 47: PV, solar boilers and heat pumps; Hybrid heat pumps (left); Electric heat pumps (right)

6.5 Summary: Answering sub question 5

Now, sub question 5 can be answered:

What are the combined effects of distributed energy resource and flexibility management integration for the key performance indicators?

The question can be answered by following the three types of experiments which were performed with the model:

1. Single flexible DERs and single flexibility management options
2. Flexible DER combinations and flexibility management combinations
3. DER combinations without flexibility management

1 The following conclusions can be drawn from the first type of experiments: Single flexible DERs and flexibility management options

All **singular DERs** cause grid limit excess, with PV causing the highest grid limit excess and hybrid heat pumps the lowest. Dynamic curtailment of PV, Switching off of electric heat pumps and Switching to gas of hybrid heat pumps are the only flexibility management options able to reduce grid limit excess to zero. Other flexibility management options, including all EVs flexibility options, reduce grid limit excess but not enough for the DSO to cancel out new grid investments.

2 The following conclusions can be drawn from the second type of experiments: Flexible DER combinations and flexibility management options

All **PV and electric heat pump combinations**, with or without EV, cause grid limit excess, with combinations of PV, electric heat pumps and EVs causing the highest grid limit excess. For the combination PV and electric heat pumps, only a flexibility management combination of Dynamic curtailment of PV and Switching off of electric heat pumps results in a reduced need for investment for the DSO. When adding EVs to the combination of PV and electric heat pumps, no combination of flexibility management options is able to reduce grid limit excess to zero.

All **PV and hybrid heat pump combinations**, with or without EV, cause grid limit excess, with combinations of PV, electric heat pumps and EVs causing the highest grid limit excess. For the combination PV and hybrid heat pumps, only a flexibility management combination of Dynamic curtailment of PV and Switching to gas of hybrid heat pumps results in zero investment needs for the DSO. Furthermore, only applying Dynamic curtailment of PV reduces the need for investment for the DSO. Including EVs into the combination of PV and hybrid heat pumps, no combination of flexibility management options is able to reduce grid limit excess to zero. However, the flexibility management combination of Dynamic curtailment of PV, Switching to gas of hybrid heat pumps and either No evening charging or At night only charging of EVs does reduce the need for grid investments.

When **comparing hybrid heat pump combinations with electric heat pump combinations**: Both for the DSO and for the house owner, hybrid heat pump combinations are more favourable financially. Although, electric heat pump combinations result in slightly better carbon emission reduction and slightly better grid independence.

Installing **home batteries** without flexibility management (Zero option charging) does not result in lower grid limit excess in any of the experiments. Applying flexibility management (Grid oriented charging) reduces grid limit excess with 75% to 105%. However, house owners do not financially benefit from home batteries, with or without flexibility management.

The **highest carbon emission reduction** reached is 65%, which occurs when a combination of PV and electric heat pumps is used, with PV flexibility not being managed and the Switching off of electric heat pumps. The lowest carbon emission reduction is 45%, which occurs when a combination of PV, hybrid heat pumps and EVs is present, with PV being dynamically curtailed, hybrid heat pumps switch to gas and EVs only allowed to charge at night.

The **highest grid independence** of house owners obtained is 43%, which occurs when a combination of PV, electric heat pumps and zero option home batteries is present, with no flexibility management of PV or electric heat pumps.

3 The following conclusions can be drawn from the third type of experiments: DER combinations without flexibility management

Adding **solar boilers** to a combination of PV and heat pumps (hybrid or electric) slightly raises grid limit excess. It raises the grid independence of house owners with a few percentage points. Carbon emission reduction is increased as well. House owner NPV reduces compared to not installing solar boilers. Combining **micro CHP with PV and solar boilers** results in a high grid limit excess. It results in a negative house owner NPV and low grid independence. A **50/50 mix of heat pumps (hybrid or electric) and micro CHP** in a project reduces peaks caused by heat pumps significantly. However, the present PV still causes high grid limit excess.

7 Discussion of results: From spreadsheet model to reality

This chapter discusses the results of the model simulation in section 6. This section answers research question 6:

What flexibility management options could the distribution system operator implement, and which distributed energy resource combinations could the distribution system operator recommend, to mitigate grid limit excess?

This discussion is based on the highlights of most interesting results in section 6, but also draws on additional detailed results which can be found in Appendix VII. In this section, first the impact of individual flexibility management options will be discussed. Second, the usefulness of applying flexibility management options in combinations of DERs will be discussed. Third, possibilities for integrating DERs without flexibility management will be discussed. Fourth, the socially preferred heat source will be discussed. Finally, a summary is given by answering research question 6.

Results will be analysed by their impact on the grid limit excess. The grid limit excess, resulting from the implementation of DERs in NDP, is the reason the DSO is interested in this problem in the first place. Conclusions and policy recommendations are thus based on the usefulness for reducing this grid limit excess

7.1 Discussion of experiment results

7.1.1 Single flexible DERs and flexibility management options

Table 40 presents the results of the single flexible DERs and flexibility management options experiments (see Section 6.2). Each result is followed by a conclusion which represents the implications of the results for the DSO.

Table 40: Single DERs conclusions

#	Result	Conclusion
1	All individual DERs cause grid limit excess, with PV causing the highest grid limit excess and hybrid heat pumps the lowest.	The DSO should apply flexibility management options or invest in the low-voltage electricity grid.
2	Dynamic curtailment of PV, Switching off of electric heat pumps and Switching to gas of hybrid heat pumps are the only flexibility management options able to eliminate grid limit excess.	DSO should pursue Dynamic curtailment of PV. If house owners don't agree with Dynamic curtailment, Static curtailment can be considered, but this option does not lower the need for grid investments of the DSO.

		The DSO should pursue Switching to gas of hybrid heat pumps and Switching off of electric heat pumps.
3	Other flexibility management options, including all EVs flexibility options, reduce grid limit excess but not enough to completely eliminate grid investments.	The DSO can pursue Static curtailment of PV and Shifting heat production of electric heat pumps. Static curtailment is interesting for house owners if they want a higher NPV.

1. Conclusion 1 can be explained by looking at the model specification. Installing DERs in all houses in a neighbourhood at the same time causes low-voltage congestion problems.

2. The only grid limit excess reducing flexibility management options are ones which 'rigorously cut off' DERs, being: Dynamic curtailment of PV, Switching off of electric heat pumps and forced switching to gas of hybrid heat pumps. It was found that Dynamic curtailment is an effective way of reducing grid investments for the DSO. However, it has a negative impact on the House owner NPV and lengthening the Payback time of PV with more than 1.5 years. Assuming economic rational house owners, this will mean that it is difficult for the DSO to pursue house owners to participate without compensation.

For the DSO Switching off of electric heat pumps would be beneficial, but as detailed results show (Appendix VII), heat pumps have to be switched off regularly by 84% in order to completely eliminate grid limit excess. House owners will not agree with, literally, being left in the cold. This problem does not occur with hybrid heat pumps, as in this case the gas fired boiler takes over. However, the latter option forces the house owner to consume more expensive gas and increases his carbon emissions.

3. Static curtailment results in a positive NPV for house owners, and a neutral NPV for the DSO. This results is also suggested by Laagland and Hartman (2016), although they expect a positive NPV for the DSO. Although grid limit excess is reduced by almost 100%, grid investments are still needed. Looking beyond the scope of this thesis, it could be possible that this will save investment costs for the higher-voltage grid.

7.1.2 PV and electric heat pump combinations

Table 41 shows the results of PV and electric heat pump combinations. Each result is followed by a conclusion which represents the implications of the result for the DSO.

Table 41: PV and electric heat pumps conclusion

#	Result	Conclusion
1	All PV and electric heat pump combinations, with or without EV, cause grid limit excess, with combinations of PV, electric heat pumps and EVs causing the highest grid limit excess.	The DSO should apply flexibility management options or invest in the low-voltage electricity grid.

2	For the combination of PV and electric heat pumps, only a combination of Dynamic curtailment of PV and Switching off of electric heat pumps results in a reduced need for investments for the DSO.	The DSO should pursue Dynamic curtailment and Forced switching off to reduce grid investments. A combination of Static curtailment and Shifting heat production reduces the grid limit excess as well, but not enough to lower low-voltage grid investments.
3	Including EVs into the combination of PV and electric heat pumps, no combination of flexibility management options is able completely eliminate grid limit excess.	The DSO should pursue the Dynamic curtailment and Switching off, but with the added option of Night only charging for EV.

1. Combining PV and electric heat pumps does not create a 'cancelling out' effect, where the electric heat pumps use the excess amount of electricity produced by PV. The DSO will still either have to invest in the grid or install flexibility management, if this is feasible.

2. When PV and electric heat pumps are combined, only a combination of 'cutting off' flexibility management options is enough to eliminate grid limit excess. Other combinations do reduce grid limit excess, but not enough to save on low-voltage grid investments. As with single DERs, for the 'cutting off' option to be effective, 84% of heat pumps needs to be switched off. This is no feasible option.

Alternatively, the DSO could install a combination of Static curtailment of PV and Shifting heat production of electric heat pumps. This flexibility management combination increases house owner NPV slightly and lowers grid limit excess by almost 100%. However, this combination does not lead to a lower grid investments need.

3. The third conclusion shows that a 'no evening' charging system in addition to 'cutting off' flexibility management measures will lower grid limit excess, but not eliminate it. Another flexibility management option could be thought of which would also 'cut off' the charging when grid limits are reached (Deconinck et al., 2015). This flexibility management option successfully applied by Alliander in the smart grid test project 'Lochem' (Alliander, 2015). However, here it was applied to only a small number of EVs in a neighbourhood. With a high penetration of EV, in combination with PV and electric heat pumps, constant 'cutting off' would be necessary during certain times. These constraints would influence the ability the charge one's vehicle effectively (Deconinck et al., 2015). It can be concluded that it will be almost impossible to mitigate grid limit excess with flexibility management in such a neighbourhood.

7.1.3 PV and hybrid heat pump combinations

Table 42 shows the results of PV and hybrid heat pump combinations. Each result is followed by a conclusion which presents the implications of the results for the DSO,

Table 42: PV and hybrid heat pumps conclusions

#	Result	Conclusion
1	All PV and hybrid heat pump combinations, with or without EV, cause grid limit excess, with combinations of PV, hybrid heat pumps and EVs causing the highest grid limit excess.	The DSO should apply flexibility management options or invest in the low-voltage electricity grid.
2	For the combination of PV and hybrid heat pumps, only a combination of Dynamic curtailment of PV and Switching to gas of hybrid heat pumps results in zero need for investment for the DSO. Furthermore, applying Dynamic curtailment of PV only reduces the need for investment for the DSO.	The DSO should pursue a combination of Dynamic curtailment and Switching to gas in order to eliminate investments needed. Combinations with Static curtailment instead of Dynamic curtailment are not favorable for the DSO, as significant grid investments still need to be made.
3	When including EVs into the combination of PV and hybrid heat pumps, no combination of flexibility management is able to eliminate grid limit excess. A flexibility management option combination of Dynamic curtailment of PV, Switching to gas of hybrid heat pumps and either No evening charging or At night only charging of EVs does however reduce the need for grid investments.	The DSO should either install the specific combination of flexibility management on all DERs, or choose to invest in the electricity grid. Individual flexibility management options reduce the grid limit excess some what, but only marginal and not enough to reduce investment needs.

1. Combining PV and hybrid heat pumps does not create a 'cancelling out' effect, where the hybrid heat pumps use the excess amount of electricity produced by PV. The DSO will either have to invest in the grid or install flexibility management.

2. Dynamic curtailment of PV and Switching to gas of hybrid heat pumps improves the Shared NPV by about €2300 per household. This is a similar 'cutting off' flexibility management option as the one with electric heat pumps. However, in this situation house owners can rely on the gas fired boiler. House owner payback time will increase by 1 year and carbon emission reduction lowers by 5 percent points. As NDP are set up to reduce carbon emissions in the build environment, house owners might not want to be forced to 'increase gas consumption'. An alternative here could come from using green gas, as described by (Pierie, Benders, Bekkering, van Gemert, & Moll, 2016). Green gas is gas produced from waste biomaterial, and is considered to be carbon emission free. However, green gas can only be applied in rural areas as the quality and amount of biomass is not enough to apply green gas in all

situations in the Netherlands. Applying hybrid heat pumps may thus force the extended use of natural gas.

3. It is noteworthy to mention that this situation advocates an 'all or nothing' scenario for the DSO. Half measures are not useful in NDP. Note that applying individual options flexibility management might still be beneficial for higher voltage grids. Furthermore, here the same conclusions apply as in the case where PV, electric heat pump and EVs are combined (see Section 7.1.3).

7.1.4 Home batteries, carbon emissions and grid independence

Table 43 shows the results of adding home batteries to the DER combinations, and other results found in this experiment range. Each result is followed by a conclusion which presents the implications of the result for the DSO.

Table 43: Miscellaneous conclusions

#	Result	Conclusion
1	Adding home batteries without flexibility management (zero option) does not result in peak reduction in any of the experiments. Applying flexibility management (grid oriented charging) reduces grid limit excess with 75-105%. However, house owners do not financially benefit from adding home batteries, with or without flexibility management option. House owners do however increase their grid independence with 50% when zero option batteries are applied, with the highest grid independence being 18%.	If house owners install home batteries, the DSO would want them to use Grid oriented charging, as significant grid excess reduction can be obtained. For house owners, it would not matter financially if home batteries would be used 'zero option' or 'grid oriented'. Zero option home batteries are better for grid independence than grid oriented home batteries. The DSO should not consider purchasing home batteries itself, as the investment cost per house are much higher than grid investments would be.
2	The highest carbon emission reduction found is 65%, which occurs when PV and electric heat pumps are combined, with PV flexibility not being managed and applying the Switch off option to electric heat pumps Switching off. The lowest carbon emission reduction is 45%, which occurs when a combination of PV, hybrid heat pumps and EVs is present, with PV being Dynamically curtailed, hybrid heat pumps Switching to gas and EVs only allowed to Charge at night.	The bandwidth of 45-65% shows that significant carbon emissions savings can be achieved by NDP. In the model, a fixed number of PV panels per house was used. Increasing the number of PV panels per house could easily reduce carbon emissions even more. Additionally, the bandwidth shows that DSOs can apply flexibility management in an environmental friendly fashion. Carbon emission savings are still high even when the most rigorous flexibility management combinations are applied.
3	The highest grid independence of house owners is 43%, which occurs when PV, electric heat pumps and home batteries are combined, with no flexibility management for any of the applied DERs.	The DSO should not worry that households will become grid independent anytime soon. Various papers describe 'islanded communities', like (Koirala et al., 2016) or (Cayford & Scholten, 2014). What stands out in these papers are the unique characteristics

	these communities have. They often have access to their own wind turbines or green gas production, and have a strong community feeling of dealing with climate issues. The 'average' household in a NDP will not be able to quit the grid. Higher grid independence may be reached when applying more home batteries and more PV. Following model trends, this will probably not result in a positive NPV.

7.1.5 DER combinations without flexibility management

Table 44 shows the results of experiments with DER combinations without flexibility management. Each result is followed by a conclusion which represents the implications of the results for the DSO.

Table 44: DER combinations with no flexibility management conclusions

#	Result	Conclusion
1	Adding solar boilers to a combination of PV and heat pumps (hybrid or electric), does not significantly reduce grid limit excess. It raises the grid independence of house owners with a few percentage points. Carbon emission reduction is increased as well. House owner NPV reduces compared to not installing solar boilers.	For the DSO it does not matter whether solar boilers are included in the combination of PV and heat pumps (hybrid or electric), as their impact on the grid limit excess is marginal.
2	Combining micro CHP with PV and solar boilers results in a high grid limit excess. It results in a negative house owner NPV and lower grid independence.	Neither the DSO nor the house owners are benefited by installing micro CHP solely. Households with higher yearly gas consumption might still benefit from micro CHP installation, but in the model households with a higher gas consumption were absent.
3	A 50/50 mix of heat pumps (hybrid or electric) and micro CHP in a project reduces peaks caused by heat pumps significantly, but PV still causes high grid limit excess.	Would PV be dynamically curtailed, then a combination of hybrid heat pumps and micro CHP would result in zero grid limit excess, even without the flexibility management of heat pumps.

7.1.6 Socially preferred heat source

In a NDP, four different options are available for heating: Electric heat pumps, hybrid heat pumps, micro CHP and traditional boilers (zero option). In Section 6.3 electric and hybrid heat pumps were compared. In this section all heat sources are compared to each other.

Table 45: Preferred heat source conclusion

#	Conclusion
1	Both for the DSO as for house owners, hybrid heat pump combinations are more favourable financially. Electric heat pump combinations have slightly better carbon emission reduction and slightly better grid independence.

Table 45 shows the conclusion resulting from the comparison between hybrid and electric heat pumps. This conclusion can be considered surprising, as in current NDP projects in the Netherlands, like Presikhaaf (Bhagwandas & Dekker, 2016), electric heat pumps are installed. The notion 'all electric neighbourhoods', which is often desired by project participants, is thus based on the wish to maximally reduce carbon emissions. However, carbon emissions do not actually differ significantly, as a neighbourhood with hybrid heat pumps and PV only emits 2% more carbon emissions than one with electric heat pumps and PV. Looking at the KPI 'Shared NPV per carbon emission reduction' for singular DERs, electric heat pumps cost three time as much to reduce yearly carbon emissions than hybrid heat pumps (€-531 compared to €-148 per ton per year). Comparing Sections 7.1.2 and 7.1.3, it can be concluded that hybrid heat pumps are more easily integrated into the low-voltage electricity grid than electric heat pumps, and that flexibility management options applied to hybrid heat pumps are more effective than flexibility management options applied to electric heat pumps.

Applying micro CHP could be interesting for mitigating grid limit excess when combined with heat pumps, as was concluded in Section 7.1.5. However, applying micro CHP only marginally reduces carbon emissions, and thus are not considered interesting for NDP project participants who want to reduce carbon emissions.

Grid maintenance has been left out of the scope of the simulation model. As concluded by (Schepers et al., 2015), the upcoming years much of the gas grid has to be repaired, or was repaired recently. The payback time of these repairs will be around 40 years. The simulation model in this study was developed with an average neighbourhood in mind, and does not take into account the gas grid. Like in Presikhaaf (Bhagwandas & Dekker, 2016), gas grid maintenance had just taken place. If maintenance has not been performed yet, a situation specific analysis has to be made if the cost for the DSO are still higher if hybrid heat pumps are installed, or that it is economically more interesting if electric heat pumps are installed, and the gas grid is abandoned.

Altogether, hybrid heat pumps can be considered the most attractive solution both for the DSO and the house owner. Incorporating gas grid maintenance might change this for the DSO's perspective, but this is very case specific and should be a topic for future research.

7.2 Summary: Answering sub question 6

Sub question 6 can now be answered:

What flexibility management options could the distribution system operator implement, and which distributed energy resource combinations could the distribution system operator recommend, to mitigate grid limit excess?

Regarding NDP with electric heat pumps and PV:

None of the flexibility management combinations will both eliminate grid limit excess and be accepted by house owners. However, Static curtailment of PV increases the House owner NPV. Additionally, a combination of Static curtailment of PV and Shifting heat production of electric heat pumps could possibly still result in less grid investments on higher-voltage grids. As such, the DSO should choose for: Grid investments, advice house owners to install Static curtailment of PV, and research the impact of Static curtailment of PV and Shifting heat production of electric heat pumps on higher-grid levels.

Adding EVs to the combination does not change these conclusions, it will only become more difficult to reduce grid limit excess. The DSO will have to invest in the low-voltage electricity grid.

Regarding NDP with hybrid heat pumps and PV:

The DSO should pursue the implementation of Dynamic curtailment of PV combined with Switching to gas of hybrid heat pumps. This combination eliminates grid limit excess and improves Shared NPV drastically, while carbon emissions are increased with only a small percentage.

House owners will incur less financial benefits from this DER combination. Whether or not the DSO should compensate for this is a topic for future research.

As with electric heat pumps, flexibility management options including Static curtailment of PV improve the NPV of house owners, but do not eliminate grid limit excess and thus grid investments for the DSO. The DSO can recommend house owners to install Static curtailment, but should rather recommend the installation of Dynamic curtailment of PV.

Adding EVs takes away the possibility to completely eliminate grid limit excess by flexibility management. However, the DSO could still install No evening charging for EVs. This relatively small measure reduces grid limit excess and does not interfere with house owners' interests.

Home batteries should be operated in a grid oriented way, although neither the DSO nor the house owner financially benefits from them.

Advice on heat source choice:

The DSO should pursue the implementation of hybrid heat pumps instead of electric heat pumps, micro CHP or traditional boilers. As such, the DSO should inform house owners on the relative small additional carbon emissions and large financial benefits of hybrid heat pumps compared to electric heat pumps.

8 Conclusion and future research

This chapter is build up as follows: First, the main research question is answered. Second, a reflection is given on the modelling process and how it could have been improved. Third, the contribution of this research to the scientific community is identified. Final, possibilities for future research are identified.

8.1 Answering the main research question

The following main research question was stated at the beginning of this thesis:

How can a distribution system operator feasibly mitigate grid limit excess in neighbourhoods with a high penetration of distributed energy resources by applying direct control flexibility management, given the current Dutch institutional context?

It can be concluded that the possibility for the DSO to feasibly apply flexibility management is dependents on the different types of DERs applied by the house owner. The possibilities for mitigating grid limit excess are highest when a combination of hybrid heat pumps and PV is installed. Hybrid heat pumps have the possibility to switch to gas, which gives high flexibility possibilities for maintaining low-voltage grid balance. PV could be curtailed dynamically, in which the output of the PV is dynamically adjusted to safeguard the grid limit. Applying Dynamic curtailment to PV and Switching to gas to hybrid heat pumps eliminates grid limit excess. However, applying this flexibility management combination is not without consequences. The payback time of the PV and hybrid heat pump combination increases one year and house owner NPV is decreased. Additionally, the carbon emission reduction resulting from applying DERs is reduced from 60% to 55%. The lost carbon emission reduction can be considered to be marginal, as the costs per saved ton carbon emission are reduced significantly. In order to make the combination more appealing for the house owner and increase the chances of the house owner accepting flexibility management options, the house owner will need to get some kind of compensation for his monetary loss.

The currently much applied combination in Dutch NDPs of PV and electric heat pumps seems less suitable for flexibility management. The only flexibility management option combination which eliminates grid limit excess, thereby taking away the need for the DSO to invest in strengthening the low-voltage grid, is a combination of Dynamic curtailment of PV and Switching off of electric heat pumps. However, this can only be successfully applied if at certain times up to 84% of electric heat pumps is switched off, leaving many households in the cold during the coldest weeks of winter. Other flexibility management options, such as Shifting heat production of electric heat pumps, do reduce grid limit excess, but not enough to save on any grid investments. The only solution for the DSO for this DER combination situation is thus to invest in strengthening the grid.

The introduction of EVs to NDP might be problematic for the working of any flexibility management option. When all households in a NDP decide to purchase an EV, the grid limit excess becomes very high, being 314% of the grid limit. During summer, the charging of EVs reduces the valley caused by PV. However, during winter, the charging of EVs stacks on top of the load profile of heat pumps (hybrid or electric). As concluded in the first paragraph, the ideal combination of DERs is one where PV and hybrid heat pumps are combined. However, when EVs are introduced, it becomes more difficult to mitigate the grid limit excess for this combination. A combination of Dynamic curtailment of PV and Switching to gas of hybrid heat pumps is able to reduce grid limit excess to about 70%, when EVs are not allowed to charge during the evening hours. Still, the DSO will have to invest in strengthening the grid.

Different DERs providing heat were compared: Hybrid heat pumps, electric heat pumps and micro CHP. The 'zero case', where traditional boilers are used to heat the house, was included as well. Next to these main heat sources, solar boilers, an 'additional' heat source, were examined as well. From the comparison it can be concluded that hybrid heat pumps are the most financially beneficial for both the house owner and the DSO. Compared to electric heat pumps, only marginal lower carbon emissions are reduced when hybrid heat pumps are applied. A micro CHP is too costly for a house owner, as the house owner in this research has a too low gas consumption. For the DSO, micro CHP would increase grid limit excess, due to the added production of electricity during summer which 'stacks' on top of the electricity production of PV. The possibility of mixing a neighbourhood with 50% heat pumps (electric or hybrid) and 50% micro CHP results in marginal grid limit excess. However, as PV is applied as well, the grid limit excess is still high. This could possibly be eliminated by applying Dynamic curtailment to PV. Still, the 50/50 heat pump/micro CHP mix results in worse financial results for house owners than an all heat pump neighbourhood. It is thus uncertain if it is realistic that house owners will decide on this possibility. The adding of solar boilers did not have any significant mitigating impact on grid limit excess.

In general, other analysed flexibility management options had less impact on the grid limit excess, independent from the specific DER combination they were applied to. Static curtailment of PV does reduce grid limit excess and it also has the added benefit that it is the only flexibility management option which reduces the payback time of the house owner. However, it does not reduce grid limit excess enough to be considered interesting for the DSO, as grid investments still have to be made. Applying home batteries with Grid oriented charging also reduces grid limit excess, although they can not completely eliminate it. However, the current home batteries available are expensive. It is more cost effective to apply grid investments than to apply home batteries.

In this research the most rigorous form of flexibility management was analysed: Direct control flexibility management which is performed by the DSO. Still, it must be concluded that even with this most rigorous form of flexibility management it is complicated to reduce grid limit excess caused by a high penetration of DERs in a neighbourhood. In many situations the best solution seems to be to just invest in strengthening the low-voltage grid, and the introduction of EVs only further confirms this solution, as EVs make the application of flexibility management more difficult. As concluded at the beginning of this research, the need for grid investments varies from neighbourhood to neighbourhood. Still, developing flexibility management options would require the introduction of nation-wide paradigm, and as such it will have to be useful for the majority of 'average' neighbourhoods. Section 8.4 further discusses the implications of the conclusions in this thesis, and identifies works which are interesting for future research. Concluding: Grid oriented direct control flexibility management in order to mitigate grid limit exceedance is possible, but depends on the DERs being applied.

8.2 Limitations of this research

Conclusions have been drawn on the basis of a model study. The model is based on certain research design choices and assumptions. As no model perfectly depicts reality, the quality of the conclusions is limited by the research design. In this section the limits of the model and possible implications of these limits for the results and conclusions are discussed.

The **scope of the research** might have an influence on the results. Within this research an 'average' Dutch neighbourhood is used to draw practical and meaningful conclusions and in order to give useful policy recommendations to the DSO. The houses in the neighbourhood have an average electricity consumption, and an average gas consumption for houses with energy label A. Still, a change in the amount of base gas and electricity consumption influences the load profiles of the DERs. This might on its turn influence the usefulness of certain flexibility management options. For example, a household with a relative low electricity consumption might require less PV panels, and as such, Static curtailment might have a much bigger impact on grid limit excess reduction. The houses in the neighbourhood are assumed to have uniform gas and electricity consumption. The usefulness of flexibility management options might be different when this is not the case. This also raises questions about 'fairness': Would a household with relative more electricity consumption be hit harder by flexibility management options? This might reduce the acceptability of flexibility management by house owners.

Furthermore, an average electricity grid was assumed. As concluded in Section 3.1, the actual capacity of the grid is very case specific. Situations exist were the electricity cable is not connected to its maximum number of houses. In these situations the low-voltage electricity system has a lot of 'spare' capacity. Installing DERs in these situations would require less mitigation of grid limit excess. This would result in flexibility management options like Static curtailment of PV or Shifting heat production of electric heat pumps to become more interesting.

A final assumption made in the scope of this research is that the costs of the flexibility management itself are not included in the analysis. Although this is left out of the scope intentionally, the costs of the ICT-infrastructure needed for flexibility management could worth considering as well. Furthermore, the development of software will require investments to be made, and the software will need to be updated regularly. The security of the ICT-infrastructure will need to very high, as interference might cause the system to shut down, leaving connected household without electricity.

The **model design** of the spreadsheet model uses static formulas which produce deterministic results. The model calculates the KPI on the basis of input variables, which values are estimates based on data found in literature. However, these input variables are not 'precise', as a certain spread exists in their value. This means that a certain spread exists in the value of the KPI as well. The model does not calculate this spread, but if it would, conclusions could be drawn on the probabilities of certain results. This also applies to the load profiles used, which are deterministic as well. An alternative method for calculating the load profiles is to use probabilistic distributions (Mumford et al., 1991). Using Monte Carlo simulation, probabilistic load profiles can be obtained. The reason this analysis has not been performed is the amount of time required to perform this analysis. In this study currently 58 different configurations were tested. For every configuration a Monte Carlo simulation would be required, increasing the amount of experiment runs significantly. The analysis of the obtained data would take a large amount of time not available within the timescale of this thesis. As such, this is a topic for future research.

The model calculates the influence of the flexibility management options on the basis of four average weeks, each representing one of four seasons. Two extra load profiles are used to calculate the grid limit excess in the case of the sunniest week and the coldest week of the year. However, these last two profiles are not used in the calculation of NPV, only the four average weeks are. A flexibility management option like Static curtailment only slightly lowers the average profile of summer, while significantly lowering the load profile of the sunniest week (which was not included in the calculation of KPI). As such, the reduction in PV production, calculated from the area under the four seasonal profiles, is influenced less than it should be.

The **model input data availability** might have an influence on the results. As stated in Section 5.6: Validation, the thoroughness of the model validation depends on the availability of data to compare model results with. Two types of data sources were used: (i) A comparison of parameter values with data found in literature, and (ii) a comparison of load profiles with historical data. The first comparison showed that most model parameter values were within the same order of magnitude as the data found in literature. However, for some model parameters the data found in literature differs between sources. For example, the electric heat pump energy bill reduction differed 109% with one source found, and 42% with another source found. Much is also dependent on the way the parameters are calculated. This makes it difficult for the researcher to make right estimates for the input data.

Load profiles were available for certain DERs, but not for all. For example, no historical load profile was available for hybrid heat pumps. First, this made it necessary for the researcher to estimate a load profile for the hybrid heat pump based on the load profile of an electric heat pump. Second, this made it difficult to validate the estimated load profile, as it can not directly be compared with historical results. This also applies to the flexibility management options. Some of these have been applied in real life situations, like curtailment of PV. However, none of the obtained load profiles were documented. This makes it difficult to validate the correctness of the outcomes.

8.3 Main contributions of this research

Despite the mentioned limitations and shortcomings of the model, interesting findings were obtained. These findings were obtained using a systems way of thinking, which not only includes the perspective of a single stakeholder or a single technology, but tries to take an aggregated view, including a multitude of different technologies and stakeholders. Resulting from this, both the DSO and the house owner perspective were taken into consideration, as well as the combinations of multiple DERs and flexibility management options. As concluded in Chapter 1, the existing literature on the topic takes a mono-disciplinary view, which does not combine the perspectives of multiple stakeholders and/or includes only a single technology or flexibility management option. As such, a comprehensive overview was missing. The systems perspective approach taken in this thesis has led to a first step of providing a comprehensive overview of the possibilities of flexibility management in the Netherlands.

This research contributes to closing the gap between theoretic literature and practice. The implementation of DERs is needed to reduce carbon emissions. Much research about flexibility management is performed, as flexibility management could possibly help facilitate the implementation of these DERs. Much of the scientific literature describes theoretical concepts, including possibilities for flexibility management or future market designs for including DERs. However, these theoretical studies are not translated to the current real world environment, ad do not show how these concepts could actually be implemented. When applied to a real life case, does flexibility management have the potential to live up to the claims some researchers have made about the benefits of flexibility management? This research showed that the 'success' of flexibility management highly depends on the DERs being installed, and that for currently much applied DER combinations, flexibility management is not feasible. This research found these conclusions by examining the real life case of the Netherlands. Based on load profiles generated by Dutch smart grid pilot projects, and using Dutch characteristics of DERs and houses, a translation was made from theory to practice.

The findings of this research also contribute to the insight of the administrative complexity DSOs in the Netherlands are currently experiencing. This research shows that the implementation of DERs causes a DSO to perform expensive grid investments, and the costs and benefits are not evenly distributed among itself and the house owner. New ICT advancements promise the possibility of flexibility management. However, this research shows that in practice it will be difficult to completely integrate flexibility management in the average neighbourhood and that flexibility management is only applicable in certain situations. Even when the progress of EVs sets through, and if EVs remain being charged at home, grid investments are inevitable. As such, flexibility management in neighbourhoods would be a temporal solution only.

8.4 Possibilities for future research

Considering the conclusion, a number of follow-up studies could be performed. These are discussed in this section.

A first topic for future research regards to the question if and how the DSO should compensate house owners in the case that the benefits of flexibility management are solely for the DSO, and house owners only experience the negative side effects. House owners do not necessarily hold a negative attitude towards the concept of flexibility management, as shown in smart grid pilot project Texel (Liander, 2015a). Still, the benefits of the application of flexibility management options have to be acceptably distributed between both stakeholders (KEMA Nederland, 2015). The business case has to be positive for all involved stakeholders. This research could further include the investment risks for both the house owner and the DSO. For example, the current ‘salderingsregeling’ is being reconsidered in 2020, which allows consumers to be fully compensated for the electricity they export (Rijksoverheid, 2016c). Abandoning this regulation would have a big impact on the House owner NPV. Future research should take a practical approach on what business propositions would be possible for the DSO and would be accepted by house owners.

A second topic for future research regards to the influence of the market environment on the applicability of the policy recommendations. Within Europe an open market exists, in which the DSO has a monopoly position and is not allowed to interfere in the free market. If the DSO would apply flexibility management, this could lead to market dynamics interference. Prices might be influenced and an unfair market advantage might be given to certain stakeholders. Future research could show how big the impact of flexibility management options is. If the market design would be different, for example with an integrated DSO and energy market, the feasibility of flexibility management options differ as well. Examples of such markets can be found in certain parts of the USA and Canada.

A third topic for future research regards the way flexibility management would fit within the Dutch legal framework. In order for flexibility management to be applied within the Netherlands, policy makers will have to draft new legislation which would legalise the flexibility management options applied by a DSO. Currently, a case-by-base exception has to be made in order for flexibility management to be applied. This was, for example, the case in many of the smart grid pilot projects. Research needs to be performed on how the current legislation would have to be adjusted.

A fourth topic for future research regards to the role of an ICT-system in facilitating flexibility management. Information about the costs of developing such a system would be needed for the DSO to make a well informed decision on choosing flexibility management instead of grid investments. Such an ICT-system would need to be developed, regularly updated and maintained. Furthermore, such an ICT-system would consume electricity as well, which could possibly contradict the goal of the DSO to reduce carbon emissions. Another big aspect worth researching, is the safeguarding of the privacy of participating households.

A final topic for future research refers to the model simulation performed in this research. Future research could include more stakeholders n the analysis. For example, an aggregator, which could perform some of the functionality of the DSO flexibility management options, could be added. Also an electricity supplier or an electricity producer could be examples of stakeholders which could possibly be included in the analysis. Furthermore, from a model technical point of view, improvements could be made. For example, the current model is deterministic. Future research could use probability ranges for both input variables and load profiles. This could result in a more thorough understanding of the effects of flexibility management by the DSO. Additionally, the model could be used to research more case specific situations. For example, the age of both the gas and electricity grid could be included in the analysis to determine the exact lost costs of the lost investments.

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Appendix I: Excel model sheets description

In this Appendix a description will be given of the sheets in the Excel model.

Sheet name	**Function**
Introduction	Description: - Model title and author information
Input	Sub-models: - House owners: DER - DSO: Flexibility management options Description: - Allows for the input variables to change: Combining different DERs and flexibility management options
Output – Energy	Sub-models: - DNP system - Output: KPI Description: - Collects technical information of the system, such as energy consumed, and calculates a part of the KPI
Output – Financial	Sub-models: - DNP system - Output: KPI Description: - Collects financial information of the system, such as investment costs, and calculates a part of the KPI
Settings	Sub-models: - Dutch technological environment - Dutch institutional environment Description: - Defines parameter values of institutional end technological environment, such as average electricity consumption per house and the price of electricity
Design of experiments	Description: - Contains an overview of the experiment design
Experiment overview	Sub-models: - Output KPI Description: - Calculates and shows the KPI. Stores KPI values of experiments.
Verification test	Description: - Shows the performed verification test
Validation test	Description: - Shows the performed source comparison test
00 Demand	Sub-models: - DNP system Description: - Calculates the base heat demand and base electricity demand
00b Heat demand production	Sub-models: - DNP system Description: - Calculates the aggregated heat profile
00c E demand production	Sub-models: - DNP system

	Description: - Calculates the aggregated electricity profile
01 PV	Sub-models: - House owners: DER Description: - Contains the base settings of PV, like investment costs and yearly electricity output
01b PV profile	Sub-models: - House owners: DER - DSO: Flexibility management options Description: - Contains the load profiles of PV, including the zero option and all flexibility management options
02 CHP	Sub-models: - House owners: DER Description: - Contains the base settings of micro CHP, like investment costs and yearly electricity output
02b CHP profile	Sub-models: - House owners: DER - DSO: Flexibility management options Description: Contains the load profiles of PV, including the zero option and all flexibility management options
03 Solar boiler	Sub-models: - House owners: DER Description: - Contains the base settings of solar boilers, like investment costs and yearly heat output
03b Solar boiler profile	Sub-models: - House owners: DER - DSO: Flexibility management options Description: - Contains the heat profiles of solar boilers
04a Heat pump – Hybrid	Sub-models: - House owners: DER Description: - Contains the base settings of hybrid heat pumps, like investment costs and yearly electricity and gas consumption
04b HP-H profile	Sub-models: - House owners: DER - DSO: Flexibility management options Description: - Contains the load profiles and heat profiles of hybrid heat pumps, including the zero option and the flexibility management option
04c Heat pump – Electric	Sub-models: - House owners: DER Description: - Contains the base settings of electric heat pumps, like investment costs and yearly electricity consumption
04d HP-E profile	Sub-models: - House owners: DER

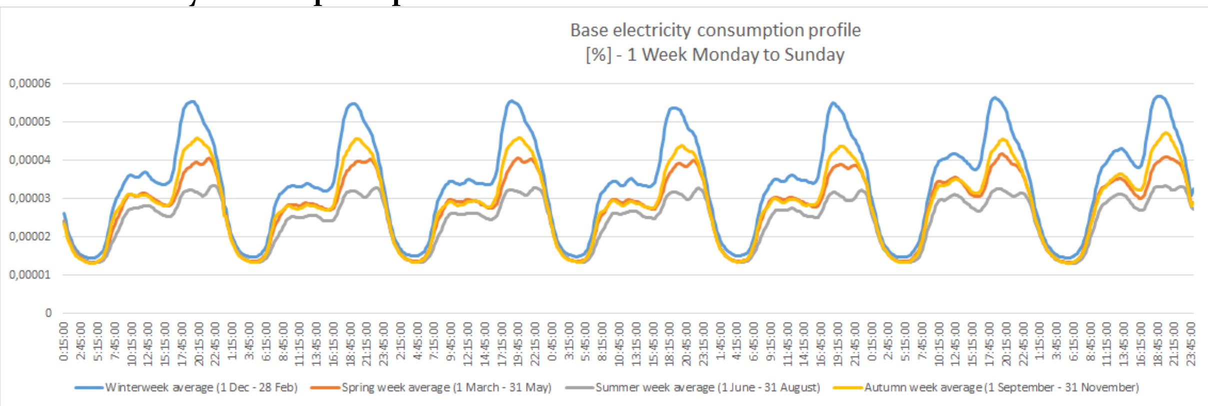
	- DSO: Flexibility management options Description: - Contains the load profiles and heat profiles of electric heat pumps, including the zero option and all flexibility management options
05 EV	Sub-models: - House owners: DER Description: - Contains the base settings of EV, like investment costs and yearly electricity consumption
05 EVs charging profile	Sub-models: - House owners: DER - DSO: Flexibility management options Description: - Contains the charging profiles of EV, including the zero option and all flexibility management options
06 E profile households	Sub-models: - Dutch technological environment Description: - Contains the base load profile of electricity consumption
08 G profile households	Sub-models: - Dutch technological environment Description: - Contains the base heat profile of electricity consumption
10 Flex menu	Description: - Contains menu options for sheet Input
11 Grid limit	Sub-models: - Dutch technological environment Description: - Contains the base grid information including grid limits and grid investment costs
13 Home battery	Sub-models: - House owners: DER Description: - Contains the base settings of home batteries, like investment costs and charging efficiency
13b Home battery profile	Sub-models: - House owners: DER - DSO: Flexibility management options Description: - Contains the charging profiles of home batteries, including the zero option and the flexibility management option
14 Subsidy settings	Sub-models: - Dutch institutional environment Description: - Contains the subsidy settings used in the model
20 Menu sheet	Description: Contains menu options for sheet Input

Appendix II: Load profiles

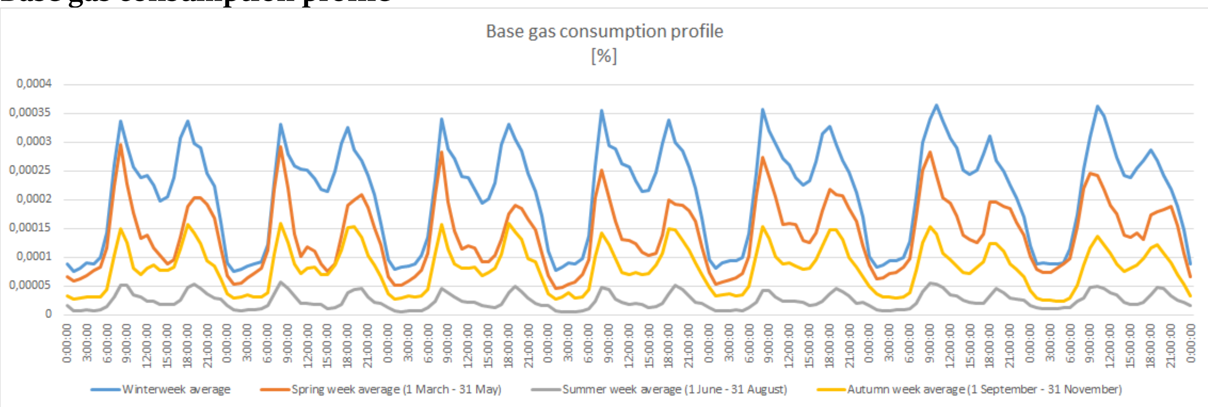
In this appendix for every DER the applied load profile is depicted. The load profiles are based on the following sources:

Technology	Profile used	Source
Base electricity consumption profile	EDSN standard electricity consumption profile	(Van Langen et al., 2016)
Base gas consumption profile	Zonnedael – slimme meter dataset gas profile	(Kaas, 2013)
Solar PV production profile	Zonnedael – slimme meter dataset PV profile	(Kaas, 2013)
Micro CHP	Zonnedael – slimme meter dataset gas profile	(Kaas, 2013)
Solar boiler	Zonnedael – slimme meter dataset PV profile	(Kaas, 2013)
Electric heat pump	Dagprofiel stroomversnellingswijk	(Bhagwandas, 2016)
Hybrid heat pump	Dagprofiel stroomversnellingswijk	(Bhagwandas, 2016)
EV charging profile	KMProfiles – EVs charging profile	(V. Dekker, 2014)

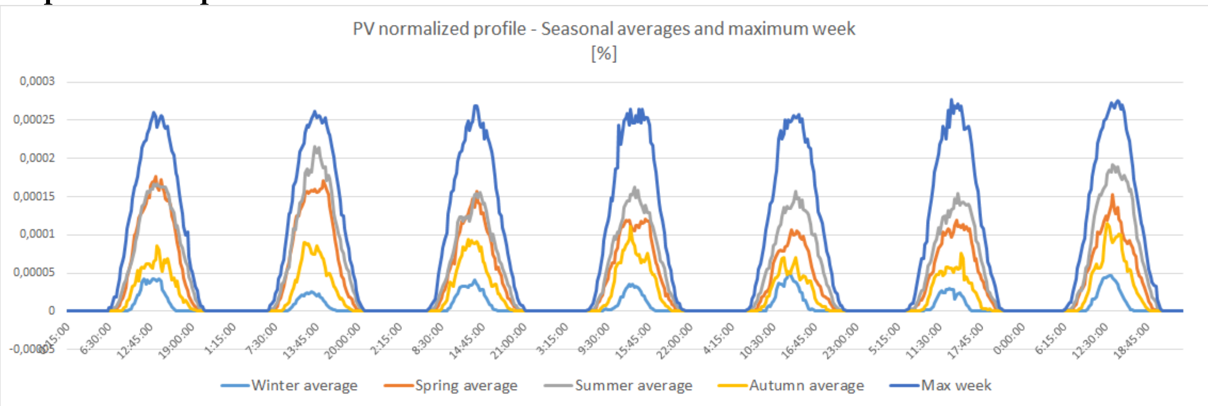
Base electricity consumption profile



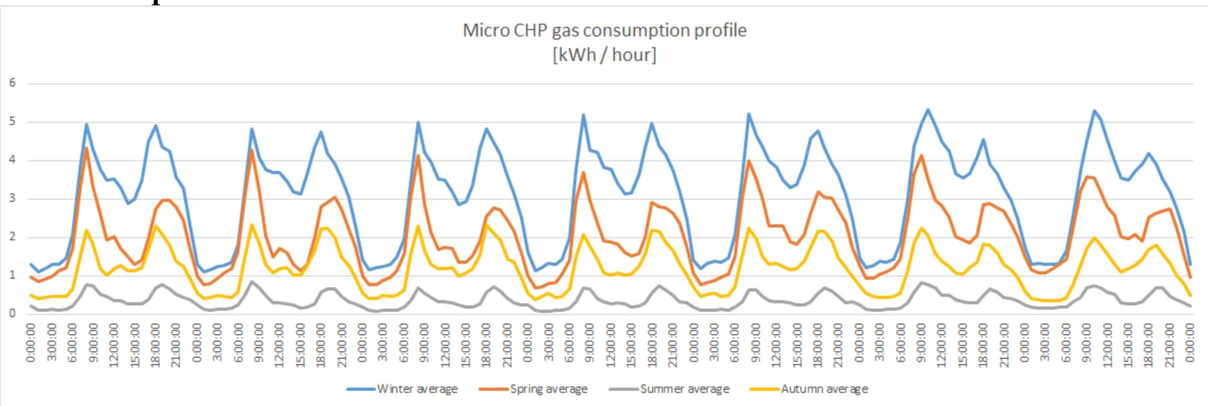
Base gas consumption profile

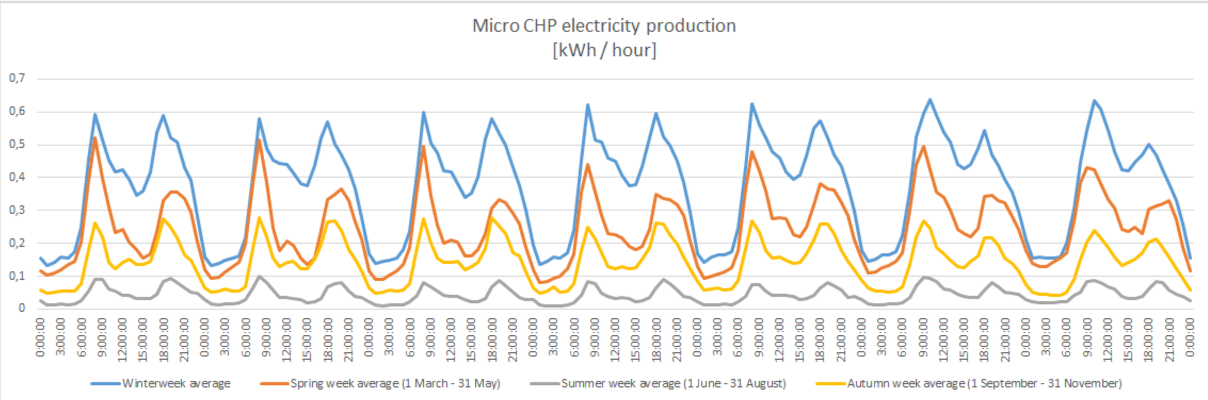


PV production profile

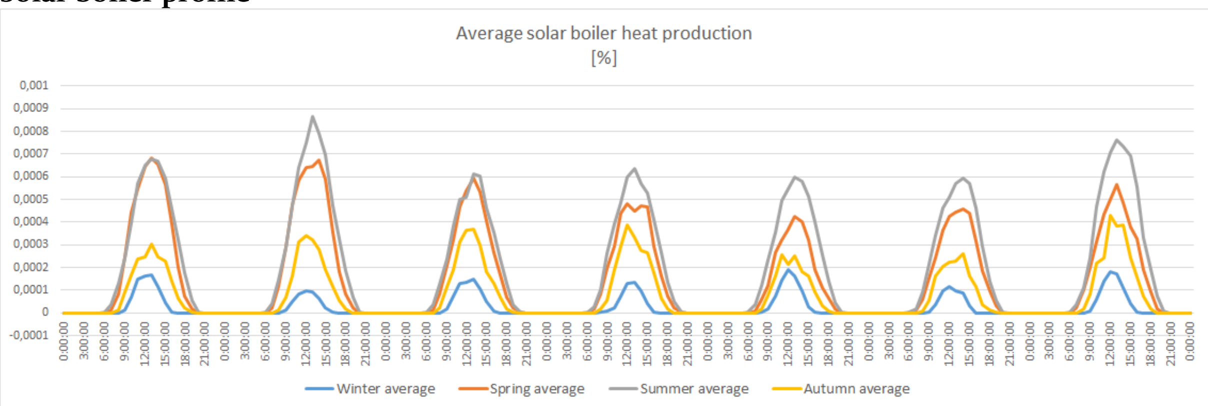


Micro CHP profile

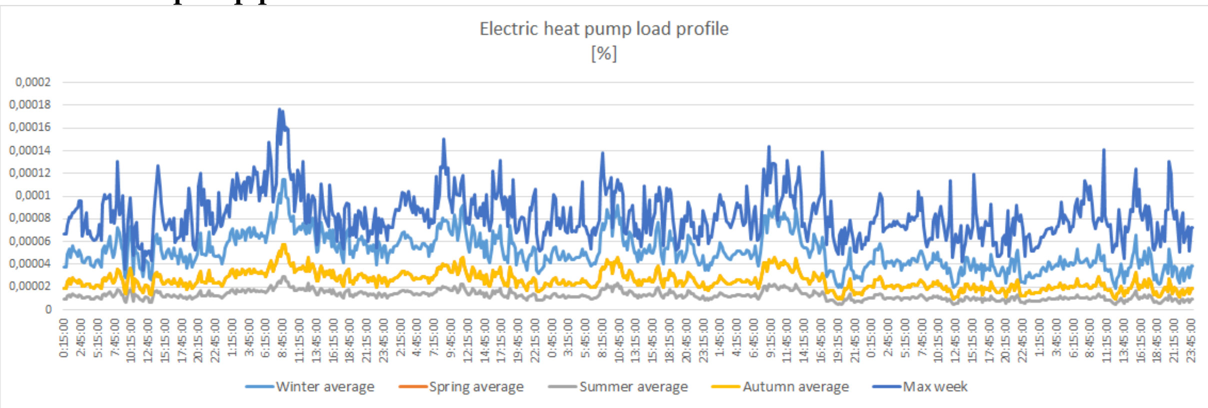




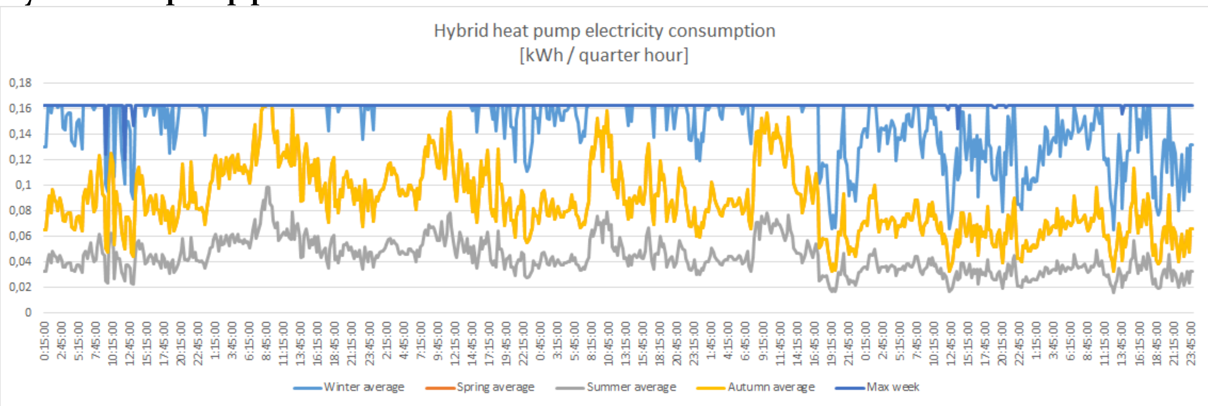
Solar boiler profile

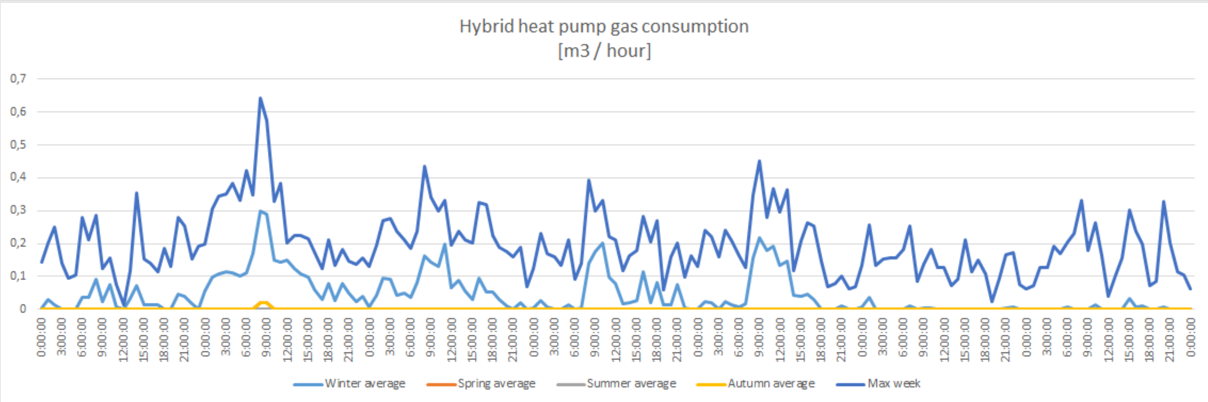


Electric heat pump profile

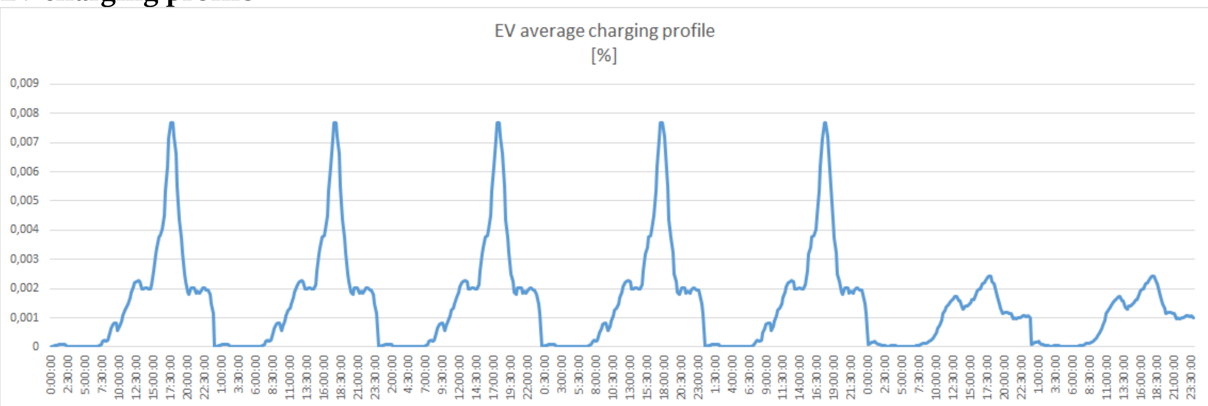


Hybrid heat pump profile





EV charging profile



Appendix III: Formulas used in the model

In this appendix the formulas used in the model are explained. The formulas make use of abbreviations for factors. The formulas for the flexibility management options are discussed per DER.

I.I Flexibility management options formulas

PV - Static curtailment

With static curtailment a fixed capacity limit is put on PV production (Section 3.3). This maximizes the possible output of a given PV panel. In literature (Laagland & Hartman, 2016) the limit α, is typically put on 70% (Section 5.2). As such, the maximal output of a static curtailed PV installation P_{sc} is the minimum of either its normal output P_{pv} and the limit times its maximum output $\alpha * P_{pvmax}$.

$$P_{sc}(kW) = MIN(P_{pv}, \alpha * P_{pvmax})$$

PV - Dynamic curtailment

Applying dynamic curtailment means the production P_{dc} is only altered when grid limit excess P_{gl} is reached (Section 3.3). The maximum output a dynamically curtailed PV installation thus can have is equal to the total grid load without PV, P_{total}, plus the grid limit.

$$P_{dc}(kW) = MIN\ (P_{pv}, P_{total} + P_{gl})$$

Electric heat pump – Switching off

Switching off is basically curtailment of electric heat pumps (Section 3.3). In practice it would mean that a heat pump is for example 20% curtailed, thus can only produce 80% of the heat necessary. This might be interesting when this only occurs a couple a times a year for short time periods. The heat pump would than use the thermic mass of the house, so a short buffer period is created. For longer periods this flexibility management option may not be useful. The consumption P_{fs} is thus equal to the minimum of either the actual consumption or the grid limit P_{gl} minus the total grid load without electric heat pumps P_{total}.

$$P_{fs}(kW) = MIN\ (P_{ehp}, -P_{total} + P_{gl})$$

Electric heat pump - Shifting heat production

The shifting heat production takes a load shifting principle (Section 3.3). This means that the heat pump will lower its production during peaks, and higher its production during valleys. This way, no heat is lost but is merely shifted to a more suitable time period using the thermic mass of the house. Excel is a static modelling environment, so to calculate the duration and intensity of the application of this flexibility management option, no use can be made of automatic iterative calculation methods. To mimic the effect, first, the following two variables have to be defined:

The power load at which the heat pump should peak clip is defined as τ_1, which is depended on the percentage of activation γ times the difference between the maximum and minimum load of the load without the electric heat pump during any given day. The power load at which the heat pump should start valley filling is defined as τ_2, which equals 1 – γ times the difference between the maximum and minimum load of the load without the electric heat pump during any given day. The variable γ is a fraction between 0 and 1, and can be obtained by using Excel software 'solver', solving for gird limit excess.

$$\tau_1 = \gamma * (\max(P_{total} \in 0 < t(day) < 1) - \min(P_{total} \in 0 < t(day) < 1)) + \min(P_{total} \in 0 < t(day) < 1)$$

$$\tau_2 = (1 - \gamma) * (\max(P_{total} \in 0 < t(day) < 1) - \min(P_{total} \in 0 < t(day) < 1)) + \min(P_{total} \in 0 < t(day) < 1)$$

The load of the shifted production heat pump P_{sp} is than defined taking the normal consumption of the heat pump P_{ehp} plus and 'if, then else function': If the total load without the electric heat pump P_{total} is smaller than the activation amount τ_1, the heat pump should produce more heat equal to P_{ehp} times extra production amount ε. If the total load without the electric heat pump P_{total} is larger than τ_2, the heat pump should lower production equal to $- P_{ehp} * \varepsilon$. Additionally, the heat pump doesn't give out heat if the heat buffer P_{buf} is empty, to safeguard the balance of total produced heat.

$$P_{sp}(kW) = P_{ehp} + if\ (P_{buf} \leq 0\ ; \max\ (0\ ; if\ (P_{total} < \tau_1\ ; P_{ehp} * \varepsilon\ ; 0))\ ; if\ (P_{total} < \tau_1\ ; P_{ehp} * \varepsilon\ ; if\ (P_{total} > \tau_2\ ; - P_{ehp} * \varepsilon\ ; 0)))$$

Hybrid heat pump - Switching to gas

Switching to gas peak clips the amount of electricity the heat pump uses (Section 3.3). When the grid limit is met, the heat pump switches to gas for the production of heat.

$$P_{fg}(kW) = MIN\ (P_{hhp}\ , -P_{total} + P_{gl})$$

Home battery - Grid oriented charging

The equation of the home battery is similar to that of the electric heat pump shifting of production (Section 3.3). First, two variables δ_1 and δ_2 are defined which trigger the activation of the charge at discharging of the battery.

$$\delta_1 = \max(P_{total} \in 0 < t\ (day) < 1)$$

$$\delta_2 = \min(P_{total} \in 0 < t\ (day) < 1)$$

Further on, the actual charging and discharging are defined. If the total load P_{total}, triggers the charge or discharge limit, the battery will charge or discharge. Additionally, both the charging and discharging flow are limited with electricity flow barriers.

Charging:

$$P_{goc}(kW) = if\ (P_{total} < (\delta_2 + \vartheta_c * (\delta_1 - \delta_2))\ ; (\delta_2 + \vartheta_c * (\delta_1 - \delta_2) - P_{total})\ ; 0)$$

Discharging:

$$P_{god}(kW) = if\ (P_{total} > (\delta_2 + \vartheta_d * (\delta_1 - \delta_2))\ ; (\delta_2 + \vartheta_d * (\delta_1 - \delta_2) - P_{total})\ ; 0)$$

In the model both equations are also limited by a home battery buffer. This home battery has a maximum capacity. When this capacity is met, charging will equal to zero. When the capacity is zero, the discharging will equal to zero.

Electric vehicle - No evening charging

Electric vehicles are not allowed to charge their vehicles between 17:00 and 20:00 with this flexibility management option (Section 3.3).

$$P_{nec} = if\ (17 \leq t\ (hour) \leq 20\ ; 0\ ; P_{ev}\ )$$

Electric vehicle - Only at night charging

Electric vehicles can only charge at night with this flexibility management option (Section 3.3). Not that the base load P_{ev} differs between different charging options, but must always equal to the same amount of charge capacity per day.

$$P_{noc} = if\ (0 \leq t\ (hour) \leq 6\ ;\ P_{ev}\ ; 0)$$

I.II KPI formulas

In this section is explained how the KPIs are calculated in the model. Also a short explanation is given on how the underlying factors of the KPIs. In the model, both the discount rate and inflation rate are assumed zero.

House owner NPV

House owner NPV is calculated on the basis of the difference between the NPV of the NDP situation without any DER (the 'Zero case'), and the NDP situation when DER and flexibility management options are applied. The NPV of the NDP situation is calculated by adding up the costs of electricity and gas over a period of 15 years. For one house the Zero case yearly energy costs amount to €1626,4. Over a 15 period the NPV is thus 15 * €1626,4 = €24396.

Following this, the NPV of the NDP situation including DER is calculated by taking adding up the new energy costs over a 15 year period, adding the cumulative investment costs and subtracting the available subsidies. Taking a neighbourhood with 1 house and 1 PV as an example: The yearly energy costs are €1002,11 and the investment costs are €6630. Over a 15 year time period the NPV amounts to €22501,22.

For calculating the house owner NPV, the difference of the two is taken: €24390 - €22501 = €1895, and is divided by the number of houses (in this case 1).

House owner payback time

House owner payback time is calculated on the same base as House owner NPV. The difference of the zero case energy cost and the DER case energy cost is taken. Now, the net investments (=investments – subsidies) is divided by the difference between the two cases. As such, the payback time is obtained.

Taking a neighbourhood with 1 house and 1 PV as an example: the difference between yearly energy costs is €1626 - €1058 = €568 per year. The net investment costs are €6630. The payback time is thus €6630 / €568 = 11,7 years.

House owner grid independence

The House owner grid independence is calculated on the basis of how much renewable energy the house produces. The amount of energy renewably produced is calculated by adding up the PV electricity production and solar boiler heat production, both in kWh. Exported electricity is subtracted from this amount. It is then divided by the total energy need of the house in kWh.

Taking a neighbourhood with 1 house and 1 PV as an example: PV produces 2842 kWh electricity in a year. However, 1588 kWh of this is exported when it is produced. As such, 2842 kWh – 1588 kWh = 1254 kWh is divided by the total amount of energy need of the house: 3300 kWh electricity and 13579 kWh gas (= 16879 kWh). The House owner grid independence is thus 1254 kWh / 16879 kWh = 7%.

DSO NPV

The DSO NPV is calculated the same way as the House owner NPV: The difference is calculated between the zero case and the DER case. The zero case NPV is calculated by adding up the yearly grid connection fees paid by the house owners over a period of 15 years.

The DER case NPV is calculated by adding up the yearly grid connection fees paid by the house owners over a period of 15 years and subtracting the investment costs. The difference between the DER case NPV and the zero case NPV is divided by the number of houses and the DSO NPV is obtained

Taking a neighbourhood with 1 house and 1 electric heat pump as an example: In the zero case, the yearly grid connection fee paid by the house owner is €309 (€186 for electricity and €123 for gas). The zero case NPV is thus 15 * €309 = €4635. In the DER case, the yearly grid connection fee paid by the house owner is €186 (as the house owner disconnects from the gas grid). The investment costs are €3000. As such, the DER case NPV is €-210. The difference between the two is the DSO NPV: €-210 - €4635 = €-4845.

Grid limit excess

The Grid limit excess is calculated by taking the largest absolute of the minimum or maximum of all load profiles, subtracting the grid limit, and dividing by the grid limit. Taking a neighbourhood with 1 house and 1 electric heat pump as an example: The largest absolute minimum or maximum of all load profiles is 2,27 kW. Subtracting the grid limit of 1 kW (2,27 kW – 1 kW = 1,27 kW), and dividing by the grid limit (1 kW) results in a grid limit excess of 127%.

Shared NPV

The Shared NPV is the product of the House owner NPV and the DSO NPV. Taking a neighbourhood with 1 house and 1 PV as example: House owner NPV is €1895 per house and DSO NPV is €-3000 per house, the Shared NPV is €270 per house.

Net yearly carbon emissions saved

The Net yearly carbon emissions saved are calculated by subtracting the yearly carbon emissions in the DER case from the yearly carbon emissions in the zero case. The yearly carbon emissions are calculated by multiplying the electricity consumed in a year with the average carbon emissions per kWh of Dutch electricity (0,000455 ton CO_2 / kWh) and adding up the product of the gas consumed in a year with the average carbon emissions per m^3 of natural gas (0,001825 ton CO_2 per m^3) (Milieu Centraal, 2016a).

Taking a neighbourhood with 1 house and 1 PV as an example: The zero case carbon emissions are 3300 kWh electricity times 0,000455 ton CO_2 / kWh, plus 1390 m^3 gas times 0,001825 ton CO_2 per m^3 equals 4 ton CO_2 per house per year.. The DER case carbon emissions are 2,5 ton CO_2 per house per year. The Net yearly carbon emissions saved is thus 4 – 2,5 = 1,5 ton CO_2 per house per year.

Percentage yearly carbon emissions saved

The Percentage yearly carbon emissions saved are calculated by taking the Net yearly carbon emissions saved and divide them by the zero case yearly carbon emissions. Taking a neighbourhood with 1 house and 1 PV as an example: The Percentage yearly carbon emissions saved is 1,5 / 4 = 37%.

NPV per net total carbon emissions saved

The NPV per net total carbon emissions saved is calculated by dividing the Net yearly carbon emissions saved by the Shared NPV.

Appendix IV: Verification analysis

In this Appendix the verification test is performed. As concluded in Chapter 5, three types of verification tests are performed (Altiok & Melamed, 2007): (1) Checking the code for errors, (2) Inspecting model output for the correctness of the code and (3) Performing consistency checks among different experiments. As concluded, the first method, checking the code for errors is done during the model construction and is difficult to document. The second method, inspecting model output for the correctness of the code, is performed in this Appendix. The third method is done by the researcher on the basis of the model results which can be found in Appendix VII.

In this Appendix two different tests are performed. First, a sensitivity analysis is performed. This test checks how sensitive the output variables are for small changes in input parameters. Second, an extreme value analysis is performed. In this test, some of the input parameters are given extreme values. It is then checked if the model performs the expected outcome.

IV.I Sensitivity analysis

In this section a sensitivity analysis is performed. In this analysis, input parameters are changed with a fixed percentage (20%), and the effect on output variables (KPI) is measured. The goal of this test to see how sensitive the results are for changes in parameter values. If output variables are very sensitive (more than 25%), an explanation needs to be found. A sensitivity analysis is performed on the following DER combination with no flexibility management: PV, electric heat pumps and EVs.

In this analysis the input parameters of **PV, electric heat pumps and EVs** are changed with plus and minus 20%. The influence is measured on all KPI. Table I shows the base case results of this DER combination. Table II and Table III show the net change of -20% and 20% respectively. Table IV and Table V show the percentage change of -20% and 20% respectively, comparing the net change with the base case KPI values.

The Grid limit excess is influenced most by a change in the 'Grid limit': 33%. When looking at the net results, it can be seen that a change of -20 in the grid limit, results in a grid limit excess of 416% instead of 313%. As the grid limit would become 0,8 kW where it was 1 kW before, the new grid limit excess would be 4,13kW – 0,8 kW / 0,8 kW = 416%.

The Shared NPV is more sensitive to changes in input parameters. As the base Shared NPV is €942, a 20% change on certain input parameters can have a large percentage influence. However, this is as expected. For example, a 20% increase in EV cost price results in a House owner NPV which is €5787 - €987 = €4800 per house lower. As the Shared NPV changes with €942 - €4800 = €-3858, a percentage change of 509% is obtained. As the NPV per net yearly carbon emission saved is directly dependent on the Shared NPV, similar sensitivity to changes in input parameters can be observed.

To conclude, house owner NPV is influenced by changes in many input variables, which results in a change in Shared NPV. As Shared NPV is smaller in absolute sense than House owner NPV, this results in seemingly large relative differences. However, when calculating absolute differences, the model results hold true. Furthermore, other KPI are not as sensitive, as all KPI changes within 25%, with the exception of Grid limit excess being influenced by the Grid limit.

Table I: Base case results

Home owner KPI			DSO kpi		Shared KPI			
NPV	Payback ti	Grid indep	NPV	Grid limit	NPV	Net yearly	Percentag	NPV per n
€ 5.787	€ 12	26%	€ -4.845	313%	€ 942	€ 3,44	€ 0,53	€ 18

Table II: Variables -20% controlling for all other variables

PV, electric heat pumps and EV		Home owner KPI			DSO kpi		Shared KPI			
Scenario 23	Base scenario	NPV	Payback time	Grid indeper	NPV	Grid limit ex	NPV	Net yearly ca	Percentage y	NPV per
Variable supplier tariff E	[€ / kWh]	€ 6.418	11	26%	€ -4.845	313%	€ 1.573	3,44	53%	€ 30
Variable supplier tariff G	[€ / kWh]	€ 4.620	12	26%	€ -4.845	313%	€ -225	3,44	53%	€ -4
Base electricity demand	[kWh]	€ 5.787	12	26%	€ -4.845	300%	€ 942	3,44	55%	€ 18
Base gas demand	[m3]	€ 5.787	12	26%	€ -4.845	313%	€ 942	3,44	53%	€ 18
Existing boiler efficiency	[%]	€ 7.851	11	27%	€ -4.845	284%	€ 3.006	3,76	57%	€ 53
100% more capacity cost	[€ / household]	€ 5.787	12	26%	€ -4.845	313%	€ 942	3,44	53%	€ 18
200% more capacity cost	[€ / household]	€ 5.787	12	26%	€ -4.245	313%	€ 1.542	3,44	53%	€ 30
Grid limit	[kW / household]	€ 5.787	12	26%	€ -4.845	416%	€ 942	3,44	53%	€ 18
Cost new boiler	[€ / boiler]	€ 5.347	12	26%	€ -4.845	313%	€ 502	3,44	53%	€ 10
Cost fossil car	[€ / FC]	€ 2.787	13	26%	€ -4.845	313%	€ -2.058	3,44	53%	€ -40
PV cost price	[€ / kWp]	€ 5.787	12	26%	€ -4.845	313%	€ 942	3,44	53%	€ 18
Heat pump electric cost price	[€ / HPE]	€ 8.187	10	26%	€ -4.845	313%	€ 3.342	3,44	53%	€ 65
EV cost price	[€ / EV]	€ 10.587	9	26%	€ -4.845	313%	€ 5.742	3,44	53%	€ 111
Heat pump electric COP	[COP]	€ 3.207	13	24%	€ -4.845	350%	€ -1.638	3,05	47%	€ -36
EV efficiency	[%]	€ 7.807	11	26%	€ -4.845	273%	€ 2.962	3,75	57%	€ 53
PV yearly production	[kWh / panel]	€ 3.807	13	23%	€ -4.845	313%	€ -1.038	3,14	48%	€ -22

Table III: Variables +20% controlling for all other variables

PV, electric heat pumps and EV		Home owner KPI			DSO kpi		Shared KPI			
Scenario 23	Base scenario	NPV	Payback tim	Grid indep	NPV	Grid limit	NPV	Net yearly c	Percentage	NPV per n
Variable supplier tariff E	[€ / kWh]	€ 5.156	12,01	26%	€ -4.845	313%	€ 311	3,44	53%	€ 6
Variable supplier tariff G	[€ / kWh]	€ 6.955	11,23	26%	€ -4.845	313%	€ 2.110	3,44	53%	€ 41
Base electricity demand	[kWh]	€ 5.787	11,72	25%	€ -4.845	326%	€ 942	3,44	50%	€ 18
Base gas demand	[m3]	€ 5.787	11,72	26%	€ -4.845	313%	€ 942	3,44	53%	€ 18
Existing boiler efficiency	[%]	€ 3.723	12,71	24%	€ -4.845	342%	€ -1.122	3,13	48%	€ -24
100% more capacity cost	[€ / household]	€ 5.787	11,72	26%	€ -4.845	313%	€ 942	3,44	53%	€ 18
200% more capacity cost	[€ / household]	€ 5.787	11,72	26%	€ -5.445	313%	€ 342	3,44	53%	€ 7
Grid limit	[kW / household]	€ 5.787	11,72	26%	€ -4.845	244%	€ 942	3,44	53%	€ 18
Cost new boiler	[€ / boiler]	€ 6.227	11,47	26%	€ -4.845	313%	€ 1.382	3,44	53%	€ 27
Cost fossil car	[€ / FC]	€ 8.787	10,02	26%	€ -4.845	313%	€ 3.942	3,44	53%	€ 76
PV cost price	[€ / kWp]	€ 5.787	11,72	26%	€ -4.845	313%	€ 942	3,44	53%	€ 18
Heat pump electric cost price	[€ / HPE]	€ 3.387	13,08	26%	€ -4.845	313%	€ -1.458	3,44	53%	€ -28
EV cost price	[€ / EV]	€ 987	14,44	26%	€ -4.845	313%	€ -3.858	3,44	53%	€ -75
Heat pump electric COP	[COP]	€ 7.507	11,01	27%	€ -4.845	288%	€ 2.662	3,70	57%	€ 48
EV efficiency	[%]	€ 3.767	12,69	25%	€ -4.845	353%	€ -1.078	3,14	48%	€ -23
PV yearly production	[kWh / panel]	€ 7.767	10,90	28%	€ -4.845	313%	€ 2.922	3,74	57%	€ 52

Table IV: Percentage changes -20%

		Home owner KPI			DSO kpi		Shared KPI			
Scenario 21		NPV	Payback time	Grid indeper	NPV	Grid limit ex	NPV	Net yearly ca	Percentage y	NPV per r
Variable supplier tariff E	[€ / kWh]	11%	-2%	0%	0%	0%	67%	0%	0%	67%
Variable supplier tariff G	[€ / kWh]	-20%	5%	0%	0%	0%	-124%	0%	0%	-124%
Base electricity demand	[kWh]	0%	0%	3%	0%	-4%	0%	0%	5%	0%
Base gas demand	[m3]	0%	0%	0%	0%	0%	0%	0%	0%	0%
Existing boiler efficiency	[%]	36%	-7%	5%	0%	-9%	219%	9%	9%	193%
100% more capacity cost	[€ / household]	0%	0%	0%	0%	0%	0%	0%	0%	0%
200% more capacity cost	[€ / household]	0%	0%	0%	-12%	0%	64%	0%	0%	64%
Grid limit	[kW / household]	0%	0%	0%	0%	33%	0%	0%	0%	0%
Cost new boiler	[€ / boiler]	-8%	2%	0%	0%	0%	-47%	0%	0%	-47%
Cost fossil car	[€ / FC]	-52%	15%	0%	0%	0%	-318%	0%	0%	-318%
PV cost price	[€ / kWp]	0%	0%	0%	0%	0%	0%	0%	0%	0%
Heat pump electric cost price	[€ / HPE]	41%	-12%	0%	0%	0%	255%	0%	0%	255%
EV cost price	[€ / EV]	83%	-23%	0%	0%	0%	509%	0%	0%	509%
Heat pump electric COP	[COP]	-45%	11%	-5%	0%	12%	-274%	-11%	-11%	-296%
EV efficiency	[%]	35%	-7%	3%	0%	-13%	214%	9%	9%	189%
PV yearly production	[kWh / panel]	-34%	8%	-12%	0%	0%	-210%	-9%	-9%	-221%

Table V: Percentage changes +20%

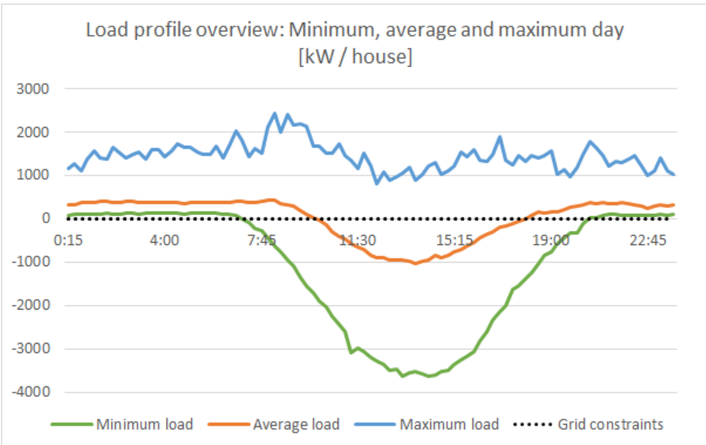
		Home owner KPI			DSO kpi		Shared KPI			
Scenario 21		NPV	Payback tim	Grid indep	NPV	Grid limit	NPV	Net yearly c	Percentage	NPV per n
Variable supplier tariff E	[€ / kWh]	-11%	2%	0%	0%	0%	-67%	0%	0%	-67%
Variable supplier tariff G	[€ / kWh]	20%	-4%	0%	0%	0%	124%	0%	0%	124%
Base electricity demand	[kWh]	0%	0%	-3%	0%	4%	0%	0%	-4%	0%
Base gas demand	[m3]	0%	0%	0%	0%	0%	0%	0%	0%	0%
Existing boiler efficiency	[%]	-36%	8%	-4%	0%	9%	-219%	-9%	-9%	-231%
100% more capacity cost	[€ / household]	0%	0%	0%	0%	0%	0%	0%	0%	0%
200% more capacity cost	[€ / household]	0%	0%	0%	12%	0%	-64%	0%	0%	-64%
Grid limit	[kW / household]	0%	0%	0%	0%	-22%	0%	0%	0%	0%
Cost new boiler	[€ / boiler]	8%	-2%	0%	0%	0%	47%	0%	0%	47%
Cost fossil car	[€ / FC]	52%	-15%	0%	0%	0%	318%	0%	0%	318%
PV cost price	[€ / kWp]	0%	0%	0%	0%	0%	0%	0%	0%	0%
Heat pump electric cost price	[€ / HPE]	-41%	12%	0%	0%	0%	-255%	0%	0%	-255%
EV cost price	[€ / EV]	-83%	23%	0%	0%	0%	-509%	0%	0%	-509%
Heat pump electric COP	[COP]	30%	-6%	4%	0%	-8%	183%	8%	8%	163%
EV efficiency	[%]	-35%	8%	-3%	0%	13%	-214%	-9%	-9%	-226%
PV yearly production	[kWh / panel]	34%	-7%	10%	0%	0%	210%	9%	9%	185%

IV.II Extreme value test

In Excel models it is important to check if the model uses the correct values, that is, are the correct cells linked to each other. A method to test this is by using extreme values. Two type of 'extreme values' are used: First, values with extreme numerical values (extremely positive or extremely negative). Second, values with nonsensical values (text where a number is expected). As the number of input parameters is high, a selection of examples is shown in this section.

Neighbourhood with 1 house, 1000 PV and 1000 electric heat pumps

The first example test takes a neighbourhood with 1 house, and a DER combination of PV and electric heat pumps. Extreme values are entered in the input variables: There are 1000 PV and 1000 electric heat pumps installed in this house. It is expected that the model will now show extremely high values for the load profile and KPI.



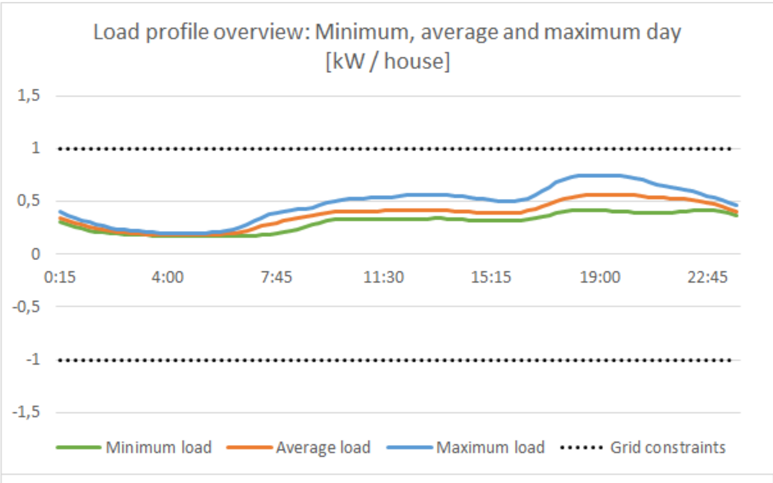
The figure on the right shows the obtained load profile of this neighbourhood. It can be seen that minimum load profile has a valley of about -3500 kW, which is caused by the production of electricity of PV. As 1 PV panel has a minimum valley of about -3,5 kW, this result is as expected. The house owners NPV is extremely negative: €-15.584.412 (Table below). This too, is as expected, as the house owner will never be able to pay back the investment costs of 1000 PV and 1000 electric heat pumps. A minor detail which is not as expected, is the functioning of the electric heat pumps, which produce heat even though there is no demand for the heat. For the model results this is not of any influence, as in every experiment 1 house is equipped with 1 electric heat pump. As the heat pumps still produce large amounts of heat and consume large amounts of electricity during winter, the grid independence is just 30%, where a higher grid independence was expected from the high number of PV. Still, the rest of the results are as expected: The grid limit excess works as expected. The DSO NPV is just €-4850, as the grid limit of 200% is reached and no further costs are specified in the model design.

Extreme value test: 1 house, 1000 PV and 1000 electric heat pumps

House owners specific KPI		
House owners NPV	[€]	€ -15.584.413,16
House owners payback time	[year]	Payback NA
House owners grid independence	[%]	30%
DSO specific KPI		
DSO NPV	[€]	€ -4.845,00
Grid limit excess	[%]	363563%
Shared KPI		
Shared NPV	[€]	€ -15.589.258,16
Net yearly carbon emissions saved	[ton CO2]	-61,22
Percentage yearly carbon emissions saved	[%]	-1516%
NPV per net total carbon emissions saved	[€ / ton CO2]	16975,37

Neighbourhood with 1 house, 0,001 solar boilers, 0,001 micro CP and 0,001 EVs.

The second example takes a neighbourhood with 1 house, and a DER combination of solar boilers, micro CHP and EVs. Extreme values are entered in the input variables: There are 0,001 solar boilers, 0,001 micro CHP and 0,001 EVs installed in this house. It is expected that the model will now show very marginal changes in the KPI and load profile.



The figure on the right shows that the base load profile is not visibly changed. This is as expected, as the influence of these DER should be marginal. Looking at the Table below which shows the results on the KPI, this can be seen as well. The house owners NPV is very slightly negative, as the result of the very small investment costs. However, as the electricity needed is 'downgraded' as well and with the same rate, the House owners payback time actually stays within 'normal' bounds. The grid limit excess is 25 lower now than the grid limit.

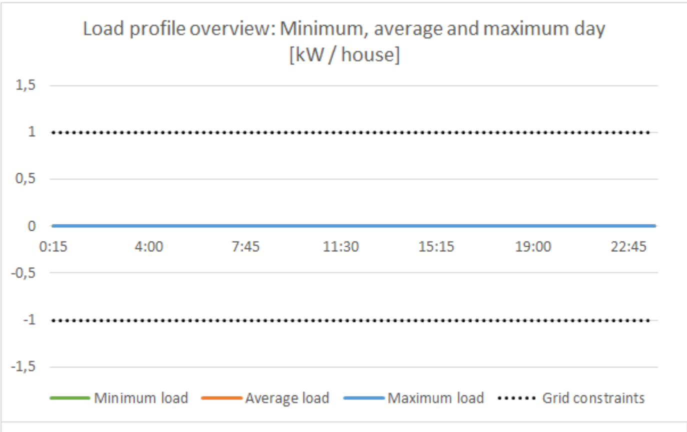
House owners specific KPI		
House owners NPV	[€]	€ -0,18
House owners payback time	[year]	15,17
House owners grid independence	[%]	0%
DSO specific KPI		

DSO NPV	[€]	€ -
Grid limit excess	[%]	-25%
Shared KPI		
Shared NPV	[€]	€ -0,18
Net yearly carbon emissions saved	[ton CO2]	0,00
Percentage yearly carbon emissions saved	[%]	0%
NPV per net total carbon emissions saved	[€ / ton CO2]	-5,92

Neighbourhood with 1 house and 'letter x' hybrid heat pumps.

The third example takes a neighbourhood with 1 house, and hybrid heat pumps. Extreme values are entered in the input variables: There are 'letter x' hybrid heat pumps installed in this house. It is expected that the model will now show nonsensical data or error values.

The figure at the right shows that, as expected, the model does not compute the 'letter x' as valid input variable. The Table below containing the KPI further confirms this.



Key Performance Indicators	Unit	Active experiment:
House owners specific KPI		
House owners NPV	[€]	#VALUE!
House owners payback time	[year]	#VALUE!
House owners grid independence	[%]	#VALUE!
DSO specific KPI		
DSO NPV	[€]	#VALUE!
Grid limit excess	[%]	#VALUE!
Shared KPI		
Shared NPV	[€]	#VALUE!
Net yearly carbon emissions saved	[ton CO2]	#VALUE!
Percentage yearly carbon emissions saved	[%]	#VALUE!
NPV per net total carbon emissions saved	[€ / ton CO2]	#VALUE!

Appendix V: Validation test

In this appendix validation tests are presented. First, a comparison is performed, comparing model data to parameter values found in existing literature. Second, a historical data test is performed, in which model parameters are compared to historical data. Third and final, an expert validation test is performed.

X.I Comparison with existing sources

In this test model parameter values are compared to two sources: Source A and Source B. The difference of the value in the model is compared to the found parameter values. Differences smaller than 25% can be considered 'very good'. Differences larger than 25% could still be correct, but further investigation is needed on where the difference comes from. This investigation is performed in Chapter 5.

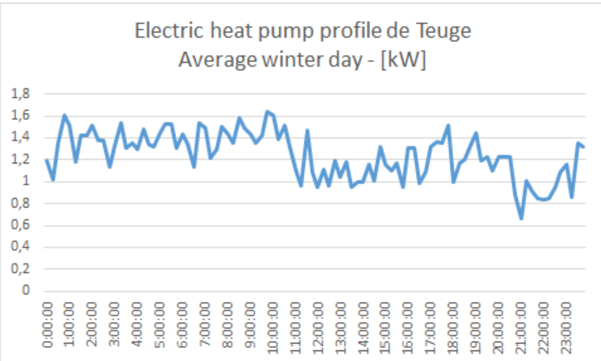
Parameter	**Unit**	**Model**	**A**	**Difference A**	**B**	**Difference B**	**Source A**	**Source B**
Electricity demand	[kWh]	3300	3300	0%	3050	8%	(Milieu Centraal, 2016d)	(CBS, 2016b)
Gas consumption	[m3]	1390	1390	0%	1410	-1%	(Energiemodule WoON, 2012)	(Milieu Centraal, 2016d)
Electricity price	[€ / kWh]	0,2	0,2	0%	0,19	5%	(Milieu Centraal, 2016c)	(CBS, 2016a)
Gas price	[€ / m3]	0,66	0,66	0%	0,73	-10%	(Milieu Centraal, 2016c)	(CBS, 2016a)
Yearly energy cost	[€]	1726	1771	-3%	1686	2%	(CBS, 2015)	(Autoriteit Consument & Markt, 2015)
DER parameters								
Parameter	Unit	Model	Source A	Difference A	Source B	Difference B	Source A source	Source B source
PV panel cost	[€ / Wp]	1,7	1,64	4%	1,99	-15%	(Milieu Centraal, 2016h)	(Zonnepanelen-info, 2016b)
PV energy bill reduction	[€]	660	440	50%	782	-16%	(Milieu Centraal, 2016h)	(Zonnepanelen-info, 2016b)
PV payback time	[year]	10	13	-23%	10	0%	(Milieu Centraal, 2016h)	(Zonnepanelen-info, 2016a)
CHP cost	[€ / CHP]	10500	11500	-9%	11000	-5%	(Milieu Centraal, 2016f)	(Mank, 2016)
CHP energy bill reduction	[€]	209	300	-30%	400	-48%	(Milieu Centraal, 2016f)	(Mank, 2016)
CHP payback time	[year]	39,7	38	4%	27,5	44%	(Milieu Centraal, 2016f)	(Mank, 2016)
Solar boiler cost	[€ / Solar boiler]	3300	3300	0%	3500	-6%	(Milieu Centraal, 2016m)	(Zonnepanelen-weetjes, 2016b)
Solar boiler energy bill reduction	[€]	145,6	150	-3%	120	21%	(Milieu Centraal, 2016m)	(Zonnepanelen-weetjes, 2016b)
Solar boiler payback time	[year]	18,3	20,4	-10%	23,75	-23%	(Milieu Centraal, 2016m)	(Zonnepanelen-weetjes, 2016b)
Hybrid heat pump cost	[€ / HP-H]	6500	5500	18%	7200	-10%	(Milieu Centraal, 2016k)	(Frenaij, 2016)
Hybrid heat pump energy bill reduction	[€]	203	300	-32%	195	4%	(Milieu Centraal, 2016k)	(Frenaij, 2016)
Hybrid heat pump payback time	[year]	15	14,16	6%	24,69	-39%	(Milieu Centraal, 2016k)	(Frenaij, 2016)
Electric heat pump cost	[€ / HP-E]	12000	12000	0%	12500	-4%	(Milieu Centraal, 2016k)	(Zonnepanelen-weetjes, 2016a)
Electric heat pump energy bill reduction	[€]	427	240	78%	400	7%	(Milieu Centraal, 2016k)	(Warmtepompforum, 2010)
Electric heat pump payback time	[year]	20	15	33%	24	-17%	(Warmtepomp-info, 2016)	(Frenaij, 2016)

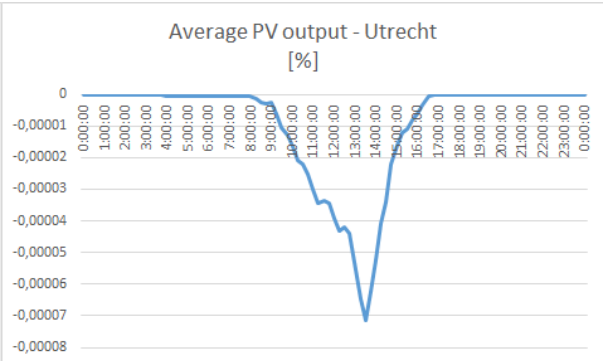
EV cost	[€ / EV]	24000	21540	11%	25990	-8%	(Kamp, 2013)	(ANWB, 2016)
EV yearly cost reduction	[€]	726	876	-17%	NA	NA	(ANWB, 2016)	
EV payback time	[year]	7,6	8	-5%	8	-5%	(RVO, 2010)	(ANWB, 2016)
Home battery cost	[€ / HB]	7250	7500	-3%	6400	13%	(Eneco, 2016)	(Milieu Centraal, 2016n)
Home battery capacity	[kWh]	6,4	6,4	0%	NA	NA	(Tesla, 2016)	

X.II Historical data test

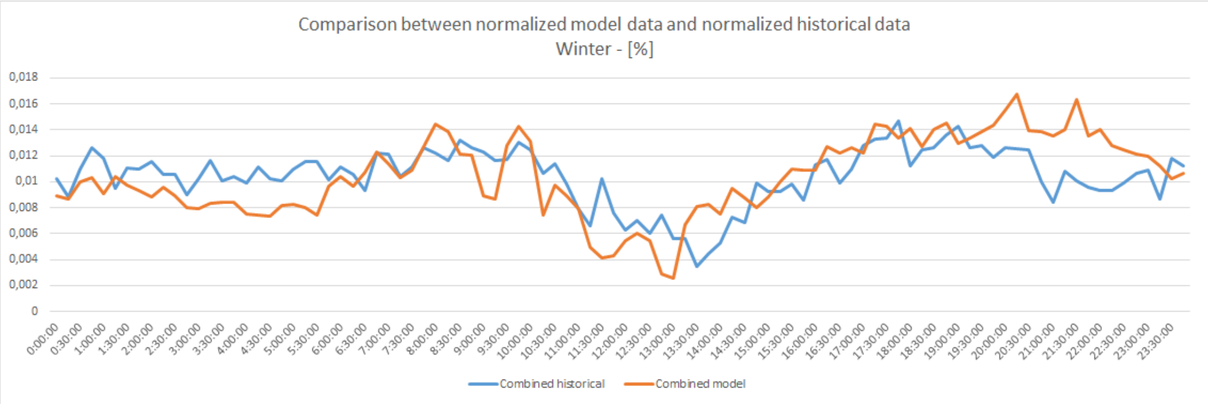
Historical data differs from 'results found in existing sources' as historical data consists of raw data files, whereas existing literature shows parameter values. For this research, a limited number of historical data was available consisting of load profiles. From the historical load profiles available, the most up-to-date and relevant ones were chosen as input load profiles for the model. As such, there were limited possibilities to compare the model output load profiles with non-used load profiles. As the load profiles not chosen are the only ones available to compare with, the similarity between the two does not say too much about the validity of the model. Still, a comparison can be useful to get an idea of the similarity between historical data sources.

There are two data sources left which are not or only partial used in the model. The first one contains both a heat pump profile based on NDP 'de Teuge' and a PV profile which is an aggregated profile of 80 households in the Dutch region of Utrecht (T. Dekker et al., 2016). De Teuge is one of the first NDP constructed in the Netherlands, however the installation of heat pumps has failed in this project (RCCK&L, 2011). Still, data was collected from the heat pumps. The figures below shows the load profile of the electric heat pump in de Teuge (left) and PV in the region of Utrecht (right) respectively.

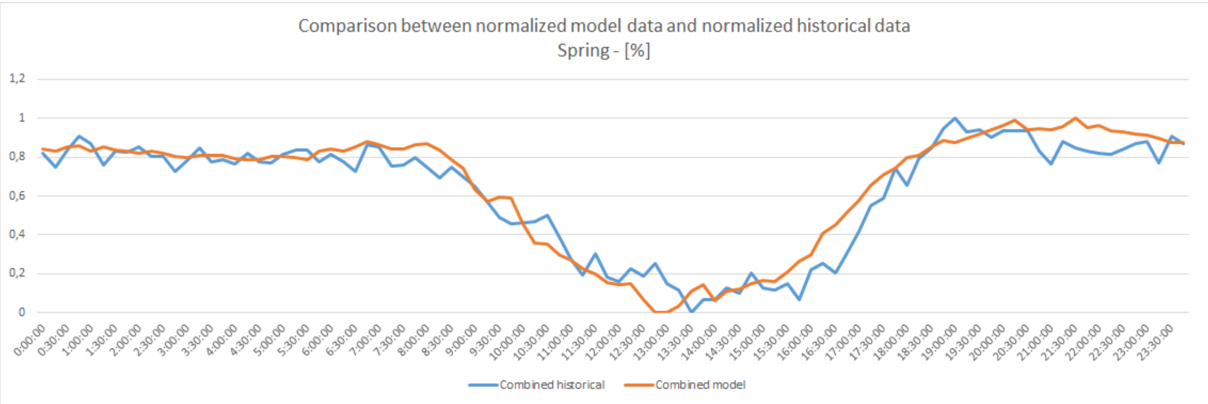




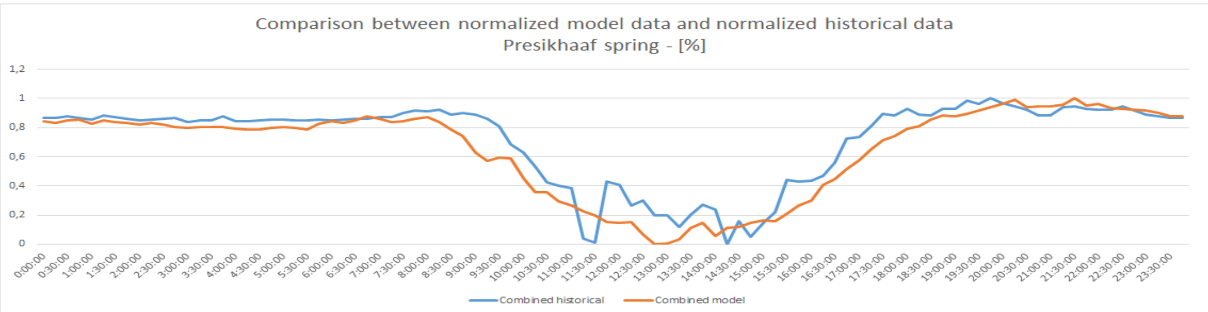
Combing the electric heat pump profile of de Teuge and the PV profile of the region Utrecht with the an base load profile, an average winter day load profile is obtained which can be used to compare the model data with. As such, an average winter day of the historical data is compared with the average winter day in the model. Both load profiles are normalized in order to compare them better. The graph below shows a comparison of both normalized load profiles. It can be seen that the behaviour in both graphs is very similar. Both have a small sized 'valley' caused by the PV, and both have a fluctuating pattern caused by the electric heat pumps. The average difference between the two load profiles is 7%, with a variance of 11%.



The de Teuge and Utrecht historical data also has the possibility to compare the spring profile of both load profiles. In this case, the both load profiles included negative values, which made the use of normalizing between 0 and 1 necessary. The figure below shows the comparison between the normalized model data and normalized historical data (normalized between 0 and 1). The average difference is -1%, and the variance of the difference is 16%.



The second data source left available was the data source used for the load profile of the electric heat pump in the model: the Presikhaaf case (Bhagwandas, 2016). However, this load profile only contained aggregated data. The winter load profile was used to construct load profile for the electric heat pump. However, the Presikhaaf data also included a spring load profile, in which PV is more prominent. This spring Presikhaaf load profile could be used to further validate the load profile of the PV load profile used in the model (Kaas, 2013). The figure below shows the difference between the normalized load profiles of the Presikhaaf case spring data and the normalized model data of a neighbourhood with PV and electric heat pumps. The average difference is 27% and the variance of the difference is 45%.



X.III Expert validation: Questions askes at end of discussion

As described in Chapter 5, an expert validation has taken place. After a presentation and discussion of the constructed model, the following questions have been asked to Dekker, V. (2016) and Westerhout, M. (2016), 'stroomversnellingswijk' (NDP) experts of DSO Alliander.

Questions about base model assumptions:

Q: What is your opinion about the dimensioning of the low-voltage grid to 1 kW?

A: The grid has been dimensioned on 1kW. In practice, this is dependent on the situation, as it is dependent on the type of cable and number of houses which is connect to a single cable.

Q: What is your opinion on the assumptions made on the cost of grid investments?

A: This should be done by taking the average of the cost of such an investment on the available 'product sheets' available within the DSO company.

Q: What is your opinion about taking an energy label of A/B for houses within neighbourhood distributed energy resource projects?

A: This should be energy label A. Houses which are being renovated have energy label E/F/G, and get renovated to have energy label A.

Questions about DER

Q: How complete is the list of possible DER?

A: This list is reasonably complete, the most important DERs are included. New technologies like infra-red warming could be included as well.

Q: How correct are the investment cost and payback times of the included DER?

A: The investment cost are correct I think. Only the home battery seams a bit expensive.

Q: What is your opinion on the way load profiles are being used within the model?

A: Good

Questions about flexibility management options

Q: How complete is the list of flexibility management options?

A: Good, but certain options are missing, like: Can you use the buffer of heat pumps to reduce the PV peak, the flexibility management of micro CHP, and possibly the slowed down charging of EVs.

Q: What is your opinion on the way flexibility management options are calculated within the model?

A: There is a lot of curtailment which is correctly calculated.

Questions about the model and reality

Q: How do the model results imitate the experiences you have from real life practices?

A: In real life experiences the peek of solar PV is much lower than in the model, up to 7kW. In practice these neighbourhoods are equipped with enough solar PV to cover both the base load and the additional load of the heat pumps. In the model only the base load is covered, as one 'scope limit' is missing: The energy bill has to be zero. In the model this is not the case, while in practice the energy bill has to be zero.

Appendix VI: Design of experiments

In this Appendix an overview can be found of the design of experiments (Table below). In the most left column, an experiment identification number can be seen. Every row contains 1 experiment with corresponding experiment identification number. The second column shows which DERs are applicable in that particular experiment. The following columns show the applied flexibility management options. Example: Experiment 1 only has PV, as shown in the second column, and has the 'zero-option': which means that no flexibility management is applied. Experiment 12 has both PV and an electric heat pump, with both having 'zero options' for flexibility management: So no flexibility management is applied. Note, as the last set of experiments does not included flexibility management, they are only presented in the second column of the left, and not by the other columns on the right.

In the model abbreviations were used. The Table below shows the meaning of these abbreviations.

Term	**Model abbreviation**
Photovoltaics	PV
Micro CHP	CHP
Solar boiler	SB
Hybrid heat pump	HP-H
Electric heat pump	HP-E
Electric vehicle	EV
Home battery	HB

Experiment information		**Zero option**	**Curtailment dynamic**	**Curtailment static**	**Zero option**	**HP-E on/off switching**	**HP-E shifting**	**Zero option**	**HP-H gas switching**	**When coming home**	**No evening**	**Night only**	**Dumb**	**Smart**
	Individual DER and flexibility management options													
1	PV	x												
2	PV		x											
3	PV			x										
4	HP-E				x									
5	HP-E					x								
6	HP-E						x							
7	HP-H							x						
8	HP-H								x					
9	EV									x				
10	EV										x			
11	EV											x		
	PV, electric heat pumps (HP-E), EVs and flexibility management options													
12	PV + HP-E	x			x									
13	PV + HP-E		x		x									
14	PV + HP-E			x	x									

15	PV + HP-E	x				x								
16	PV + HP-E						x							
17	PV + HP-E		x			x								
18	PV + HP-E		x				x							
19	PV + HP-E			x		x								
20	PV + HP-E			x			x							
21	PV + HP-E + HB	x			x								x	
22	PV + HP-E + HB	x			x									x
23	PV + HP-E + EV	x			x					x				
24	PV + HP-E + EV	x			x						x			
25	PV + HP-E + EV	x			x							x		
26	PV + HP-E + EV		x		x					x				
27	PV + HP-E + EV	x					x			x				
28	PV + HP-E + EV		x			x					x			
29	PV + HP-E + EV		x			x						x		
30	PV + HP-E + EV			x			x				x			
31	PV + HP-E + EV			x			x					x		
32	PV + HP-E + EV + HB	x			x					x			x	
33	PV + HP-E + EV + HB	x			x					x				x
	PV, hybrid heat pumps (HP-H), EVs and flexibility management options													
34	PV + HP-H	x						x						
35	PV + HP-H		x					x						
36	PV + HP-H			x				x						
37	PV + HP-H	x							x					
38	PV + HP-H		x						x					
39	PV + HP-H			x					x					
40	PV + HP-H + HB	x						x					x	
41	PV + HP-H + HB	x						x						x
42	PV + HP-H + EV	x						x		x				
43	PV + HP-H + EV	x						x			x			
44	PV + HP-H + EV	x						x				x		
45	PV + HP-H + EV		x					x		x				
46	PV + HP-H + EV	x							x	x				
47	PV + HP-H + EV		x						x		x			
48	PV + HP-H + EV		x						x			x		
49	PV + HP-H + EV + HB	x						x		x			x	
50	PV + HP-H + EV + HB	x						x		x				x

	Combinations of DERs, without flexiblity management													
51	PV + HP-E + SB	x			x									
52	PV + HP-E + SB + EV	x			x					x				
53	PV + HP-H + SB	x						x						
54	PV + HP-H + SB + EV	x						x		x				
55	PV + CHP + SB	x												
56	PV + CHP + SB + EV	x								x				
57	PV + 50CHP + 50 HP-H + SB	x												
58	PV + 50CHP + 50HP-E + SB	x												

6.1.2 Obtaining results with the model

In order to obtain results, all experiments are coded into the excel model in the sheet 'Input' (Appendix I). As such, a user can easily pick a performed experiment, and check if the results correspond to the presented results. Figure I shows the coding of the different experiments in the Excel model. Every experiment has an experiment identification number, as well as a code which shows abbreviations the specific combination of DERs and flexibility management used in this experiment.

	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	
1																
2	**Experiments**															
3			**Level 4a experiments**											**Level 4b experiments**		
4		**Custom scenario**	1	2	3	4	5	6	7	8	9	10	11	12	13	
5			A00	A01	A02	E00	E01	E02	D00	D01	F00	F01	F02	A00E00	A01E00	A
6	Construction date	Energy label A/B	Energy labe	Energy labe	Energy labe	Energy labe	Energy labe	Energy labe	Energy labe	Energy labe	Energy labe	Energy label	Energy label	Energy label	Energy label	E
7	Total number of houses	100	100	100	100	100	100	100	100	100	100	100	100	100	100	
8																
9	Policy options home owners															
10	PV [A]	100	100	100	100	0	0	0	0	0	0	0	0	100	100	
11	Micro CHP [B]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
12	Solar boiler [C]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
13	Heat pump hybrid [D]	0	0	0	0	0	0	0	100	100	0	0	0	0	0	
14	Heat pump electric [E]		0	0	0	100	100	100	0	0	0	0	0	100	100	
15																
16	EV [F]	0	0	0	0	0	0	0	0	0	100	100	100	0	0	
17	Home battery [G]		0	0	0	0	0	0	0	0	0	0	0	0	0	
18																
19	Policy options DGO															
20	**PV Flex**															
21	Curtailment dynamic [A01]	Yes	No	Yes	No	No	No	No	No	No	No	No	No	No	Yes	N
22	Curtailment static [A02]	No	No	No	Yes	No	No	No	No	No	No	No	No	No	No	Y
23	**HP Flex**															
24	HP-E on/off switching [E01]	No	No	No	No	No	Yes	No	No	No	No	No	No	No	No	N
25	HP-E shifting [E02]	No	No	No	No	No	No	Yes	No	No	No	No	No	No	No	N
26	HP-H gas switching [D01]	No	No	No	No	No	No	No	No	Yes	No	No	No	No	No	N
27	**EV Flex**															
28	EV loading [F00,01,02]	When coming home	When comi	When comi	When comi	When comi	When comi	When comi	When comi	When comi	When comi	No evening	At night only	When comin	When comin	W
29	**Home battery flex**															
30	Charging [G00,01]	Dumb	Dumb	Dumb	Dumb	Dumb	Dumb	Dumb	Dumb	Dumb	Dumb	Dumb	Dumb	Dumb	Dumb	D

Figure I: Sheet 'input' experiments coding:

Results are stored in the sheet 'Experiments overview' (Appendix I). The KPI of the loaded experiment are shown in this sheet as well. The results of the different experiments are stored next to each other. The results are colour coded. Favourable results are coloured green, whereas unfavourable results are coloured red. Complete results can be found in Appendix VII.

Appendix VII: Overview of results

In this appendix the complete results of all experiments can be found. The results are colour-coded from green to red. Red means that, in comparison to all experiments, an experiment scores bad on that particular KPI. Green means a good score. The Table below shows a legend to the combination in a particular set up. A combination example: AooEoo means PV / no flex with electric heat pumps / no flex.

Legend of scenario codes

	DER ID
PV / Zero option	A00
PV / Dynamic curtailment	A01
PV / Static curtailment	A02
Micro CHP / Zero option	B00
Solar boiler / Zero option	C00
HP-H / Zero option	D00
HP-H / Switching to gas	D01
HP-E / Zero option	E00
HP-E / Switching off	E01
HP-E / Shifting heat production	E02
EV / Zero option	F00
EV / No evening charging	F01
EV / Only at night charging	F02
HB / Zero option	G00
HB / smart	G01

In the model abbreviations were used. Table x shows the meaning of these abbreviations.

Term	**Model abbreviation**
Photovoltaics	PV
Micro CHP	CHP
Solar boiler	SB
Hybrid heat pump	HP-H
Electric heat pump	HP-E
Electric vehicle	EV
Home battery	HB

VII.I Single DERs and flexibility management results

Scenarios 1: Combining	1	2	3	4	5	6
	A00	A01	A02	E00	E01	E02
House owner specific KPI						
Home owners NPV	€ 3.270,00	€ 1.894,78	€ 3.765,01	€ -2.889,39	€ -911,73	€ -2.889,39
Home owners payback time	10,05	11,67	9,29	22,66	16,79	22,66
Home owners grid independence	7%	7%	7%	0%	0%	0%
DSO specific KPI						
DSO NPV	€ -3.000,00	€ -	€ -3.000,00	€ -4.845,00	€ -1.845,00	€ -4.845,00
Grid limit exceedance	234%	0%	141%	184%	0%	127%
Shared KPI						
Shared KPI	€ 270,00	€ 1.894,78	€ 765,01	€ -7.734,39	€ -2.756,73	€ -7.734,39
Net yearly carbon emissions saved	1,50	1,29	1,50	0,97	1,16	0,97
Percentage yearly carbon emissions	37%	32%	37%	24%	29%	24%
NPV per net yearly carbon emissions	11,99	97,70	33,98	-530,76	-158,75	-530,76

Scenarios 1: Combining	7	8	9	10	11
	D00	D01	F00	F01	F02
House owner specific KPI					
Home owners NPV	€ 0,23	€ -196,68	€ 5.406,50	€ 5.406,50	€ 5.406,50
Home owners payback time	15,00	16,03	7,56	7,56	7,56
Home owners grid independence	0%	0%	0%	0%	0%
DSO specific KPI					
DSO NPV	€ -2.000,00	€ -	€ -3.000,00	€ -2.000,00	€ -2.000,00
Grid limit exceedance	40%	0%	170%	71%	64%
Shared KPI					
Shared KPI	€ -1.999,77	€ -196,68	€ 2.406,50	€ 3.406,50	€ 3.406,50
Net yearly carbon emissions saved	0,90	0,85	0,97	0,97	0,97
Percentage yearly carbon emissions	22%	21%	15%	15%	15%
NPV per net yearly carbon emissions	-147,54	-15,46	165,23	233,90	233,90

VII.II PV and electric heat pumps results

Scenarios 1: Combining	12	13	14	15	16
	A00E00	A01E00	A02E00	A00E01	A00E02
House owner specific KPI					
Home owners NPV	€ 380,61	€ -439,07	€ 875,62	€ 1.310,56	€ 380,61
Home owners payback time	14,63	15,45	14,16	13,81	14,63
Home owners grid independence	28%	28%	28%	29%	28%
DSO specific KPI					
DSO NPV	€ -4.845,00	€ -4.845,00	€ -4.845,00	€ -4.845,00	€ -4.845,00
Grid limit exceedance	224%	184%	184%	224%	224%
Shared KPI					
Shared KPI	€ -4.464,39	€ -5.284,07	€ -3.969,38	€ -3.534,44	€ -4.464,39
Net yearly carbon emissions saved	2,47	2,35	2,47	2,61	2,47
Percentage yearly carbon emissions	61%	58%	61%	65%	61%
NPV per net yearly carbon emissions	-120,35	-149,99	-107,04	-90,14	-120,35

Scenarios 1: Combining	17	18	19	20
	A01E01	A01E02	A02E01	A02E02
House owner specific KPI				
Home owners NPV	€ 490,89	€ -444,44	€ 1.805,57	€ 875,62
Home owners payback time	14,53	15,45	13,36	14,16
Home owners grid independence	29%	28%	29%	28%
DSO specific KPI				
DSO NPV	€ -1.845,00	€ -4.845,00	€ -4.845,00	€ -4.845,00
Grid limit exceedance	0%	126%	127%	127%
Shared KPI				
Shared KPI	€ -1.354,11	€ -5.289,44	€ -3.039,43	€ -3.969,38
Net yearly carbon emissions saved	2,49	2,35	2,61	2,47
Percentage yearly carbon emissions	62%	58%	65%	61%
NPV per net yearly carbon emissions	-36,26	-150,19	-77,54	-107,04

VII.III PV, electric heat pumps and home batteries

Scenarios 1: Combining	21	22
	A00E00G00	A00E00G01
House owner specific KPI		
Home owners NPV	€ -7.045,35	€ -7.058,42
Home owners payback time	21,87	21,89
Home owners grid independence	43%	38%
DSO specific KPI		
DSO NPV	€ -4.845,00	€ -4.845,00
Grid limit exceedance	224%	150%
Shared KPI		
Shared KPI	€ -11.890,35	€ -11.903,42
Net yearly carbon emissions saved	2,45	2,44
Percentage yearly carbon emissions	61%	61%
NPV per net yearly carbon emissions	-324,04	-324,65

VII.IV PV, electric heat pumps and EVs results

Scenarios 1: Combining	23	24	25	26	27
	A00E00F00	A00E00F01	A00E00F02	A01E00F00	A00E02F00
House owner specific KPI					
Home owners NPV	€ 5.787,11	€ 5.787,11	€ 5.787,11	€ 5.606,29	€ 5.787,11
Home owners payback time	11,72	11,72	11,72	11,80	11,72
Home owners grid independence	26%	26%	19%	26%	26%
DSO specific KPI					
DSO NPV	€ -4.845,00	€ -4.845,00	€ -4.845,00	€ -4.845,00	€ -4.845,00
Grid limit exceedance	313%	234%	236%	313%	278%
Shared KPI					
Shared KPI	€ 942,11	€ 942,11	€ 942,11	€ 761,29	€ 942,11
Net yearly carbon emissions saved	3,44	3,44	3,44	3,42	3,44
Percentage yearly carbon emissions	53%	53%	53%	52%	53%
NPV per net yearly carbon emissions	18,24	18,24	18,24	14,86	18,24

Scenarios 1: Combining	28	29	30	31
	A01E01F01	A01E01F02	A02E02F01	A02E02F02
House owner specific KPI				
Home owners NPV	€ 9.245,64	€ 9.037,21	€ 6.282,12	€ 6.282,12
Home owners payback time	10,37	10,44	11,44	11,44
Home owners grid independence	29%	21%	25%	19%
DSO specific KPI				
DSO NPV	€ -3.845,00	€ -3.845,00	€ -4.845,00	€ -4.845,00
Grid limit exceedance	70%	64%	220%	236%
Shared KPI				
Shared KPI	€ 5.400,64	€ 5.192,21	€ 1.437,12	€ 1.437,12
Net yearly carbon emissions saved	3,97	3,94	3,44	3,44
Percentage yearly carbon emissions	61%	60%	53%	53%
NPV per net yearly carbon emissions	90,73	87,92	27,83	27,83

VII.V PV, electric heat pumps, EVs and home batteries

Scenarios 1: Combining	32	33
	A00E00F00G00	A00E00F00G01
House owner specific KPI		
Home owners NPV	€ -1.539,78	€ -1.862,98
Home owners payback time	15,88	16,07
Home owners grid independence	31%	29%
DSO specific KPI		
DSO NPV	€ -4.845,00	€ -4.845,00
Grid limit exceedance	313%	208%
Shared KPI		
Shared KPI	€ -6.384,78	€ -6.707,98
Net yearly carbon emissions saved	3,43	3,38
Percentage yearly carbon emissions	52%	52%
NPV per net yearly carbon emissions	-124,01	-132,18

X.VI PV and hybrid heat pump results

Scenarios 1: Combining	34	35	36	37	38	39
	A00D00	A01D00	A02D00	A00D01	A01D01	A02D01
House owner specific KPI						
Home owners NPV	€ 3.270,23	€ 2.450,56	€ 3.765,24	€ 3.122,13	€ 2.302,45	€ 3.617,14
Home owners payback time	11,21	11,97	10,64	11,34	12,12	10,76
Home owners grid independence	25%	25%	25%	24%	24%	24%
DSO specific KPI						
DSO NPV	€ -3.000,00	€ -2.000,00	€ -3.000,00	€ -3.000,00	€ -	€ -3.000,00
Grid limit exceedance	224%	40%	127%	224%	0%	127%
Shared KPI						
Shared KPI	€ 270,23	€ 450,56	€ 765,24	€ 122,13	€ 2.302,45	€ 617,14
Net yearly carbon emissions saved	2,41	2,28	2,40	2,36	2,24	2,36
Percentage yearly carbon emissions	60%	56%	60%	59%	55%	59%
NPV per net yearly carbon emissions	7,49	13,17	21,22	3,45	68,56	17,41

Scenarios 1: Combining	40	41
	A00D00G00	A00D00G01
House owner specific KPI		
Home owners NPV	€ -4.155,72	€ -4.073,83
Home owners payback time	19,88	19,75
Home owners grid independence	39%	34%
DSO specific KPI		
DSO NPV	€ -3.000,00	€ -3.000,00
Grid limit exceedance	224%	136%
Shared KPI		
Shared KPI	€ -7.155,72	€ -7.073,83
Net yearly carbon emissions saved	2,38	2,39
Percentage yearly carbon emissions	59%	59%
NPV per net yearly carbon emissions	-200,57	-197,25

X.VII PV, hybrid heat pumps and EVs results

Scenarios 1: Combining	42	43	44	45
	A00D00F00	A00D00F01	A00D00F02	A01D00F00
House owner specific KPI				
Home owners NPV	€ 8.676,73	€ 8.676,73	€ 8.676,73	€ 8.495,92
Home owners payback time	9,54	9,54	9,54	9,62
Home owners grid independence	24%	24%	17%	24%
DSO specific KPI				
DSO NPV	€ -3.000,00	€ -3.000,00	€ -3.000,00	€ -3.000,00
Grid limit exceedance	235%	191%	224%	235%
Shared KPI				
Shared KPI	€ 5.676,73	€ 5.676,73	€ 5.676,73	€ 5.495,92
Net yearly carbon emissions saved	3,38	3,38	€ 3,38	€ 3,35
Percentage yearly carbon emissions	52%	52%	52%	51%
NPV per net yearly carbon emissions	112,10	112,10	€ 112,10	€ 109,42

Scenarios 1: Combining	46	47	48
	A00D01F00	A01D01F01	A01D01F02
House owner specific KPI			
Home owners NPV	€ 7.759,69	€ 7.515,93	€ 6.710,94
Home owners payback time	9,93	10,03	10,40
Home owners grid independence	19%	19%	13%
DSO specific KPI			
DSO NPV	€ -3.000,00	€ -2.000,00	€ -2.000,00
Grid limit exceedance	191%	70%	64%
Shared KPI			
Shared KPI	€ 4.759,69	€ 5.515,93	€ 4.710,94
Net yearly carbon emissions saved	€ 3,12	€ 3,07	€ 2,93
Percentage yearly carbon emissions	48%	47%	45%
NPV per net yearly carbon emissions	€ 101,79	€ 119,69	€ 107,32

VII.VIII PV, hybrid heat pumps, EVs and home batteries

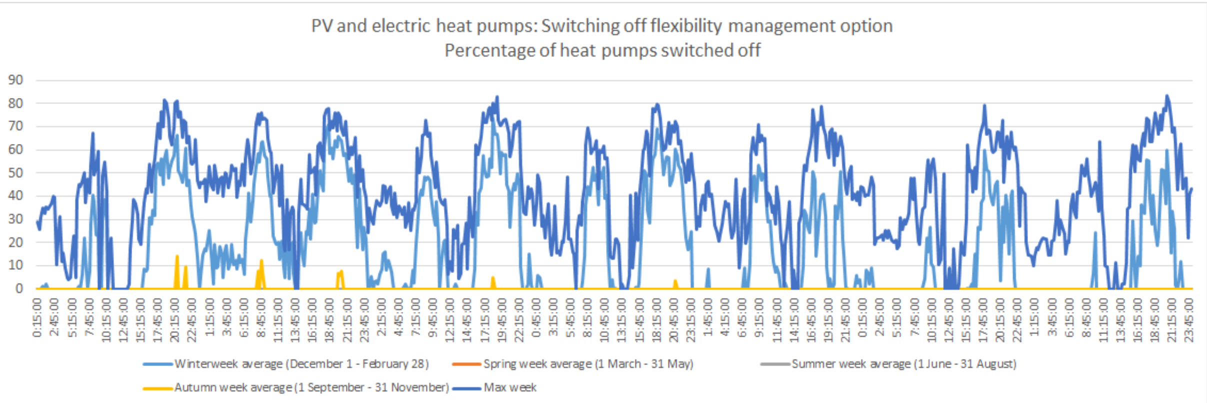
Scenarios 1: Combining	49	50
	A00D00F00G00	A00D00F00G01
House owner specific KPI		
Home owners NPV	€ 1.349,85	€ 1.030,43
Home owners payback time	14,15	14,34
Home owners grid independence	29%	27%
DSO specific KPI		
DSO NPV	€ -3.000,00	€ -3.000,00
Grid limit exceedance	235%	157%
Shared KPI		
Shared KPI	€ -1.650,15	€ -1.969,57
Net yearly carbon emissions saved	€ 3,36	€ 3,32
Percentage yearly carbon emissions	51%	51%
NPV per net yearly carbon emissions	€ -32,70	€ -39,60

VII.IX DERs without flexibility management results

Scenarios 1: Combining	51	52	53	54
	ACE	ACEF	ACD	ACDF
House owner specific KPI				
Home owners NPV	€ -1.654,91	€ 3.751,59	€ 919,70	€ 6.326,20
Home owners payback time	16,53	12,92	13,96	11,07
Home owners grid independence	27%	26%	26%	24%
DSO specific KPI				
DSO NPV	€ -4.845,00	€ -4.845,00	€ -3.000,00	€ -3.000,00
Grid limit exceedance	227%	313%	225%	235%
Shared KPI				
Shared KPI	€ -6.499,91	€ -1.093,41	€ -2.080,30	€ 3.326,20
Net yearly carbon emissions saved	€ 2,59	€ 3,56	€ 2,48	€ 3,45
Percentage yearly carbon emissions	64%	54%	61%	53%
NPV per net yearly carbon emissions	€ -167,38	€ -20,48	€ -55,95	€ 64,28

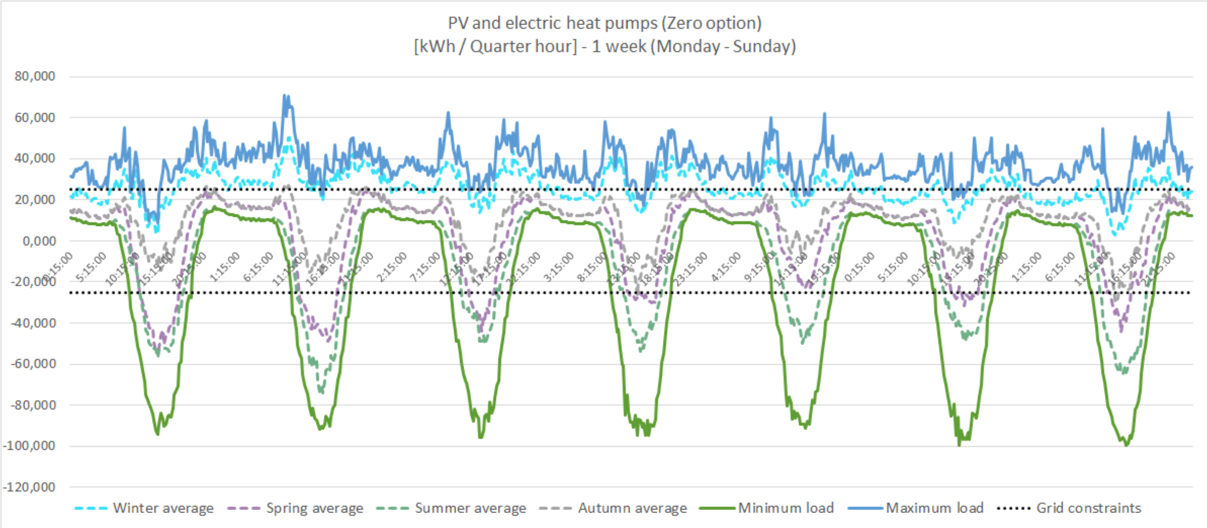
Scenarios 1: Combining	55	56	57	58
	ABC	ABCF	ABCD	ABCE
House owner specific KPI				CHP only
Home owners NPV	€ -3.077,02	€ 2.329,48	€ -620,90	€ -3.201,60
Home owners payback time	18,18	13,62	15,65	18,31
Home owners grid independence	6%	11%	13%	14%
DSO specific KPI				
DSO NPV	€ -3.000,00	€ -3.000,00	€ -3.000,00	€ -3.000,00
Grid limit exceedance	234%	201%	234%	234%
Shared KPI				
Shared KPI	€ -6.077,02	€ -670,52	€ -3.620,90	€ -6.201,60
Net yearly carbon emissions saved	€ 2,43	€ 3,40	€ 2,55	€ 2,58
Percentage yearly carbon emissions	60%	52%	63%	64%
NPV per net yearly carbon emissions	€ -166,86	€ -13,15	€ -94,69	€ -160,50

VII.X Switching off heat pumps



VII.XI Examples of seasonal load profiles of experiment results

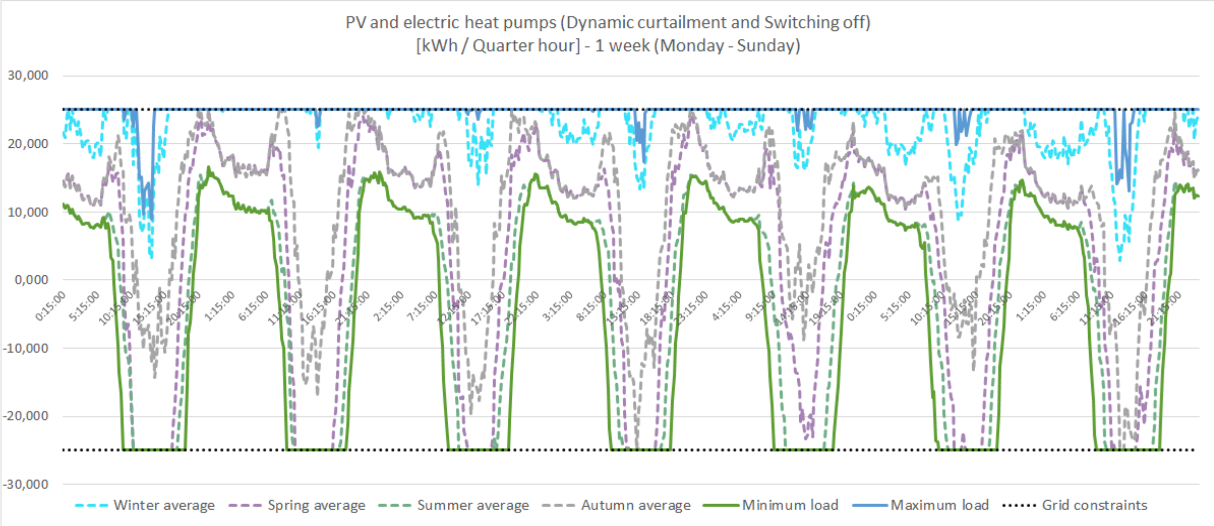
In this appendix a number of seasonal load profiles are shown which give some examples to the results in Chapter 6, as in Chapter 6 only minimum, average and maximum load profiles were shown for 1 day periods. In this appendix the load profiles are shown as they appear in the model: Based on 4 weeks each representing 1 season, and added with a minimum and maximum yearly load profile, with a 1 week time period.



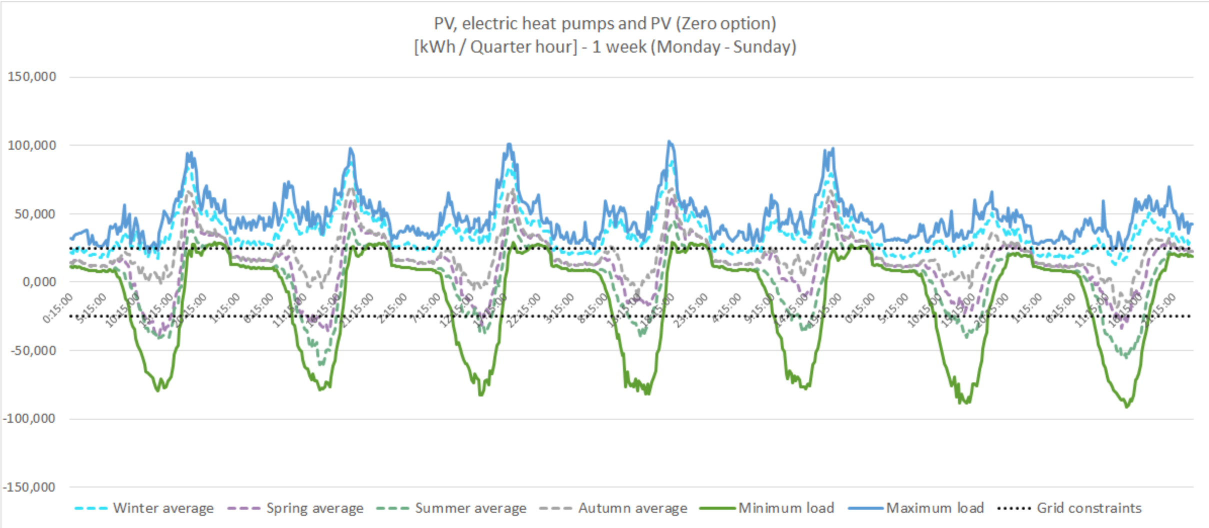
An explanation of the behaviour of the load profiles can be found in Chapters 5 and 6. A DER combination of PV and electric heat pumps with no flexibility management will be used as an example on how to understand the other load profiles in this Appendix. In the profile seven days can be seen, starting at Monday morning 00:00 and ending at Sunday evening 23:59. The dotted lines represent the grid constraints. Each coloured line represents a load profile: Average Winter profile (dotted Sky blue), average Spring profile (dotted Purple), average Summer profile (dotted turquoise), average Autumn profile (dotted grey), minimum load profile (solid green) and maximum load profile (solid blue). It can be seen that every day a 'valley' occurs, caused by the excess electricity production of PV. During the coldest Winter week (maximum load profile), the electric heat pump results in a continuous grid limit excess.

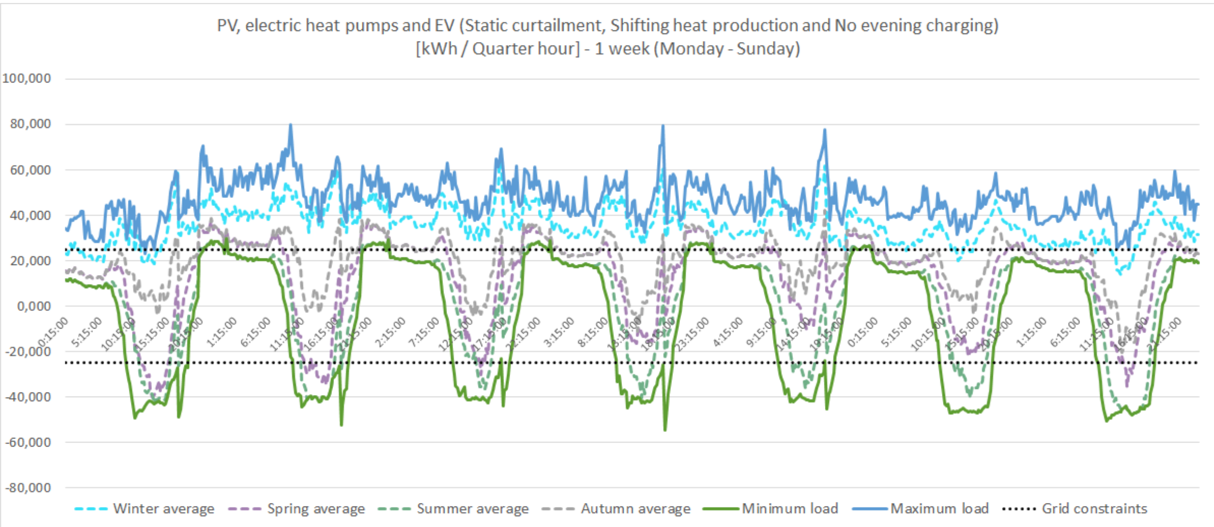
The example load profiles given on the following pages represent 2 load profiles per DER combination from the second experiment set: Combinations of flexible DER and flexibility management options. One load profile will be the zero option, and the other will include a flexibility management combination. Furthermore, a load profile of a combination of PV, heat pumps (electric or hybrid) and home batteries is shown.

PV and electric heat pumps

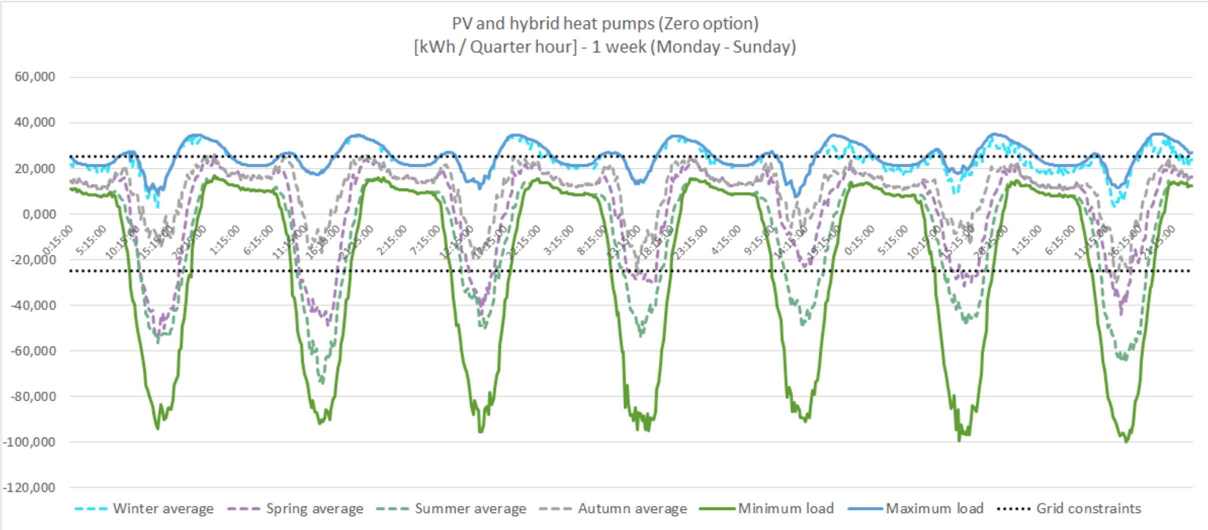


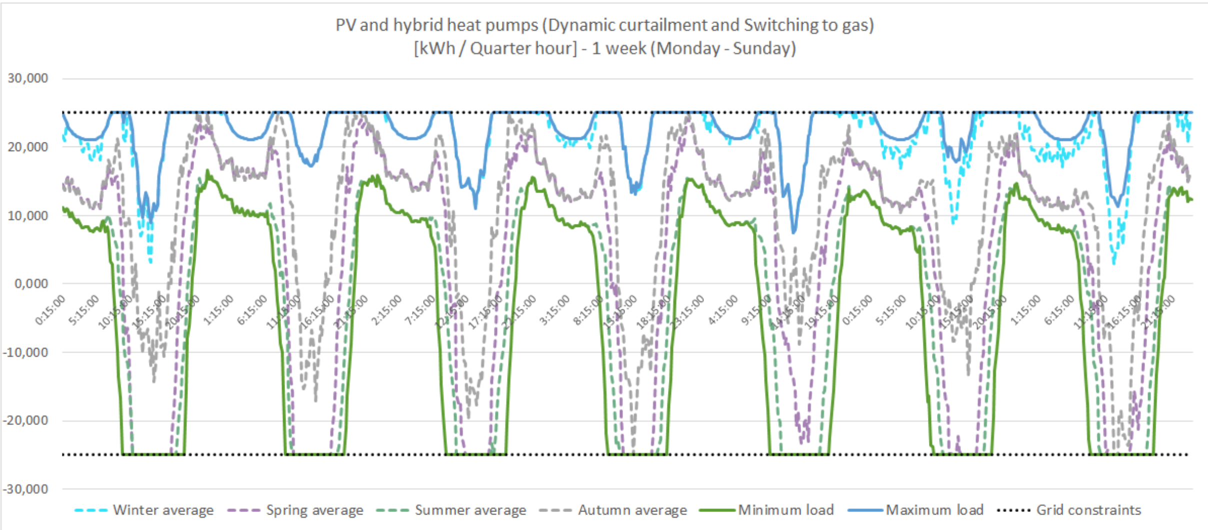
PV, electric heat pumps and EVs



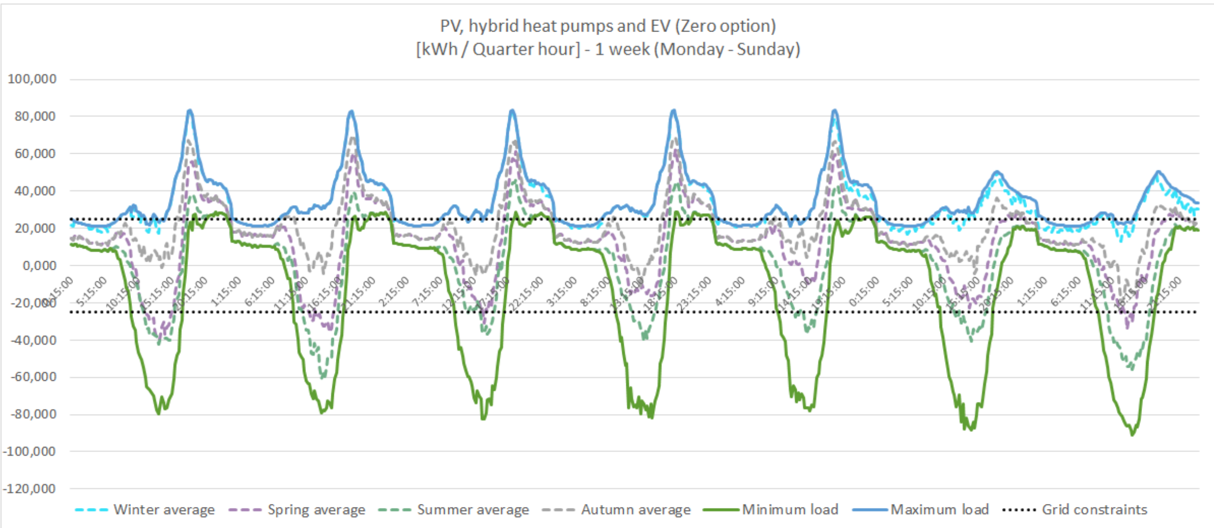


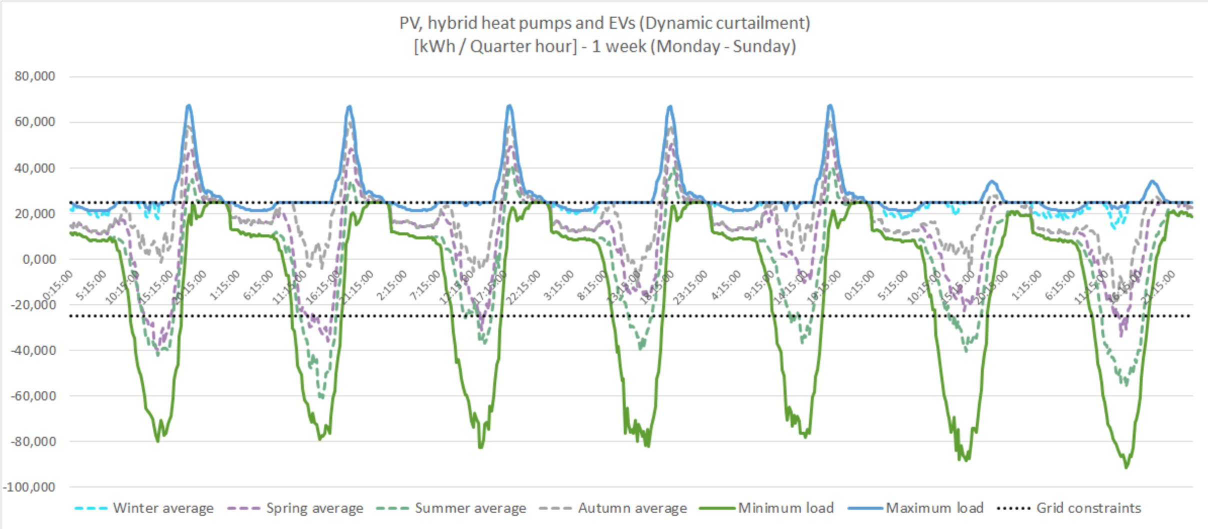
PV and hybrid heat pumps





PV, hybrid heat pumps and EVs





PV, heat pumps and home batteries