# Scalable model districts for geographic load forecasting in the distribution grid

*Analysing the different paces of the energy transition in the Dutch build environment*

**Master thesis Jurgen Meerkerk**

**Delft University of Technology**

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# Scalable model districts for geographic load forecasting in the distribution grid

By

**Jurgen Meerkerk**

*(1510940)*

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|---|---|
| Professor: | dr. ir. Zofia Lukszo, *Section Energy & Industry (TU Delft, TPM)* |
| First supervisor: | dr. Martijn Warnier, *Section Systems Engineering (TU Delft, TPM)* |
| Second supervisor: | dr. Laure Itard, *Section OTB (TU Delft, Architecture)* |
| External supervisor: | ir. Jan Pellis, *Department Strategy and Regulation (Stedin)* |

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# Preface and Acknowledgements

One thing was certain when I was searching for my master thesis project: renewable energy needs to be the main subject. I visited Stedin and Eneco to talk about the future developments in the energy sector that they deemed most important. Luckily this aligned with my interest in the energy efficiency of the build environment, and after some proposals the regional differences of the energy transition became the main topic. After a quick start the challenges emerged, ranging from data limitations to difficulties in determining the scope. This report signifies the last learning experiences for my period at the university, and the start of many more learning moments and my contribution to increase the speed of the energy transition.

Without the help of others the learning experience would not be as steep. Martijn Warnier helped me focus and maintain the overview of the project, either by himself or by connecting me to the right people; Zofia Lukszo kept me sharp on using the work of others, and to increase the scientific contribution; Laure Itard introduced me to the world of the build environment, and provided a valuable 'outsiders' look on the energy sector.

Much appreciated is the help of my colleagues at Stedin, especially of Jan Pellis who is great in maintaining the balance between in-depth knowledge, and generalisation of the outcomes. Also I really liked the discussions with Rob Cloosen and Arnoud Rijneveld on how to approach this broad scope project. There are so many other people that I came across during the project and gave their input during interviews or just at a cup of coffee. Thank you all for your support.

And last, but definitely not least, I would like to thank my parents for their unconditional support throughout my study, and during the last phase of the master thesis.

*Jurgen Meerkerk*
*Delft, June 2015*

# Executive Summary

The initiated energy transition for increasing the sustainability of the energy system results in an increased decentralised generation of renewable energy (such as solar-PV), increased electrification of appliances (such as heat pumps, and electric vehicles), and increases in energy efficiency (such as an energy neutral build environment). It is unsure if the current capacity of the distribution transformers is sufficient to deal with the resulting increases in high demand and high supply.

Distribution network operators need to maintain the reliability of supply and determine if network expansion is required, or how demand and supply can be matched by increasing the flexibility. The speed at which the energy transition trends manifest itself are location dependent, meaning that geographical differences of the required capacity can emerge in the future.

### *Knowledge gap*

Network operators apply load forecasting on different hierarchical levels to analyse the capacity of the transformers. The most appropriate hierarchical level depends on the purpose of the analysis (high level strategic, or low level network planning). In order to allow decision makers to include the geographical factor, the high aggregation level is too abstract, and the low aggregation level is too detailed. An intermediate level that maintains the overview for the entire operating area, while including the regional specific demand, and technology characteristics of the build environment, is lacking.

### *Research aim*

The aim of the research is to construct representative model districts for the Dutch build environment in order to determine the (future) effect of the regional deployment of PV (photovoltaic) panels and heat pumps on the distribution transformers. The scope of the research is on the PV and heat pump deployment, excluding other technologies such as electric vehicles. The research focusses on the outlook in the year 2040, and includes the residential and small utility consumers on the low-voltage distribution grid. The approach is applied to the operating area of the Dutch network operator Stedin.

### *Research approach*

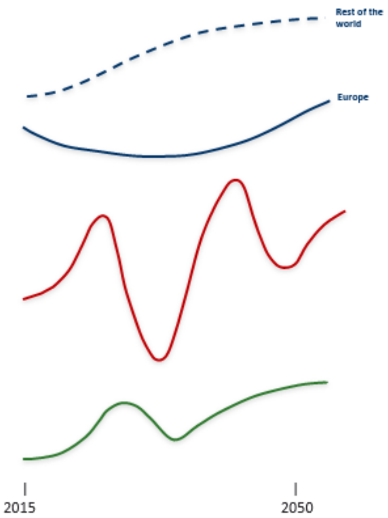
***Model districts*** - The first step in the research approach is the segmentation of the operating area into different model district types. A major research choice concerns the size of the areas in which the operating area is segmented (see differences in Table 1). The four digit postal code (PC4) area size is used since on this level the statistics are publicly available.

*Table 1: Differences between PC4, PC5, and PC6 area sizes.*

| | PC4 | PC5 | PC6 |
|---|---|---|---|
| Number in the Netherlands | 4.046 | 32.869 | 453.575 |
| Average number of buildings | 2.412 | 297 | 22 |
| Average number of transformers | 33 | 4,1 | 0,3 |

For each PC4 area in the operating area the applicable model district is determined, and coupled to the available statistics on the number of residential and commercial buildings. This resulted in a segmentation into 18 model district types as presented in Table 3. The types range from completely urban (centrum-urban plus), to completely rural (rural accessible). The model districts are further specified by determining the distribution of the types of buildings. For households 7 reference buildings are used; detached, semi-detached, terraced, common staircase and galleries, common staircase no galleries, maisonette, and other flats buildings. Commercial building are not further diversified.

***Scenarios*** - Three future energy transitions are applied, which are constructed for the situation in the Netherlands, and based on different worldwide economic developments; **Paces**, **Tides**, and **Circles**. The deployment rates of technologies and the energy demands are coupled to these expectations (see Figure 1).




| Ratios beteen scenarios in 2040 | Paces | Tides | Circles |
|---|---|---|---|
| Residential electricity demand (compared to 2013) | 79% | 98% | 93% |
| Commercial electricity demand (compared to 2013) | 87% | 68% | 64% |
| PV deployment | 0,1 | 0,2 | 0,7 |
| Heat pump deployment - Residential | 0,2 | 0,3 | 0,6 |
| Heat pump deployment - Commercial | 0,3 | 0,2 | 0,5 |

*Figure 1: (**left**) Expected economic developments in the 3 Eneco scenarios. Blue is scenario **Paces**, red is scenario **Tides**, and green is scenario **Circles**.*
*(**right**) Ratios between main variables in the year 2040. The basic electricity demand is presented as the increase in demand compared to 2013. The PV and heat pump deployment are scaled in relation to the other scenarios, meaning that each row adds up to 1.*

***Model district specification*** - The effects of the national future energy scenarios are specified for each model district by using the number of buildings, and the characteristics of the types of buildings within the districts, such as the specific electricity and heat demand, the available roof surface for PV, and the types of buildings on which heat pumps can be applied. Additional differentiation of PV is applied by using the current deployment rates in the model districts as registered in the Product Installation Register, and for the future differentiation this is linearly converting to equal deployment rates in 2050 for the different model districts. Heat pump capacity is based on the types of buildings in which heat pumps can be applied, and the national deployment percentage of the buildings applicable for heat pumps. Two types of heat pumps are applied: hybrid and full-electric heat pumps. Hybrid heat pumps contain an additional gas burner that can be used during moments of high demand.

To construct the annual load profiles of the demands and supply with an hourly interval, the annual demand or the installed capacity are multiplied with the EDSN load profiles. These standard profiles provide the electricity demand as a fraction of the annual demand, and are based on measured data of consumers in the Netherlands.

***Connecting to transformers*** - For each of the distribution transformers the applicable model district is determined. The current loading rate is specified as the percentage of the nominal capacity currently required. Future loading rates are calculated by adding the increase in peak demand between 2013 and 2040 for each of the model districts, to the current loading rate of the transformers.

## *Important results*

***Load profiles*** - The load profiles show a substantial increase in electricity demand. As an example the load profile of the centrum-urban plus district is included in Figure 2. The **Paces** and **Tides** scenarios result in similar load profiles in 2040 and the winter peak remains dominant in most districts, except for the two most rural districts; village and rural accessible. In these districts the summer peak becomes dominant due to the large deployment rates of PV. In the **Circles** scenario all districts have a summer peak, caused by the large deployment rates of PV. Overall, the rural districts have a higher deployment rate of PV than the urban districts. In the districts with a winter peak the increase is caused by the additional electricity demand of the heat pumps.

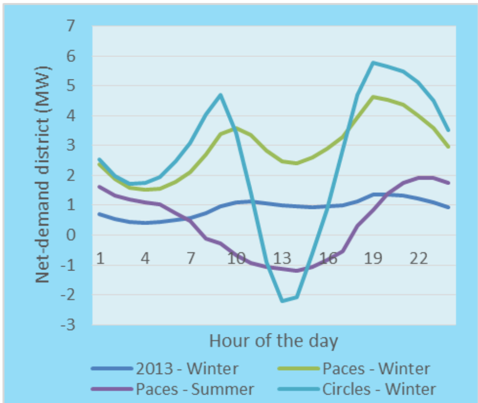



*Figure 2: Load profile for the centrum-urban plus district. The extreme summer profile of the **Circles** scenario is not included*

**Peak demand** - The peak demand per dwelling is different for each of the model districts. It ranges between 0,6 kW and 9,5 kW per dwelling. The residential peak demand is lowest in the most urban districts (first 5), highest in the most rural districts (last 3), and the remaining districts have a relatively intermediate peak demand. Generally speaking, the more rural a district is, the higher the peak demand per dwelling. The large increase in the Circles scenario is caused by the PV supply peak. For the utility buildings the differences between the model districts are much smaller. This is due to the absence of different types of commercial buildings. In the Circles scenario the maximum peak demand of the residential buildings is smaller than the maximum peak demand of commercial users due to the high electricity reduction of the commercial buildings compared to the residential buildings, and the higher deployment rates of PV in the residential buildings.

*Table 3: Average peak demand for residential consumers and small commercial consumers*

| | Peak demand residential | | Peak demand commercial | |
|---|---|---|---|---|
| | Minimum | Maximum | Minimum | Maximum |
| Current | 0,6 kW | 1,1 kW | 4,2 kW | 4,3 kW |
| Paces | 0,5 kW | 1,7 kW | 4,4 kW | 4,5 kW |
| Tides | 0,7 kW | 2,0 kW | 3,2 kW | 3,3 kW |
| Circles | 2,9 kW | 9,5 kW | 4,3 kW | 9,0 kW |

*Table 2: Percentage of transformers overloaded for each model district, with the current situation in 2013 and the future scenarios for 2040.*

| Model districts | Current | Paces | Tides | Circles |
|---|---|---|---|---|
| Centrum-urban Plus | 0% | 0% | 0% | 82% |
| Centrum-urban | 1% | 0% | 1% | 86% |
| Urban <1940 - Peak 1 | 0% | 0% | 0% | 91% |
| Urban <1940 - Peak 2 | 0% | 0% | 1% | 96% |
| Urban >1940 compact | 1% | 1% | 1% | 91% |
| Urban >1940 groundbased - Peak 1 | 1% | 1% | 9% | 92% |
| Urban >1940 groundbased - Peak 2 | 1% | 1% | 1% | 94% |
| Green urban - Peak 1 | 1% | 1% | 1% | 80% |
| Green urban - Peak 2 | 0% | 0% | 0% | 94% |
| Centrum-small urban - Peak 1 | 2% | 2% | 3% | 91% |
| Centrum-small urban - Peak 2 | 0% | 0% | 0% | 92% |
| Small urban - Peak 1 | 1% | 1% | 1% | 92% |
| Small urban - Peak 2 | 0% | 0% | 0% | 87% |
| Green-small urban - Peak 1 | 2% | 2% | 2% | 86% |
| Green-small urban - Peak 2 | 0% | 0% | 0% | 93% |
| Centrum-village | 1% | 1% | 3% | 91% |
| Village | 2% | 6% | 17% | 92% |
| Rural accessible | 1% | 5% | 16% | 92% |

**Transformer loading** - Damages in distribution transformers are a function of the degree of overloading and the duration. Transformers are considered overloaded when reaching 120% of the nominal capacity. This research only focussed on the degree of overloading. The village and rural accessible districts have the highest number of overloaded transformers in the Paces and Tides scenarios (see Table 2). The annual peak demand is caused by the PV supply peak. In the '*urban >1940 groundbased peak 1*' districts in the Tides scenario the highest peak is caused by the basic electricity demand and the heat pump demand. In the Circles scenario most transformers are overloaded, without an exception of a district type, and caused by the (extreme) PV supply peak during the summer.

## Conclusions

It is concluded that the approach is appropriate to identify geographical differences in the impact of the energy transition on the distribution transformers. Additional differentiation is expected if smaller areas sizes, and reference buildings for commercial buildings, are applied. The PC4 area size is too large for accurate network planning purposes, for which a smaller area size better aligns with the number and types of buildings per transformer.

In the year 2040, all scenarios show a substantially larger impact on the distribution grid for the village and rural accessible districts. In the remaining districts for the Paces and Tides scenarios the loading of transformers is comparable to the current situation. Therefore the current transformer capacity is sufficient in those districts. However, the Circles scenario with the highest deployment rates of PV and heat pumps results in insufficient transformer capacity for nearly all transformers in all model districts.

This study provides an indication of the geographical differences for the stress on the distribution transformers caused by the energy transition. Electric vehicles and cooling by heat pumps need to be included to draw complete conclusions. It is recommended to include these aspects in the approach. Applying smaller areas of interests better aligns with the decision making on the required capacity of the distribution transformers, and also results in an increased differentiation of the model districts. It is therefore recommended to perform the approach on smaller areas of interest. The results of this analysis can still be used in the initial exploration on the effectiveness of flexibility solutions as an alternative for expensive grid extension. It is especially recommended to pay more attention to the speed of the energy transition in the rural districts, since the impact on the distribution transformers is largest in these areas.

# Table of Contents

# 1. Introduction

The international and national goals for increasing the sustainability of the energy system lead to increases in renewable energy capacity, and an additional electrification of appliances. In the Netherlands for example, decentralised (sustainable) collectives of citizens are gathering together to form local energy cooperation's that create an increase in regional deployment of renewable energy [ASISEARCH, 2013]. Another trend is the increased energy efficiency in the (new and existing) build environment by creating energy neutral households by installing PV (photovoltaic) panels, heat pumps and increasing the insulation [Platform 31, 2014]. The resulting increase in decentralized electricity generation and peak load demand are expected to increase the fluctuations of the electricity demand, and endanger the future reliability of the electricity distribution [Blokhuis, Brouwers, van der Putten, & Schaefer, 2011].

Therefore, distribution network operators (DNOs) are increasingly interested in flexibility solutions such as demand side management and storage, to reduce the fluctuations and cope with the changing capacity demands. These solutions can reduce the investment costs in comparison to traditional grid extension, eventually resulting in lower costs for society and the consumers. However, throughout the operating area the fluctuations in electricity demand differ in size due to different deployment rates of (renewable) technologies and demand characteristics between those districts. The effectiveness of the flexibility solutions is thus not the same in different geographical areas of the operating area. In order to determine the effectiveness of the flexibility solutions, the regional differences in the future electricity demand and the impact on the distribution grid needs to be determined first. Currently, these regional differences are not sufficiently understood.

The goal of this report is to develop an approach to understand the future electricity demand in different districts of the build environment, and to determine the impact on the distribution grid. The approach focusses on geographical differences in PV and heat pump deployment, and is applied on the operating area of the Dutch DNO Stedin to determine the future load demand of the distribution transformers. This leads to a better understanding on the geographical factor associated with the deployment of renewable technologies and the influence on the distribution grid. The results can be used in follow-up research to determine the (cost) effectiveness of flexibility solutions.

This chapter continues by discussing the problem background in order to substantiate the main goal of this research. This is followed by the problem statement and specific knowledge gaps of interest for this research. The research is specified by discussing the objective, delineation, and contributions to the body of knowledge. These aspects define, in combination with the problem statement, the research questions. The final part provides an overview of the structure of this thesis and the activities to be performed.

## 1.1 Problem background and knowledge gap

***What is the problem?***

The aim of the Dutch government is to have 14% of the energy production provided by renewable sources in 2020, 16% of renewable energy in 2023, and a completely renewable energy supply in 2050 [Rijksoverheid, 2014]. Furthermore, the building related energy uses are subject to stricter energy performance coefficient rules to increase the energetic efficiency, with the aim to have an energy neutral build environment by 2050. The sustainable design of buildings can be achieved through application of the three basic steps of Trias Energetica [Lysen, 1996]:

- Reduce the energy consumption by limiting wastage.
- Make maximum use of energy from renewable sources.
- Use fossil fuels as efficient as possible for the remaining energy demand.

This policy has recently led to developments in the building industry to implement net-zero energy households through application of better insulation, PV panels for electricity supply, and heat pumps for heat supply. These innovations have initially focussed on newly build districts, but developments are cascading towards the existing build environment, and increasing the peak demand.

Most of the distribution networks have sufficient capacity for the next 20 years to facilitate the traditional growth of around 1%/year for the current domestic demands [Laborelec, 2012]. However, current developments are likely to exceed this small growth rate with the demand becoming larger than the capacity of the network. The technologies that are expected to influence the distribution network most significant are electric vehicles, PV-panels, and electric heat pumps [Vanhoudt et al., 2014; Zhao, Kucuksari, Mazhari, & Son, 2013]. The transformers between the low-voltage (LV) and medium-voltage (MV) networks are the initial bottleneck when peak demand increases [Ochoa, Dent, & Harrison, 2010].

The large differences of deployment rates of new technologies and demand characteristics result in a larger differentiation between the required peak capacities for different districts. Not all households are capable of installing PV and heat pumps. Also the reserve capacity available in the current electricity networks differs per location. Therefore, the impact of adding PV and/or heat pump capacity to the network is location dependent.

***What are potential solutions?***

Distribution network management involves provision of electricity in the current, and anticipation on future developments in the energy sector to enable a reliable and continuous provision of electricity. The deployment rate of the new electricity generating and demanding technologies are however unsure, leading to uncertainties in the required electricity network capacities in the future. Much of these network elements are capital intensive and have a long lifetime, meaning that replacements due to changing network capacity demands are capital intensive and have long lasting effects [Strbac, 2008].

To achieve a renewable, affordable and reliable electricity supply there are broadly four categories to address the increased peak demand: flexible generation, storage, demand side response and interconnection [Pudjianto, Aunedi, Member, & Djapic, 2014]. Additionally the traditional method of expanding grid capacity can be applied.

***What is the current method of analysis?***

Literature shows two approaches for determining the effectiveness of the solutions to reduce the peak demand. The first approach is analysis on a high aggregation level by using uniform deployment rates throughout the operating area of DNOs. The purpose of this type of research is to provide insights for strategy development in dealing with the energy transition. Scenarios are often constructed to determine the total PV and heat pump capacity, which is assumed to be distributed uniformly over the operating area, after which the future peak demand is determined. This type of approach provides insight into the general trends and the general effectiveness of the possible solutions, but lacks the distinct characteristics of individual districts and the network in place.

Another approach is on a low aggregation level by analysing the distinct properties and expected developments of a specific region operated by a certain type of transformer (see e.g. Kleiwegt, 2011). This requires real life data about the district, prognoses about future development of the customers connected to the transformer, the (reserve) capacity of the transformers, and other detailed data. This type of approach is applied by asset management divisions of DNOs to determine the required capacity of new transformers, or by analyst that perform case studies on the influence of new techniques or developments on a detailed aggregation level.

### *Knowledge gap*

Two modelling methods have been discussed; the high aggregation level with modelling of operating areas, and the low aggregation level to model case specific transformer. However, the deployment rates of PV and heat pumps, as well as building characteristics, are significantly different when considering the geographical distribution. The high level modelling approach is therefore not applicable for obtaining realistic results on the effectiveness of peak demand reduction alternatives. The low level analysis requires a significant amount of data processing when considering the entire operating area of the client, which consists of 22.000 distribution transformers. An intermediate level that maintains the overview for the entire operating area, while including the regional specific demand and technology characteristics, is lacking.

Overall, the balancing of supply and demand, as well as maintaining the security of supply, is increasingly important with the rapidly increasing deployment rates of renewable technologies. The peak load development is the most important variable to influence the future load demand of the distribution transformers, and is influenced by the PV and heat pump deployment. The deployment rates differ per geographical location, which the current methods of analysis do not take into account. There is no method to maintain the overview of the entire operating area, while also considering the different deployment rates within that operating area.

## 1.2 Research scope

### *Purpose of the research*

The purpose of the research is to construct representative model districts for the Dutch build environment in order to determine the effect of the regional deployment of PV and heat pumps on the distribution transformers. This has a practical relevance for network operators since the decision making on implementing demand response, storage, grid extension, or whether no action at all is required can be improved. Additionally the coupling of geographical criteria on the deployment rates of PV and heat pumps, as well as their interrelation with the electricity grid contributes to the theoretical knowledge. The objectives of this research is to perform a more detailed analysis of the expected peak demand for different model districts, a categorisation of model district types, an indication on the relation between model district type and the type of transformer, the future loading rate of distribution transformers in different model districts, and providing insight into the consequences for managing the entire operating area.

### *Research delineation*

The focus of the research is on the deployment rates PV and heat pumps. PV deployment is included since it continues to increase, and the provision of excess electricity to the electricity network has a significant influence on the distribution network stability [see e.g. Yan & Saha, 2012; Yazdani & Dash, 2009]. The impact of heat pumps on the electricity demand is significant, but the implementation rates are more questionable.

In consultation with the client Stedin the peak demand, and the resulting loading rate of the distribution transformers are the main output of interest of the model since it is deemed most influential for future network capacity decisions. Peak capacity is included through high-over, but regional characteristics dependent calculations to give an approximation for the required network investment costs. Problems with increasing demand of the distribution network manifest themselves initially at the distribution transformers between the LV and MV network [Laborelec, 2012].

The research is performed for the Dutch distribution network operator Stedin (referred to as client). The operating area of the client is provided in Figure 3. Although the operating area of the client is used as a case study the aim is to make the approach and (to some extend) the deliverables applicable for any DNO in the Netherlands.

*Figure 3: The operating area of the client Stedin is indicated with the yellow areas. Largest cities in the area are Rotterdam, The Hague, Utrecht, Amersfoort, Haarlem and Gouda.*

The research is performed for the long-term time frame until the year 2040. This year is chosen because:

- Large scale market penetration of relatively new technology takes time.
- Changing the electricity network takes network operators often longer than 10 years and the life span of upgraded network elements is more than 70 years [Blokhuis et al., 2011].
- The climate policy of the Dutch government and goals formulated by the municipalities for high renewable deployment and energy reductions are mainly formulated for 2040 [Ministery of Infrastructure and the Environment, 2013].

### *Research delineation and limitations*

The research only focusses on PV and heat pump deployment, without considering other techniques like micro-CHP (small effect on the electricity grid), or wind turbines (connected to the MV grid). An overview of the demarcation is provided in Table 4, and is further elaborated upon in chapter 2.

*Table 4: Demarcation of the research problem and output of the research. In chapters 2 and 3 the demarcation and the approach are discussed in more detail.*

| Category | Inside scope | Outside scope |
|---|---|---|
| **Technology** | Building integrated PV, heat pumps | Electric vehicles, storage, wind turbine, micro-CHP, CHP, ground based PV, etc. |
| **Energy flows** | Electricity demand and supply, heat demand (for heat pumps) | Heat demand (other supply than heat pump) and supply |
| **Output of interest models** | Load profiles, peak demands, loading of MV/LV-transformers. | Voltage fluctuations, network investment cost estimations, peak mitigation measures, etc. |
| **Network technology** | MV/LV-transformers (aggregated) | Power lines, MV/LV-transformers (detailed) |
| **Network types** | Low-voltage (LV) network | Medium-voltage (MV) network, High-voltage (HV) network |
| **Building types** | Residential buildings, commercial buildings | Large scale businesses, industrial customers, governmental buildings |
| **Area types** | Rural and urban areas | Harbour |
| **Output research** | **Model districts (distribution), future energy scenarios, relation districts and transformer types, future load demand transformers** | |

One other important technology that has been left outside the scope are the demand characteristics of electric vehicles (EV) [see e.g. Shao, 2011]. This creates a significant reduction in the complexity of the system, and the peak demand will be lower compared to (realistic) future values. The danger exists that with exclusion of these techniques the outcomes are oversimplified. Electric vehicles are excluded from the analysis due to the time constraint of the research and the desire of the client for the initial focus on PV and heat pumps. This limitation will be discussed in more detail in the discussion chapter.

## 1.3 Research aim

This research focusses on the geographical deployment rates of PV and heat pumps in order to determine the future peak demand, and the load demands for the distribution transformers. The novelty of this research is the construction of model districts that are representative for the building stock of the operating area, and can be used to build-up the operating area in a scalable manner. Therefore, model districts are created to introduce an intermediate level between individual transformer analysis and general analysis of the entire operating areas. The main research question is:

- ***Which model districts can be used to represent the Dutch distribution grids in a scalable manner, in order to analyse the future regional deployment rates of PV and heat pumps, and the effect on the load demand of the distribution transformers?***

To answer the main research question several sub-questions need to be answered:

- What is the current status of PV and heat pump deployment?
- How can the consumers of the Dutch distribution grid be divided into representative model districts?
- How will the load profiles and peak demands develop in the future for the different model districts?
- How can the model districts be coupled to the distribution transformers?
- How does the future load demand of the distribution transformers in the operating area develop?

These questions are answered by means of literature reviews, modelling of the (future) load profiles and peak demands of the model districts, as well as through modelling of the (future) loading of the distribution transformers

## 1.4 Outline of report

The research questions are answered in the remaining chapters. The outline of this research is as follows.

**Chapter 2**: **background knowledge** on the technical system (electricity grid, PV systems, heat pump systems), the sociological system (actors, interest, and power), the relation with existing methods for load calculations, as well as research choices and delineation descriptions.

**Chapter 3**: **research approach** by description of the activities that are performed, the required data, and interaction between individual subsystems.

**Chapter 4**: **model district classifications**. Possible ways to classify districts, choice on model districts to be used, as well as description of the different types of districts and their deployment in the operating area.

**Chapter 5**: **future energy scenarios**. Energy scenarios for future deployment of PV and heat pumps, qualitative description of chosen transition scenarios, and quantitative description of scenarios for the Netherlands and the operating area of Stedin.

**Chapter 6**: **specification of the model districts** by coupling the energy scenarios to the model districts. Description on how the PV and heat pump deployment of the operating area is divided among the districts, the number of buildings in the district, and the load profiles for electricity demand and supply within the districts.

**Chapter 7**: **specification distribution transformers**. The load of the districts is provided by the MV/LV-transformers. This chapter describes the current transformer stock in the operating area for numbers, location and current loading. Also the influential parameters for future (problematic) loading are described.

**Chapter 8**: **results** of the analysis for the 3 scenarios, including future load profiles for the entire model districts, peak demand per building, and future loading expectation of the MV/LV-transformers.

**Chapter 9**: **discussion** on the modelling approach and results of the research in relation to other research and usability of the outcomes.

**Chapter 10**: **conclusions and recommendations**. Includes the answers to the research questions and other conclusions, limitations, and recommendations for future research.

**Chapter 11**: **reflection** on the approach, the data limitations and the process of the research from a personal point of view.

# 2. Background: socio-technical system description

The electricity system is a socio-technical system. A socio-technical system refers to an interaction between the complex infrastructures and the human behaviour, combining the elements of people, society and technology [Geels, 2004]. This creates a system integration for "*the process of jointly shaping the technical and institutional sub-systems in a way that supports the transition to a renewable, affordable and reliable energy system*" [Herder, 2014].

The aim of this chapter is to provide background knowledge about the electricity system from both a technological point of view and a sociological point of view. This chapter also includes the research choices regarding the delineation and research direction. Additionally, the existing methods for load calculations are discussed, resulting in the knowledge gap that this research aims to fill. Overall the literature review results in the most important variables to be included in the modelling approach.

The technical system description starts by defining and describing the distribution network to provide context and to identify the main problematic parameters with increasing peak demands (2.1). Next sections describe the PV system (2.2), and the heat pump system (2.3) by describing the technology and the current deployment rates. In the actor system description (2.4) the main stakeholders are identified, after which these are analysed for their power and interest in participation. Section 2.5 elaborates upon the existing methods of load calculation and provides the background information to place this work in the field of knowledge.

## 2.1 Background knowledge electricity system

### 2.1.1 System description of the electricity sector

The European electricity market is liberalised by the Electricity Directive 96/92/EC in 1996, and in 2006 the Dutch Electricity act of 1998 was adapted to enforce unbundling of production and delivery of electricity of the network. The goal of unbundling is to reduce the costs for the end-users while also providing better services through competition [Pagani & Aiello, 2014]. This allows for increases in competition for production and supply, but transport remains a monopoly as it is considered a natural monopoly. New generation possibilities are within reach since renewable sources are becoming more accessible. This creates a higher participation rate of some of the consumers that both supply and demand electricity, also called prosumers, who most likely demand a free energy trading market [Vaitheeswaran, 2003].

The current Dutch electricity market can be divided in a physical, institutional and economical layer as presented in Figure 4. The institutional and economic layer include the roles and responsibilities of the parties, as well as the markets in which they operate. The physical layer shows the generation, transmission, distribution and load use with the accompanying voltage levels. Distribution network operators are responsible for the medium voltage (MV) grid and the low voltage (LV) grid, on which the small and large consumers are connected.

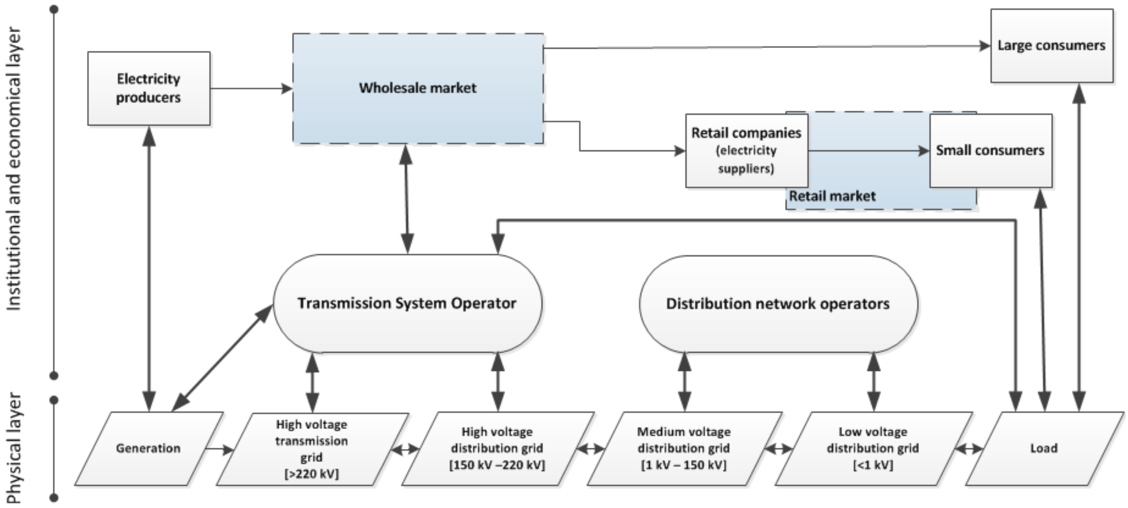



*Figure 4: Representation of the Dutch electricity system for the physical, institutional and economical layer. Adapted from [De Vries, Correljé, & Knops, 2013; Gómez-Expósito, Conejo, & Cañizares, 2009]*

The public goals for the electricity supply in the Netherlands are reliability, affordability and environmental responsibility [De Vries et al., 2013]. These goals interrelate with the functions of the power delivery system [Lee Willis, 2004]:

- Reach all consumers in the service territory.
- Provide satisfactory continuity of service (reliability) to consumers.
- Provide sufficient capability to meet the peak demands.
- Provide stable voltage quality at all time.

Distribution network operators (DNOs) are obliged by law to connect all consumers in the service territory regardless of the business case. The peak demands and reliability are discussed in-depth in the following sections after the hierarchy of the network is described.

The voltage quality is not further discussed since it on a too detailed aggregation level for this research[1]. The focus remains on the medium-voltage/low-voltage (MV/LV) transformers, without taking into account the specifics of low-voltage (LV) power lines and the corresponding voltage deviations within the LV network. The reason for focussing on the MV/LV-transformers rather than the specifics within the LV network is that most problems are expected to occur on the transformer level when decentralised (renewable) generation increases [Laborelec, 2012].

### 2.1.2 Hierarchy in voltage levels

The electricity grid connects the producers to the consumers through high voltage (HV), medium voltage (MV) and low voltage (LV) networks. The HV networks are used for long distance transportation since network losses are lower at higher voltages, while the LV networks are used for regional distribution to households. Traditionally the power flow is characterised as few large scale producers to a large number of dispersed users [Morren, 2006]. The energy transition has led to an increase in distributed energy sources, resulting in a larger degree of small generators and changing energy demands of users. Users are connected to the voltage level which they require, which is the low voltage for small consumers.

The electricity network consists mainly of transformers, power lines and network openings (see Figure 5). The electricity from the HV (transmission) grid is converted by HV/MV-transformers (switching) and either connected to MV transmission lines or directly to MV substations. These

[1] In section 2.5 the existing load calculation methods are discussed. That section provides additional background on the aggregation level of interest.

substations can either be network stations or large consumer stations. The network openings in the MV distribution network are used for fault regulation and designed on the basis of the n-1 principle, meaning one faulty line still allows for the provision of electricity. These redundancy measures are included in the HV and MV networks, but not in the LV network [Netbeheer Nederland & Movares, 2014]. The network substations consists of MV/LV-transformers, which connect the MV distribution grid to the LV distribution grid, of which the latter is operated at 230/400 volt.

The effect of PV and heat pumps on the HV network is considered to be minimal, while the effect on the MV and LV network can be significant in the future [Laborelec, 2012]. Therefore, this research focusses on the MV/LV-transformers with special attention for the LV network connections with corresponding electricity demands and installed PV and heat pump capacities.

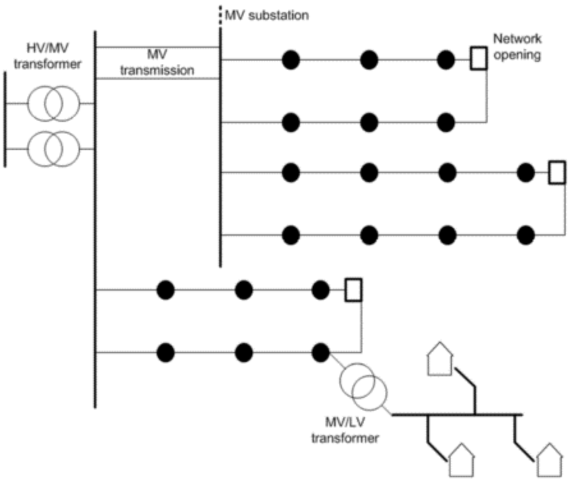



*Figure 5: Connection between the high to low voltage network with inclusion of transformers, power lines and LV network consumers. Adapted from: [Kleiwegt, 2011].*

The MV/LV-transformers provide several users of electricity in the LV network. The small consumers include the household connections (usually 1x25 Ampere connection) and small to medium sized companies (maximum connection of 3x80A). Other users are the large consumers with a connection between 3x80A and 250A, and public lighting provision [Grond, 2011].

### 2.1.3 Physical characteristics LV network

The focus of this research is on the LV network. The MV/LV-transformer is connected to a LV rail on which the strings are connected (see Figure 6). The number of strings attached to the LV rail and the number of consumers on each string are arbitrary. The topology of the network depicted in the figure is a star-topology with the centre being the MV/LV-transformer. In urban, suburban and rural areas the two foremost used grid topologies are star and bus topologies [A. M. Hassan, 2010]. A bus topology is a linear sequence of consumers (nodes), which means a single string is attached to a MV/LV-transformer. The redundancy of the topologies in the LV network is limited, resulting in a longer average outage times compared to the MV network [Netbeheer Nederland & Movares, 2014].

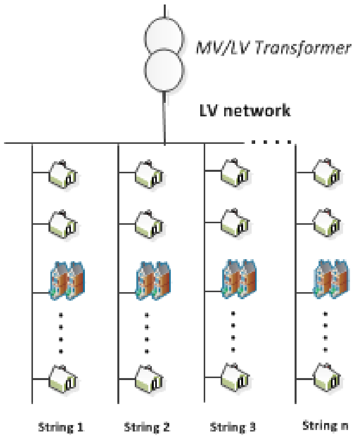



*Figure 6: Example topology of a LV network*

Compared to other European countries the technical characteristics in the Netherlands are substantially different. In the Netherlands the highest share of underground LV and MV network cables are located underground compared to other European countries [CEER, 2014]. This results in high (re-)placement costs due to the difficult location characteristics.

### 2.1.4 Reliability of the grid

The reliability of the grid is measured through outages and power quality disturbances, which both depend on the variables frequency, duration and influence range [Bhatt, Shah, & Jani, 2014]. The number of outages in the Netherlands between 2004 and 2013 are presented in Figure 7. The numbers indicate that most outages occur on the MV level, followed by the LV level. Not all disturbances result in outages since there is redundancy in the network. The LV network has only limited redundancy and therefore 99% of the disturbances also lead to outages for the consumer [Lee Willis, 2004; Netbeheer Nederland & Movares, 2014].

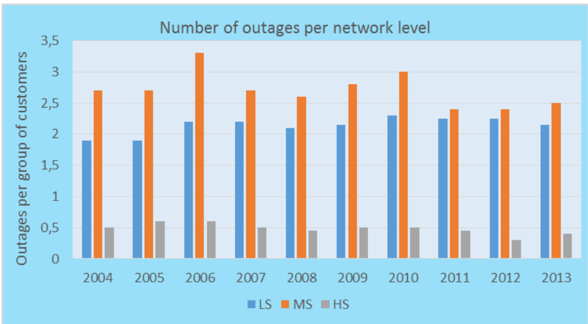



*Figure 7: Normalised number of outages per network level in the Netherlands. Since the number of customers changes, the numbers have been normalised with LV = 1000, MV=10.000, HV=100.000 customers. Adapted from: [Netbeheer Nederland & Movares, 2014]*

The annual number of minutes that consumers on the LV network were not provided with electricity was 23,4 minutes in 2013, so that the total availability of electricity is 99,995545% per year [Netbeheer Nederland & Movares, 2014]. Compared to other countries in the European Union this is a very high reliability. Of the surrounding countries only Germany is slightly better with 22 minutes, but for England and France the annual outage time consisted of around 80 minutes. In the EU the Netherlands is on the 4$^{th}$ place of all 27 participating countries for the annual interruption time in 2012 [CEER, 2014]. These numbers provide some insight, but registration methods are not uniform causing differences in outcome.

### 2.1.5 Capacity requirements distribution transformers

The optimum tariff for consumers depends on the operation effectiveness of network components. Components of the electricity grid have a different lifetime that depends on variables such as the required reliability, operational use and investment costs. Planning concepts for network components should be dealing simultaneously with the quantity (demand and capacity) of the distribution system, as well as the quality (reliability of service) [Lee Willis, 2004].

Jongen [2012] performed a statistical lifetime study on the stock of distribution transformers of the Dutch DNO Liander, and reported a mean lifetime of 71 years, with a 90% confidence interval between 60 and 84 years. Since the investment costs are high the aim of network operators is to extend this lifetime as far as possible to obtain a better cost effectiveness. Therefore, the required capacity of network elements for 60 till 84 years upfront are needed to be able to determine the required capacity of the equipment[2]. The capacity requirements depend on the maximum demand of consumers (peak demand)[3], and the simultaneity of demand between consumers.

### *Maximum demand of consumers*

The required capacity of MV/LV-transformers has historically been calculated on the basis of the maximum demand of previous year, with an additional annual increase of demand for the lifetime of the transformer. Demand growth calculations for existing households are determined on the basis of current capacity demand, with annual increases of +1,5% per year [Stedin, 2010]. For industry and commerce up till 2MW an annual increase of +1.2% per year is used, which is slightly lower due to increases in energy-efficiency in this sector [Stedin, 2010]. Consumers with newly build buildings are assessed separately, for which the peak demand for households is expected to be 0.63 – 1.17 kVA on the 25/10 kV-level. However, increased renewable energy applications like heat pump deployment can result in a ten-fold capacity demand per household. This calls for more precise calculation methods which include regional differences of the consequences of the energy transition.

It is important to realise there is a large time dependency of electricity demand. For households there is often an increase in demand during breakfast time, and a second peak during dinner time. Additional differences occur between seasonal demands, weekday and weekend demands, and different user demands (industry and households) [Paatero & Lund, 2006]. In weekends the demand of a certain industry can be low due to less working activities, while the demand of households is higher due to higher occupation rates, and at the same time another industry might require a lot of electricity. The time dependency is important to consider when modelling the future energy demand, and is the key parameter for efficiency of solutions to reduce the peak demand (see e.g. Luo, Ault, & Galloway, 2010). These solutions often focus on certain (groups of) appliances. The distribution of electricity demand of residential appliances is presented in Figure 8.

[2] Asset management divisions of DNOs have additional considerations, such as the 'standardised' distribution transformer capacities, additional future extensions of the demand, and the difference between requested demand by commercial entities and the actual demand. We return to these aspects in Chapter 7 in the analysis of the stock of distribution transformers of Stedin.

[3] The peak load is defined as the maximum load that occurs in a given period of time.

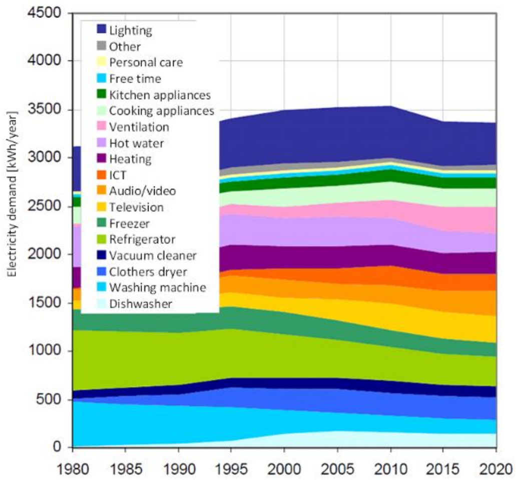



*Figure 8: Historical (before 2008) and forecast (until 2020) of residential electricity demand for different appliances. Adapted from* [SenterNovem, 2008b].

### *Simultaneity factor (coincident load behaviour)*

The peak demand of a transformer is not equal to the sum of peak loads of individual users. Utility companies represent the electricity demand of consumers on a class by class basis with 24 hour peak load curves. These present the average load curve of many households combined. Individual households have much more erratic load curves with many short peaks due to appliance duty cycles. Each consumer has a slightly different living pattern, with slightly different appliance duty cycle, resulting in different times on which these peaks occur.

The simultaneity factor (also called the coincidence function) is used to express the overlap of load peaks during of a group of users during the same time. The IEC [1973] defines it as: *"the ratio, expressed as a numerical value or as a percentage, of the simultaneous maximum demand of a group of electrical appliances or consumers within a specified period, to the sum of their individual maximum demands within the same period"*. A household has a nominal power of 8 kW[4], while at the MV level that same household is only assigned a load of around 1 kW[5]. The transformation of the erratic individual user load curve into a smooth average load curve of a group of consumers increases with increasing number of consumers. At 25 households the smooth pattern begins to occur, and at 100 households the curve is smooth [Lee Willis, 2004].

The simultaneity factor can be determined for n consumers that are connected to a specific network element through [Gwisdorf, Stepanescu, & Rehtanz, 2010; A. Hassan, 2013]:

$$\text{Simultaneity factor (n)} = \frac{\text{Peak load of group of N customers}}{\sum \text{Individual peaks}}$$

However, determining the simultaneous factor and the way in which this factor is chosen is currently fuzzy [Ji, Xie, Zhang, Hu, & Lü, 2014]. Still the simultaneous factor is the most relevant parameter for the planning and operation of the distribution grids including the transformers capacity [Gwisdorf et al., 2010]. This is due to the application of the factor in the determination of the group peak [Lee Willis, 2004]:

$$\text{Group peak for n consumers} = \text{Simultaneous factor (n) x n x (average individual peak load)}$$

[4] The nominal power (maximum load that can be supplied) is calculated using a 1x35A connection at 230V.

[5] Previous paragraphs described a peak demand of between 0.63 – 1.17 kVA for newly build houses. Q(kVA)=P(kW)*cosØ with cosØ=0,9 results in a peak demand of 0.50 – 0.94 kW.

The group peak is the required peak load that the transformer has to cope with. Typical values of the simultaneous factor depend on the load characteristics of the sector of interest with its specific distribution of consumer types, although general rules of thumb are established. Generally the simultaneous factor for two users is around 0,85 up till 0,8, while larger number of users cause the factor to drop between 0,5 and 0,3 [Lee Willis, 2004]. The shape of the simultaneous curve can be different for different user groups. This should be considered when determining the group peak. Also, deployment of new technologies can actually change the simultaneous factor. Heat pumps, for example, currently have a simultaneousness of 100% (or 1) since at very cold days the heat pumps are all up and running to provide enough heat. These new developments should be incorporated in future explorations.

### *Spatial distribution of electricity demand*

The most important function of the electricity grid is to deliver power to the consumers. These users are scattered throughout the operating area and the different users have different load duration curves, resulting in different requirements for the distribution grid. The load curves are useful for the time of demand (or supply), while the spatial load distribution is useful for the location of demand (or supply) and the required capacity in each section. The total electric load in each section is *"a function of the type of consumers, their number, their uses for electricity, and the appliances they employ"* regardless of whether an area is urban, suburban or rural [Lee Willis, 2004].

### *Capacity MV/LV-transformers*

The required capacity of MV/LV-transformers depends on the maximum demand of all the connected users in the LV network (the section) and their simultaneous factor, both throughout the lifetime of the transformer. Capacity of transformers is expressed in VA (Volt-Ampere). The substations between the MV and LV network can contain a single transformer, two transformers with one as a spare, two transformers operated in parallel, or more transformers in similar settings [see ABB, 2008]. In this way the capacity can be expanded by adding additional transformers to the substation if required.

Each transformer has a specific 'nameplate' rating that is predetermined based on the conditions that must apply for normal life expectancy. These conditions are based on continuous operation, ambient temperature and rated operating conditions, and if exceeded the risk of increased ageing increases [IEC 60076-7, 2005]. This risk can be taken if the overloading can provide flexibility for supply during extreme situations. Therefore, three loading levels are established [Grond, 2011]:

- *Normal loading*: the load is lower or equal to the nominal electrical capacity of the transformer. This capacity is based on the expected demand at the end of the lifetime of a MV/LV-transformer.
- *Overloading*: higher loading than the nominal capacity, which increases ageing and reduces the lifetime of a transformer. At the client, a distribution transformer is considered overloaded when reaching 120% of the nameplate rating.
- *Maximum load*: the IEC norm describes the maximum load of a MV/LV-transformer.

The transformers are an important group of assets for both reliability of the network and for investment costs. Asset managers optimize the transformer stock and are mainly concerned with the age of the equipment and the power demands [Schijndel, Wetzer, & Wouters, 2006]. The ageing of the transformers occurs mainly at the deterioration of the insulation of the transformer windings [Schijndel et al., 2006], which is caused by the time function of the temperature, moisture content, and oxygen content [Gong, Midlam-Mohler, Marano, & Rizzoni, 2012]. However, the moisture and oxygen can be minimized in the most applied oil cooling systems, making the main parameter of interest the temperature [Gong et al., 2012]. The temperature increases when increasing the electrical stress, which in turn reduces the lifetime [Chmura, Boorn, Morshuis, & Smit, 2013]. The maximum values for the current and temperature are provided in standards for loading above the nameplate rating (or nominal capacity), for which the IEC Standard 60076-7: 2005 provides limits for the transformer categories of distribution, medium power and large power transformers [Kulkarni & Khaparde, 2013]. There are three types of loadings, namely normal cyclic loading, long-time emergency cyclic loading, or short-time emergency loading. During normal cyclic loading the current can be increased to a maximum of 150% of the nominal capacity[6] for a maximum period of 30 minutes, and the temperature of the oil can increase to a maximum of 120 degrees Celsius [Kulkarni & Khaparde, 2013]. However, this is the maximum load for the transformers. Overloading at distribution transformers starts at 120% of the nominal capacity. Below 120% of the nominal capacity the operating is considered normal, relating to the normal loading.

### 2.1.6 Conclusion distribution network

To conclude, the capacity of MV/LV-transformers is predetermined for its entire lifetime, although modular expansion of capacity (parallel operating transformers) is possible. The capacity calculations requires future exploration which historically has been relatively linear, but with the upcoming energy transition is likely to become dynamic. To determine the impact of energy trends on the future load capacity of transformers the demand per period of time needs to be determined, as well as the simultaneousness of demand within that specific sector. The spatial distribution of consumer classes combined with their load profile thus need to be coupled to the characteristics of the electricity grid to create a more detailed calculation for the load demand of distribution transformers.

## 2.2 PV system and development

This section starts by a short description of the developments of PV panels throughout the years, and the typical characteristics of a PV installation. Thereafter, the market developments and deployment rates are described.

### 2.2.1 Technical description PV

A "photovoltaic" material or device is able to absorb light and transform the energy of the light photons into electric energy in the form of a current and voltage [Bube, 1998]. The initial development op photovoltaic cells dates back to 1839 when Becquerel discovered the transforming property [Spanggaard & Krebs, 2004]. The space industry provided the initial practical application in 1958, after which R&D led to increases in efficiency of 14% in the 1970s, followed by weight reductions and increased life-time, as well as further increases of efficiency to 26.9% in the 1990s [Bailey & Flood, 1998]. After the initial space applications the industry started to expand. The technology is still relatively expensive, but the costs are being reduced and are expected to fall further, and the market for application is expanding [Singh, 2013].

***Types of PV systems***

Photovoltaic systems can be divided into the categories of stand-alone, system for vehicle applications, and grid-connected systems on which this research focusses. The grid-connected PV systems consists of building integrated PV (BIPV) systems , rooftop PV systems, and utility scale PV systems [Eltawil & Zhao, 2010]. The utility scale PV systems are large providers of electricity and therefore connected to the MV-network, and thus fall outside the scope of the research.

[6] The overloading of 150% of the nominal capacity is defined as 50% above the nominal capacity.

### *Components PV system*

A PV system consists of a PV array that often consists of multiple panels, an inverter to change the DC current to AC current since appliances and the distribution network require AC current, and the main distribution panel available at each connection (see Figure 9) [Eltawil & Zhao, 2010; Singh, 2013]. The result of the PV generation is a reduction of electricity demand from the power grid, or supply of electricity if supply surpasses demand.

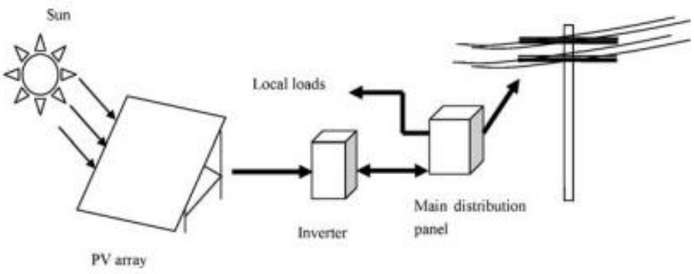



*Figure 9: Graphical representation of a grid-connected PV system. Source: [Eltawil & Zhao, 2010]*

## 2.2.2 PV market development

### *Worldwide capacity*

In 2013 the largest cumulative PV capacity was installed in Europe, followed by the Asia Pacific, China and the Americas. When looking at newly installed capacity, Europe has seen increases up until 2011 in which 22 GW was installed, after which a decline in installation capacity occurred leading to 11 GW of newly installed capacity in 2013 [EPIA, 2014]. Sharp increases in PV deployment have manifested itself in China and the Asia Pacific, which caused the worldwide installed capacity to increase to 40 GW in 2013 compared to 30 GW in 2011 and 2012. New installation rates are still largely dependent on the government incentives and large scale project development coordinated by national authorities, although price reductions have led to a reduction of dependency on governmental support.

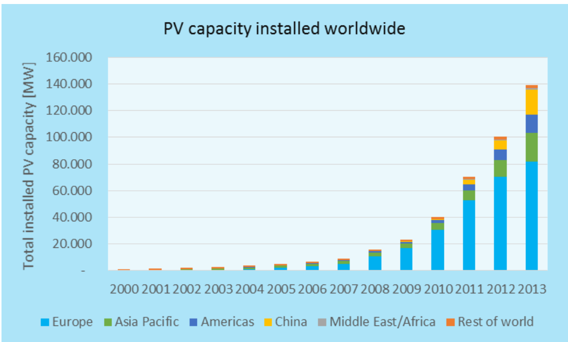



*Figure 10: Global installed capacity PV 2000 – 2013. Data source: [EPIA, 2014]*

### *National capacity (commercial and households)*

After slow deployment rates before 2011, the PV market has grown significantly in the Netherlands ever since, resulting in a cumulative installed capacity of 739 MW in 2013 (see Figure 11). In 2012 electricity generation by PV accounted for 0,2% of total electricity demand, and increased to 0,5% in 2013 [CBS Statline, 2014]. According to the EPIA [2014] around 80% of the installed capacity in the Netherlands is residential, followed by around 15% of commercial deployment and the remainder is by industrial and ground mounted application. This is close to the estimations of Van Sark & de Rijk [2014], which estimate that around 90% of the capacity is installed by private parties. PV deployment can be considered as being individualistic, meaning individual users are able to install a system without the need for a collective collaboration.

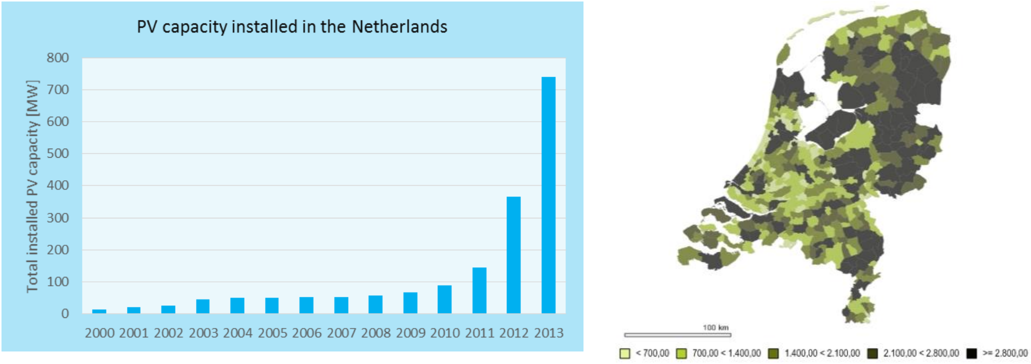



*Figure 11: (**left**) PV capacity installed in the Netherlands 2000 – 2013. Data source: [CBS Statline, 2014]. (**right**) Regional differences in deployment of PV installations in the Netherlands. The colours indicate the number of $kW_p$ installed per region. Source: [Ministery of Infrastructure and the Environment, 2014]*

#### *Regional capacity*

The installed capacity of PV in $kW_p$[7] differs significantly for different municipalities in the Netherlands (see Figure 11). The numbers are based on voluntary registrations in the Product Installation Register[8] (PIR) and it is possible that 20% more capacity is installed than registered [van Sark & de Rijk, 2014]. There is a large regional difference in deployment of PV, ranging from 1 $kW_p$ per four-digit postal code area, up until 6000 $kW_p$. The more rural areas generally contain a higher installed capacity than the more urban areas.

## 2.3 Heat pump system and development

This section starts by a short description of the developments of heat pumps, and the typical elements in a heat pump installation. Thereafter, the market developments and deployment rates are described.

### 2.3.1 Technical description heat pumps

The first description of the thermodynamic cycle is provided by William Thomson in 1852, after which the first working heat pump was built in 1856 [Laue, 2006]. After these initial testing's it took nearly 70 years before further testing occurred in Europe and the USA, after which deployment increases in the USA and Japan from the 1950s onwards. In the 1970s the heat pump market in Europe continued to grow by the influence of the first and second oil crisis, although coming to a stop in the 1990s due to falling electricity prices [Laue, 2006]. From the mid-1990s onwards the market increased in Europe due to increased attention for energy efficiency and environmental protection, although still lacking behind the markets of the USA, Japan and China. The technology is currently believed to be mature [Staffell, Brett, Brandon, & Hawkes, 2012].

#### *Types of heat pumps*

Heat pumps extract external heat from a heat source and increase the temperature so that it can be used for space and water heating. The increase in temperature requires external power in the form of electricity or natural gas. By reversing the flow, the heat pump provides a cooling capacity. The overarching term related to the functions of a heat pump is HVAC (heating, ventilating, and air

[7] $kW_p$ is the acronym for kilowatt peak, used for peak power (or nominal power) that specifies the output power of a PV module under full solar radiation (1000 watts per square meter under standard test conditions).
[8] In Dutch referred to as Productie Installatie Register (PIR)

conditioning). This research focusses on the heat pumps for the provision of heat, and therefore excludes air conditioning appliances only.

There are three categories of heat pumps when looking at the power source; electricity driven, natural gas driven, or hybrid. This research focusses on the electricity system, and thus including electricity driven and hybrid heat pumps.

Within these categories, two types can be distinguished: ground-source heat pumps (GSHP), and air-source heat pumps (ASHP). Main difference is the heat source, being either the ground or the air. The main applied technology in Europe are the air source heat pumps (ASHP) followed by the ground source heat pumps (GSHP) [Bayer, Saner, Bolay, Rybach, & Blum, 2012]. In literature the two concepts are mostly considered in isolation, with limited articles including both ASHP and GSHP. The main differences between ASHP and GSHP are:

- GSHPs have larger cooling and heating performances and are therefore often used in cooler climates.
- Efficiency of a heat pump depends on the temperature difference between the circulating fluid and the room. The ground temperature (which is relatively constant throughout the year) in the winter is warmer compared to the air temperature, and colder compared to the air temperature in summer, meaning that GSHPs are more efficient than ASHPs [Koohi-Fayegh & Rosen, 2012].
- Even though GSHPs save primary energy compared to ASHPs and gas fired furnaces, the costs are not always lower, although increasing R&D efforts, variable electric rates, and/or carbon taxing can reduce the costs for GSHP and increase the incentive for installation [Cooperman, Dieckmann, & Brodrick, 2012].

### *Components heat pump system*

Ground source heat pumps (GSHP) use the earths subsurface at low depth for the provision and storage of heat, which can be used (after enhancement) for space heating and hot tap water heating. This requires the heat source, often a borehole heat exchanger (BHE), and a heat pump. The heat exchange with the subsurface can be accomplished through open systems (using groundwater), or through closed systems (using a heat carrying fluid), after which the heat pump increases the temperature to a usable level with additional energy (either electricity or natural gas). The efficiency of the heat pump is expressed by the Coefficient of Performance (COP), indicating the required electricity in comparison to the heat output. The electricity driven GSHP are by far the most applied type [Mustafa Omer, 2008].

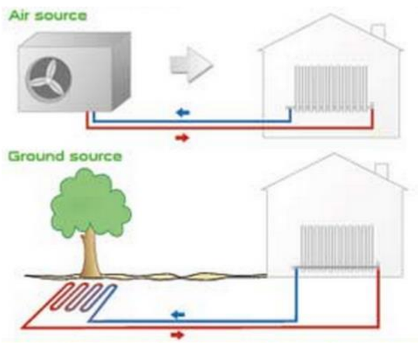



*Figure 12: Air and Ground Source Heat Pumps. Adapted from: [Council, 2014]*

Air source heat pumps (ASHP) consists of a small heat exchanger and a fan for circulation, and can be considered as reverse refrigerators. The ASHP can be used in direct form for single room heating (air-to-air), or connected to the central heating system (air-to-water) [Staffell et al., 2010]. The heat source of the ASHP is the air.

Hybrid heat pump systems are extensions of ASHP or GSHP by combining heat sources. There is a large range of novel technologies with diverse configurations, such as with renewable sources or fossil fuels. In the Netherlands the main applied hybrid heat pumps is a combination of a small air-water heat pump for the basic load, and a natural gas burner for the peak load provision [RVO, 2013].

The main components of a heat pump system are [Staffell et al., 2012]:

- A compressor unit, increasing the pressure of the refrigerant and thereby increasing the temperature, turning low grade heat into higher grade heat (in terms of exergy).
- An internal heat exchanger/condenser, distributes the higher grade heat to the building or hot tap water.
- An expansion valve, returning the refrigerant to below ambient temperature.
- An external heat exchanger/evaporator, collecting the heat from the heat source.

Additionally, the hybrid heat pumps contain an additional heating system that can be deployed during moments of high demand.

### 2.3.2 Heat pump market development

***Worldwide capacity***

In Europe the number of heat pumps currently increases by 5.4 million units each year, reaching a total of 70 million installed systems in 2020 when extrapolating from 2012 [Bayer et al., 2012]. This forecast is based on the number of the European Heat Pump Association (EHPA) and only includes single-family household applications. World leaders of installed units of GSHP are the United States, China, Sweden, Germany, and the Netherlands [Lund, Freeston, & Boyd, 2011]. Residential heating is the largest application for GSHPs in Europe [Bayer et al., 2012], and the heating load is the main design variable with the aim to provide base load with fossil fuel peaking[9] for the remaining heating demands [Lund et al., 2011].

Due to the dispersed market of different types of heat pumps the world overview of installed units is lacking. The annual sale numbers (with an outlook for future years) are included in Figure 13.

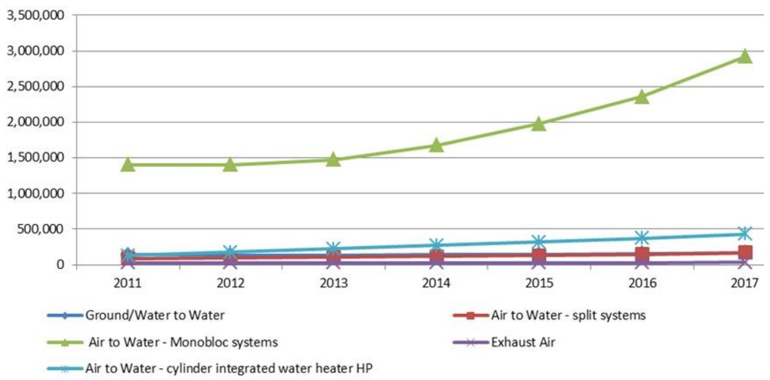



*Figure 13: Global heat pump market outlook, sale by volume in units. Source: [BSRIA, 2014]*

***National capacity (business/households)***

In the 1980s the R&D was mainly focussed on the larger applications using ground water wells for commercial buildings, rather than for the residential houses [Lund et al., 2011]. Since the 1990s the vertical borehole heat exchanges have become the main geothermal heat pump technology with 25.000 small scale units for households, small offices and commercial buildings in operation in 2010 [Lund et al., 2011]. For households the main applications are heating and hot tap water, while for the offices and commercial buildings both heating and cooling is desired. The residential installed capacity consists for 60% of GSHPs and for 40% of ASHPs in 2013 [CBS, 2013a] (see Figure 14).

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[9] This thus involves a hybrid heat pump.

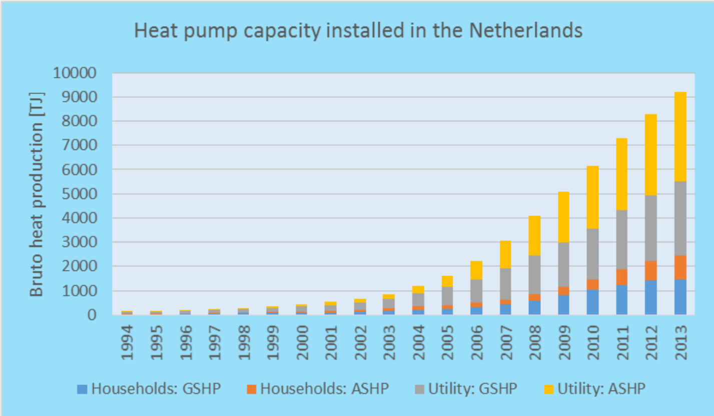



*Figure 14: Installed capacity heat pumps in the Netherlands. Data source: [CBS, 2013a]*

***Regional capacity***

At the best of our knowledge, the regional deployment numbers or installed capacities of heat pumps are not available in detail in the Netherlands.

## 2.4 Actors involved in the problem area

The deployment of (decentralised/renewable) energy, increased energy efficiency and the energy infrastructures related to it are positioned in a multi-actor setting. Multiple actors are involved in the policy making and technology deployment, which each have their own perspective on, and interest in the problem area. The energy policy contains a policy problem, which can be defined as *"a perceived gap between a norm or value and an existing or expected situation for which holds that the bridging of the gap is subject to public policy"* [Van der Lei, 2009, p. 19]. The deployment of technologies such as PV and heat pumps depends on the national and regional policy, as well as the other actors involvement regarding power, interest and attitude towards the deployment. The actor analysis is performed to enhance the understanding of the perspective that different actors have towards the regional deployment of PV and heat pumps, and the ability to influence the regional deployment rates.

### 2.4.1 Theoretical background

The analysis of the actors is based on the methodology of Hillson & Simon [2007], which describes each actor on the elements of power, interest and attitude towards the problem area. The definitions as used in this research are as follows.

**Power**: the degree to which an actor can influence the deployment rates of PV and heat pumps. The influences of an actor is defined as either powerful (+), neutral (0), or hardly any power (-).

**Interest**: the interest an actor has in achieving high deployment rates of PV and heat pumps. Those actors with little interest do not care if the ambition succeeds or fails. Actors with a high interest are positive or negative towards a high deployment rate, which depends on their attitude. Interest categories are high (+), medium (0), or low (-).

**Attitude**: those actors that expect to benefit from high deployment rates have a positive attitude (+). Actors that are not affected by the deployment of PV and heat pumps are neutral (0), while those negatively affected have a negative attitude (-).

### 2.4.2 Actor analysis

The main perspective towards future deployment rates of PV and heat pumps are briefly described in Table 5. The powerful actors that have a medium or high interest, as well as a neutral or positive attitude, are the most influential actors in the development of the future deployment rates.

*Table 5: Perspective of main actors towards future PV and heat pump deployment rates, combined with their power, interest and attitude.*

| Actor | Main perspective | Power (+, 0, -) | Interest (+, 0, -) | Attitude (+, 0, -) |
|---|---|---|---|---|
| **Policy actors** | | | | |
| Ministry of Economic Affairs (EZ) | Achieving a completely renewable energy supply in 2050 in the most cost-effective way. Subsidy PV through net-metering dwellings [Rijksoverheid, 2015], no subsidy for residential heat pumps [Rijksoverheid, 2014], and energy investment costs deduction for companies (EIA). | + | 0 | 0 |
| Ministry of Infrastructure and the Environment (I&E) | Formulate climate policy aimed to reduce risks of climate change. Completely renewable energy supply in 2050. Sustainable city coalitions, and facilitating local initiatives [Ministery of Infrastructure and the Environment, 2013]. Regulation of electricity network operation. | + | +[10] | 0/+ |
| Municipalities | Local energy policy, differs largely between municipalities. Ability to provide support in legislation, licences, and example projects (see e.g. Vereninging Klimaatverbond Nederland, 2013) | + | ? | 0 |
| **Electricity sector actors** | | | | |
| Distribution network operators | Remain network stability by balancing the electricity demand and supply, and prevent outages. Increase in PV and heat pumps results in good sustainable transition, but increases costs of operation. | - | + | - |
| Electricity producers and retailers | Continuity of operation to be achieved. Either by provision of centralised electricity or new business models to function as facilitator. Large uncertainty on business model change due to increasing decentralised renewable energy deployment. | 0 | + | ? |
| **Technology deployment actors** | | | | |
| PV and heat pump companies | Contribute in demonstration projects. Sell as much appliances as possible. Increase the efficiency of the appliances. | 0 | + | + |
| Consumers (households and small businesses) | Diversified group, but main perspective is to reduce the energy bill, while maintaining current comforts. (Some idealistic to increase renewable energy, others aim for self-sufficiency, or other believes.) | + | 0 | 0 |
| Rental organisations | Increasing the energy efficiency of the building stock, either by implementing new energy neutral buildings, or retrofitting the existing stock. Pushed by policy to increase energy efficiency, with average energy label B in 2021 [Aedes, 2012] | + | 0 | 0 |
| **Other actors** | | | | |
| Media | PV and heat pumps are existing technologies, without large social objections. Can provide a positive influence on the national thought on deployment of PV and heat pumps, although uncertain. | 0 | 0 | 0 |
| Environmental groups | Change from fossil fuels towards renewable energy solutions as fast as possible. PV and heat pumps are two suitable options. | 0 | + | 0 |

One of the most important conclusions drawn from the actor analysis is that the attitude for national and local policy makers is often neutral. There can be a high interest to change the energy provision, but the consequences if the increase in renewable energy is not achieved are not local, but rather global (the difficulties associated with a common good). Only the inistry of I&E is attributed a positive attitude since the ministry is held accountable if the policy goals are not achieved.

It is, however, remarkable that the focus of the energy transition for the policy makers is shifting. On the one hand, the future renewable energy targets are formulated on a national scale, while the execution relies on the local scale initiatives between the private and the public sector. However, the municipalities are free to formulate own policies or visions regarding renewable energy stimulation. Therefore, the current policy relies heavily on the market initiatives. This increases the regional

[10] Source: [SenterNovem, 2008a]

dependency, and could therefore increase the regional differentiation of PV and heat pump deployment.

These are manifested in the rental organisations and the consumers, which have different believes and opinions, as well as different strategies for achieving renewable energy and energy efficiency targets. Large refurbishment of the existing building stock of rental organisations can largely affect the network stability.

Also the distribution network operators embrace the deployment of PV and heat pumps, but are required to deal with the increasing investment costs. This creates a split-incentive between stimulating renewable energy deployment and maintaining low costs for the distribution of electricity. Application of network stabilizing measures, such as demand side management or storage, might be the solution.

## 2.5 Existing methods for load calculations

This section discussed the current methods for load calculation and load forecasting as found in literature. Load calculation methods can be categorised as a combination of different approaches for construction of the load profiles, and of the hierarchical level, or scope, of the network calculations.

### 2.5.1 Hierarchical level of network calculations

The forecast of the load demand in the distribution grid is a main tool for decision makers in the energy sector. The load forecast tools differ in terms of the time horizon and the accuracy, and the suitability depends on the purpose of the research. The purpose is mainly characterised by the hierarchy of interest in the electricity system and the time horizon.

***Time horizon***

The time horizon of the forecast can be divided into 3 periods, with each having its own main purpose.

- Short-term: prediction up till one-week ahead. Used for the day-to-day operation of the electricity system [Kyriakides & Polycarpou, 2007]
- Medium-term: prediction from one week till one year ahead. Used for medium-term activities like contract negotiation [Hahn, Meyer-Nieberg, & Pickl, 2009]
- Long-term: prediction longer than one year ahead, often with a time horizon of 20 years. Used for decision makers in planning of facilities (e.g. transformers) [Kyriakides & Polycarpou, 2007]

This research provides an outlook to the year 2040, which is thus regarded as a long-term time horizon. Most long-term load forecasting models try to predict the load profiles and the peak demands [Kyriakides & Polycarpou, 2007].

***Purpose of the research***

The future load demands can be analysed on different hierarchical levels of interest for the electricity system. The most appropriate hierarchy level depends on the purpose of the research. Also different starting points can be distinguished, starting from the consumer group characteristics or starting from the electricity network characteristics. The highest level on the consumer group differentiation is load forecasting on the (inter)national scale, followed by the regional scale, the district scale, the neighbourhood scale, and the individual consumer scale. A different hierarchy division is a division based on the grid characteristics, with the highest being the high-voltage, followed by the medium-voltage, and the low-voltage network.

The problem of interest in this research is to determine the effect of the energy transition on the (low-voltage) distribution grid. This problem can be approached on the national scale, the individual consumer scale, and anywhere in between. Example of the high level approach are network impact calculations for an entire operating area of a DNO, such as investigation of the cascading failures of blackouts in the electricity grid [e.g. Koç, Warnier, & Mieghem, 2013], or social cost benefit analysis of smart grid solutions [e.g. CE Delft & KEMA, 2012]. Low hierarchical areas of interest focus on specific districts or small groups of consumers, or on individual connections. The purpose of this type of research is to calculate the load demand as detailed as possible (e.g. Brandão de Vasconcelos, Pinheiro, Manso, & Cabaço, 2015).

### 2.5.2 Load profile construction

A multitude of methods and approaches to construct current and future load profiles are found in literature (see Figure 15). The most applied approaches are reviewed by Swan & Ugursal [2009] in which they make a distinction between top-down and bottom-up approaches, that both depend on different aggregation levels of required information and modelling techniques.

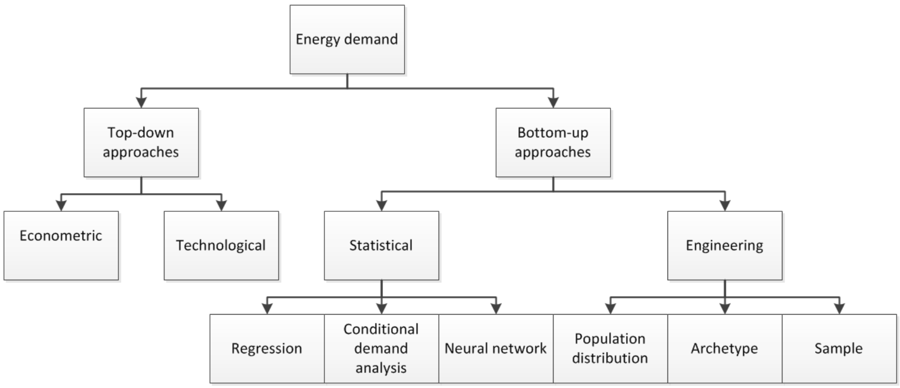



*Figure 15: Top-down and bottom-up approaches to determine the energy demand of the build environment. Adapted from [Asare-Bediako, Kling, & Ribeiro, 2014; Swan & Ugursal, 2009].*

#### *Top-down approaches*

The top-down approach considers the residential consumers as an energy sink without considering individual end-consumption. This approach uses the total energy consumption of the area of interest and *attributes* the energy consumption by using main variables that characterise the build environment [Swan & Ugursal, 2009]. Different examples of the top-down approaches are clustering, forecasting, demand-supply scenarios and demand response policies to estimate load demands [Asare-Bediako et al., 2014]. Also synthetic load profiles (SLP's) are often deployed by network operators or energy suppliers, which are profiles constructed for different consumer types and based on historic demands. The organisation Energie Data Services Nederland (EDSN) provides these profiles in the Netherlands. Two main initial departure views are the econometric view, focussing on price and income, and the technological view, focussing on characteristics in the consumer stock such as appliance distributions. The top-down approaches are useful in case of a limited availability of historic data and their strength lies in its simplicity, but the limitations are that the individual peak demand, and consumers behaviour are not included [Swan & Ugursal, 2009]. Since the SLP's are based on historic data another limitation is the difficulty to model non-continuous developments in technology deployment. Also the attribution of the energy consumption to different energy consumption technologies is not possible due to the high aggregation level, meaning energy reduction areas of interest are neglected.

### *Bottom-up approaches*

Bottom-up approaches do focus on the individual end-users for energy demand and behaviour, which in turn are extrapolated to form the load demand of the neighbourhoods or districts [Swan & Ugursal, 2009]. This approach uses *calculation* of the energy demand for the individual consumer after which the results are extrapolated for larger regions [Swan & Ugursal, 2009]. Examples of bottom-up approaches are probabilistic and scenario based modelling approaches [Asare-Bediako et al., 2014]. The main categories are statistical methods that focus on regression analysis to attribute energy consumption levels, and engineering methods that use the power ratings of appliances for electrical and heating demands [Hahn et al., 2009]. This requires detailed input data on consumer characteristics such as geometry, envelope fabric, equipment, climate conditions, and occupant behaviour [Swan & Ugursal, 2009]. The strengths of the bottom-up approach are the ability to analyse end-use consumption technologies in a detailed manner without relying on historic data. The drawback are the high information requirements and extensive modelling procedures [Asare-Bediako et al., 2014]. The bottom-up approach is also often deployed to investigate the influence of new end-use technologies at the consumers' location, such as electric vehicles [Brandão de Vasconcelos et al., 2015].

### *Comparing top-down and bottom-up approaches*

The top-down and bottom-up approaches each have their advantages and disadvantages, and the best fit depends on the purpose of the research. The most important difference is the required input data.

For the top-down approaches the low data requirements allow for a relatively fast development of the model and inclusion of macro-economic factors such as price, income, technology development, and climate changes [Swan & Ugursal, 2009]. The basis for the models are the historic development rates of technologies and demand of energy. Results are especially useful in determining the required energy due to changes in economic developments on a national or large regional scale, but lack the ability to include non-continuous developments in energy demand. Therefore the top-down approaches are recently including bottom-up elements such as technology and distributed generation elements [e.g. EIA, 2013]. However, according to Swan & Ugursal [2009] this improves the future technology deployment estimates, but lacks the analysis on the potential impact that these technologies can have.

The bottom-up approaches require a large amount of input data in the form of end-use consumption caused mainly by appliances, lighting, and occupant behaviour. The statistical bottom-up approaches combine both detailed consumer analysis with regional econometric factors, and are thereby bridging the gap between detailed bottom-up approaches and top-down econometric approaches [Swan & Ugursal, 2009]. Since the statistics are based on billing data of energy suppliers the occupant behaviour can be distinguished, providing statistical analysis with an advantage over engineering approaches. The bottom-up engineering approaches have, however, the advantage that they do not require any historic data. This comes at the cost that large amount of input data are required and long computation times are needed.

## 2.5.3 Discussion on the knowledge gap

The main conclusions of the previous sections are:

- The most appropriate aggregation level for analysis depends on the purpose of the research and the data availability.
- Top-down approaches attribute the energy demand by using variables that characterise the build environment.

- Bottom-up approaches calculate the energy demand using detailed data on individual consumers and extrapolating the results for obtaining demands for larger regions.
- The main difference between the top-down and bottom-up approaches is the ability of the bottom-up approaches to assign the energy demand of individual technologies within the overall demand.

Existing methods to calculate the load demand of the build environment are positioned on the hierarchical level of interest and the approach to construct load profiles (see Figure 16). This research contributes to the body of knowledge in the categories of a high hierarchical area of interest, combined with a combination of top-down and bottom-up load profile construction. The hierarchical area of interest is the entire operating area of Dutch DNOs, within which multiple districts are distinguished. Therefore, it can also be considered as a multitude of intermediate areas of interest as presented by model districts. However, the overall interest remains on the entire operating area making the high hierarchical level in combination with the intermediate hierarchical level most appropriate.

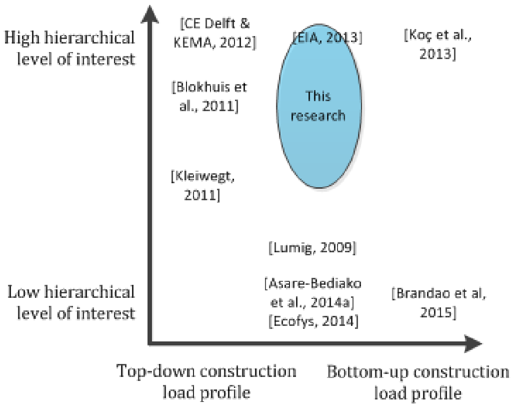



*Figure 16: Positioning of this research in relation to the existing load calculation methods. The methods are plotted on the hierarchical level of interest, and the approach to construct the load profiles.*

The load profiles of the consumers are based on historic data (top-down characteristic) of the EDSN profiles, but adapted for annual electricity and heat demand by using reference buildings[11] (bottom-up characteristics). Also the electricity demand of the end-use appliances are included for PV and heat pumps (bottom-up characteristics). Although reference buildings are used in this research, they cannot be considered a purely engineering bottom-up approach since the load profiles are not determined for each of the reference building type, but only scaled to the annual demand. Therefore the shape of the load profile is similar, and only the height differs.

## 2.6 Conclusion

This chapter provided background information on the electricity system, PV system, heat pump system, and the actors involved in those systems. Several important notions are discussed that require additional detailing in the following chapters.

For the load characteristics the following notions need to be considered:

- The simultaneousness factor of supply and demand
- The load profiles of consumers and producers

[11] In literature the term ‘archetypes’ is often used to describe ‘reference buildings’.

- Type of connections on the LV network
- Energy demand growth
- Distribution of typologies in the operating area

For the distribution transformers the following notions need to be included:

- Number of MV/LV-transformers operating area
- Number of users connected to one MV/LV-transformer
- Age of current equipment
- Additional reserve capacity
- (over)loading level of transformers
- Average lifetime of transformers

The future deployment rates of PV and heat pumps, as well as the energy demand of the connected users, depend on the market and policy developments. The national policy is executed by the Ministry of Economic Affairs and the Ministry of Infrastructure and the Environment, in which the execution relies on the market parties. The market parties that are most influential are the rental organisations and the individual consumers. Especially the degree of refurbishment of the build environment to increase the energy efficiency, and eventually needs to result in an energy neutral build environment in 2050, can have a significant influence on the energy demand and deployment rates of PV and heat pumps. DNOs are stimulating these developments, although a split incentive exists between the low investment and operational costs of the distribution of electricity and the stimulation of renewable energy technologies.

A knowledge gap exists in the current methods for load calculation. This research creates an intermediate level that focusses on district load forecasting, with the aim to provide insights for decision makers for the entire operating area. This involves the use of detailed statistical data for the districts, while maintaining the general overview of the entire operating area. Therefore this research is positioned as a medium to high aggregation level, with a combination of elements of bottom-up and top-down load profile construction.

# 3. Research approach

The most important aspects to be considered in performing electricity network analysis are described in Chapter 2. This chapter describes the approach for the remaining chapters, including the notions to be included from the previous chapter. An abstract version of the approach is included at the introduction of the remaining chapters to maintain the overview and interrelation between the chapters (see Figure 17).

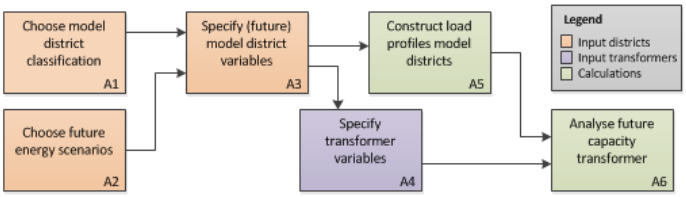



*Figure 17: Abstract version of the approach of this research.*

This chapter starts by describing the IDEF0 theory that is used to formally describe the approach (section 3.1). This methodology is used to describe the approach of this research to construct model districts and analyse the future load demand of the distribution transformers (section 3.2).

## 3.1 Theory IDEF0 for approach description

The functions that the model is required to achieve are described with the IDEF0-standard (an acronym for Integrated computer aided manufacturing Definition for Function modelling). IDEF0 functional modelling is used to model actions and activities of an organisation or a system [Grover & Kettinger, 2000]. The US Air Force created the modelling approach in 1981 on the basis of the Structured Analysis and Design Technique (SADT), and reconstructed it to communicate and analyse the functions of a system [NIST, 1981]. Therefore the building blocks have to be constructed on the basis of the formal format in order to maintain easy and uniform means for communication. The building block consists of the function box which is described as a verb, and the arrows (input, output, control, and mechanism) representing the data and objects that interrelate with the function (see Figure 18). The function can describe an activity, process or transformation that needs to be achieved [NIST, 1981]. The diagram consists of multiple layers, by which the highest function block can be decomposed into multiple lower function blocks to further specify the underlying functions. Additional information about the IDEF0 modelling approach can be found in [Defense Acquisition University Press, 2001; Grover & Kettinger, 2000; NIST, 1981].

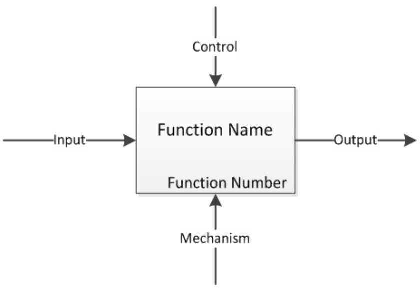



*Figure 18: The IDEF0 formal format building blocks.*

The arrow inputs definitions as defined in the [NIST, 1981] are as follows:

- "**Input Arrow:** The class of arrows that express IDEF0 Input, i.e., the data or objects that are transformed by the function into output."
- "**Output Arrow:** The class of arrows that express IDEF0 Output, i.e., the data or objects produced by a function."
- "**Control Arrow:** The class of arrows that express IDEF0 Control, i.e., conditions required to produce correct output. Data or objects modelled as controls may be transformed by the function, creating output."
- "**Mechanism Arrow:** The class of arrows that express IDEF0 Mechanism, i.e., the means used to perform a function." These are the physical aspects of the activity, such as people, machines or tools.

## 3.2 Approach in remaining chapters

Using the IDEF0 methodology the activities and actions to be performed in the following chapters are visualised in Figure 19. Brief descriptions are included below for each of the blocks. The chapters provide the main elements of the content, for which a more detailed description is often included in the appendix to which is referred in the chapters.

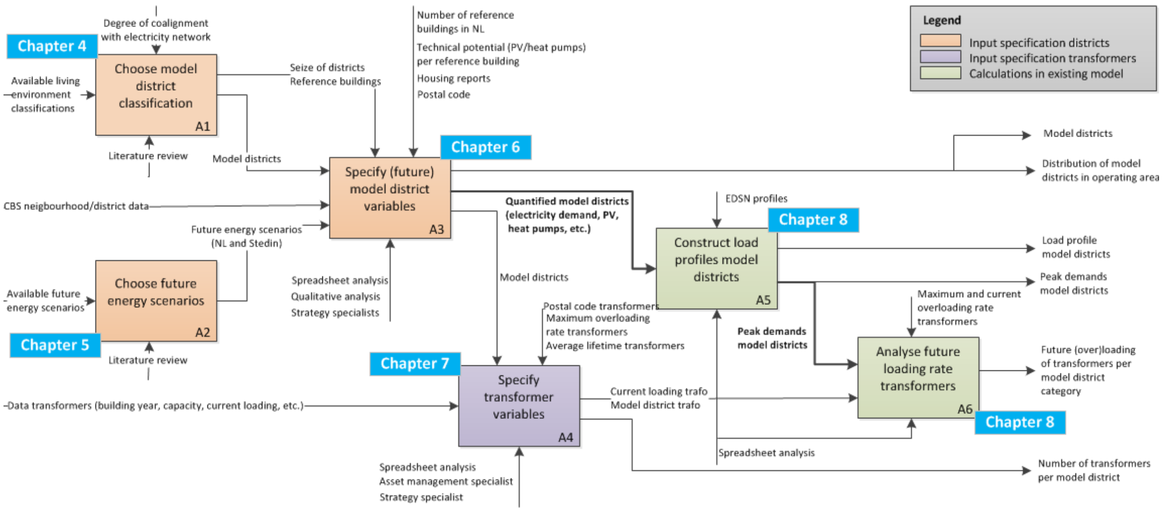



*Figure 19: IDEF0 overview of activities and actions in remaining chapters*

### *Chapter 4: 'Choose model district classification'*

The first activity is to determine which methods have been used to classify groups of buildings, or geographical areas as specific sub-living environments. Different theoretical approaches are discussed on applicability to construct model districts that encapture the dynamics of the electricity grid. This includes the notions of Chapter 2, of which the main are the network typology and the spatial distribution of demands. The output of chapter 4 are the model districts theoretical description, the size of the districts, and the types of reference buildings that are included.

### *Chapter 5: 'Choose future energy scenarios'*

The future is uncertain, especially in a socio-technological system as dynamic as the electricity system with changing functions and technologies that are applied in the (upcoming) energy transition. Existing future exploration methods are therefore discussed theoretically, after which the preferred future energy scenario is determined and discussed. As discussed in Chapter 2, it has to comply with the required year of interest of 2040, be applicable to the operating area of Stedin, and contain (at least) information about PV deployment, heat pump deployment, electricity demand, and heating demand.

### *Chapter 6: 'Specify (future) model district variables*

The model districts have now been described in theoretical terms. In this chapter the model districts are specifically constructed for the operating area. This means that for each postal code area the type of model district is determined, after which the data about the demographics are used to specify the number of reference buildings for each model district type. After this the future energy scenarios for the operating area of Stedin are used to determine (for each model district type) the installed capacity of PV, the number of heat pumps, electricity and heating demand, and other variables. These are the input values for the future load demand calculations of the distribution transformers.

### *Chapter 7: 'Specify transformer variables'*

After the peak demand and the load profiles of the model districts are constructed (in Chapter 8), the impact of the electricity demand and supply on the transformers needs to be determined. The current capacity of the transformers is either sufficient, or insufficient. In this chapter the current stock of transformers in the operating area is analysed on nominal capacity, current loading rates, location, etc. Additionally the number and types of transformers per model district are analysed. The results of this analysis, combined with the required variables to consider when performing capacity calculations for transformers (like the simultaneousness factor, reserve capacity, network losses), are used to gather relevant data to determine the future (over)loading of the transformers for each group of model districts.

### *Chapter 8: Results*

In Chapter 8 the input variables for each model district from Chapter 6 are used to construct the extreme load profiles and peak demands for each model district, of which the results are presented. These results, in combination with the transformer characteristics of Chapter 7, are used to determine the future (over)loading of the transformers, which are the final results of this research.

### *Other chapters*

Chapter 9 discusses the modelling approach and results of the research in relation to other research and the usability of the outcomes. Chapter 10 includes the conclusions and recommendations, as well as a discussion on the ability of the approach of this research to determine future load profiles, peak demands and the impact on MV/LV-transformers. The report ends with a reflection on the research.

# 4. Model district classifications

The previous chapter provided the approach to segmentate the operating area of DNOs. This approach aims to bridge the gap between the high level and the detailed hierarchical level of analysis of the future load distribution on the low-voltage (LV) network. As found in chapter 2, the main users connected to the LV network are residential connections, and small business connections. Constructing an intermediate level to analyse the load development on the LV-network requires a segmentation of the residential and small business connections throughout the operating area.

In this chapter the operating area is therefore segmented by constructing model districts that are representative for the Dutch build environment. This requires model districts that contain multiple buildings, and within which the renewable technologies deployment are distributed uniformly within those model districts. To do this a literature review is performed to determine the different theoretical types of district classifications that form the basis for a discussion on the most appropriate segmentation for the LV-network.

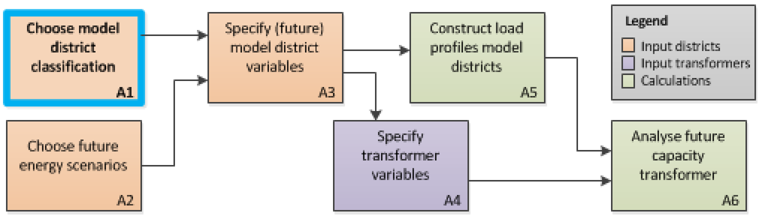



*Figure 20: Overview general approach of this research. This chapter focusses on the (theoretical elements in the) construction of model districts.*

The structure of this chapter consists of six section. In the first section (4.1) the theoretic foundation of segmentation is investigated by means of a literature review. This theoretic background is used to structure the research choices for section 4.2 that are elaborated upon and result in the type of classification that is most appropriate. Currently existing living environment typologies of this type are provided in 4.3, which is followed by section 4.4 that contains a detailed description of the model district types that are used in this research. The chosen model districts are further specified by the different types of buildings in section 4.5. Lastly, the implications of using these model districts with the relevant reference buildings are discussed and the conclusions are provided (4.6).

## 4.1 Theory on constructing residential environment typologies

Literature provides different means for dividing the build environment on the basis of certain criteria. The division can be singular, based on building year, or contain a multitude of criteria like physical, geographical and behavioural criteria. Generally there is a distinction between soft and hard criteria for the construction of typologies.

### *Background on typologies*

Construction of residential environment typologies has been developed in the 1970s as a tool for city planners to identify the need for urban restructuring in order to connect to the wishes and needs for residential dwellings and neighbourhoods [Raat & Wassenberg, 1998]. Centre, suburban and rural types of living environments have different characteristics in both physical and sociological terms. One way to describe different residential environments is through a combination of physical-spatial factors (e.g. construction year of houses) and socio-spatial factors (e.g. average household composition) [Meesters, 2009]. By combining and defining these factors different residential environment typologies can be constructed [Diepen & Arnoldus, 2003]. In the Netherlands residential environment typologies are widely used in the building sector, especially for policy documents of the Dutch government [Meesters, 2009]. Institutions extensively applying the residential environment typologies in the Netherlands are OTB, VROM, NICIS Institute and Platform 31.

### *Definitions typology*

A residential environment is hard to define and diverse definitions exists [Reinders, 2004]. It can consists of different elements like the age of buildings, types of dwellings, street image, ownership characteristics, type of residents, and/or location of the region. Different definitions for the term residential environment are being used in literature, but the central idea is that it is about the direct living environment of people [VROM, 2006]. Grunfeld [1988] defines the living environment as the quality of the surrounding of a delineated spatial area that is often used by its residents and is relevant for their activities and communications, and in which they can assign uniformity.

According to Diepen & Arnoldus [2003] the goal of constructing typologies is to provide information in a compact and insightful manner about residential environment to provide insights in the variation of characteristics that are encapsulated in the residential environment. The aim is to create order in the amount and complexity of factors. The possibility to characterise the areas in their diversity and divide them into discrete types, simplifies the large amount of information.

Since the 1980s the term residential environment (in Dutch “woonmilieu”) has been used extensively in the Dutch field of urban renewal research and policy memorandums. Within this residential environment the perception of residents has shifted throughout the years. The accent has shifted from a dwelling for the purpose of shelter, towards living space which needs to enable a right environment to achieve a certain lifestyle [Diepen & Arnoldus, 2003]. This shows that the residential environment consist of physical characteristics as well as sociological characteristics.

### *Types of criteria in typology*

Typologies divide residential environments on the basis of certain criteria. Generally there are three categories of divisions [VROM, 2006]:

- Singular divisions: on the basis of one criterion e.g. construction year or selling price;
- Monothematic divisions: on the basis of one theme, e.g. physical or social characteristics;
- Multi-thematic divisions: based on multiple themes, e.g. a combination of physical, and social criteria.

### *Hard or soft criteria*

The above division includes another division; on the basis of hard or soft criteria. Hard criteria are objectively measurable and include criteria like architectonic properties, urban structures, social factors like education and income [VROM, 2006]. Soft criteria are often used to describe the perception of people, including subjective and non-rational dimensions like memories, principles, feelings, emotions and identities.

A soft criteria analysis on the segmentation of the consumers in the client area has been performed for the domains of energy, energy efficiency, sustainability and innovation orientation [Randsdorp & Schoemaker, 2014]. This resulted in a segmentation into ‘unconscious energy users’, ‘pragmatic comfort seekers’, ‘environment improving consumers’, and ‘duty driven environment consumers’, which is used to determine the willingness to adopt renewable energies and perform renovations or other activities. This division is based on the properties of consumers that are above average present in the group.

### *Size of area*

The residential environment typologies thus divide a region (or a country) into a certain number of groups of residential environments, and thus always requires data delineation on a geographical basis. Analysis have been performed on the level of municipalities, districts, neighbourhoods or areas that coincide with the four or six digit postal code areas[12] [Diepen & Arnoldus, 2003; VROM, 2006]. Six character postal area information consists of a dozen of dwellings, and are comparable to the street level. The level chosen in analysis is often predetermined by the data availability [Diepen & Arnoldus, 2003], and the purpose of the analysis.

For the ordering of data in the Netherlands, the districts are often delineated geographically on the basis of postal codes [Meesters, 2009]. In the Netherlands there are 4046 four-digit postal code areas (e.g. 2625), of which 1000 are located in urban areas. These areas are increasingly heterogeneous with smaller municipalities, and can consist of just a few up until a few thousand of households. A more homogeneous delineation is the six-digit postal code area (e.g. 2625 AZ) which has been divided in the 1970s on the basis of the time that the postman requires to deliver the mail, and consist of around a maximum of 15 till 20 houses [VROM, 2006]. The number of postal code areas per aggregation level is as follows:

- PC4 (four-digit postal code): 4.046 areas
- PC5 (five-digit postal code): 32.869 areas
- PC6 (six-digit postal code): 453.575 areas

The number of areas thus substantially increases by using a more detailed level of interest.

### *Level of detail*

The different levels are not clearly hierarchical since combining multiple smaller areas does not automatically lead to a unity on a higher aggregation level. Postal areas sometimes consist of multiple districts (e.g. in medium-sized cities, or villages), but can also coincide with a single district (e.g. in larger cities). Combining smaller areas therefore does not necessarily mean the correct larger area characterisation is provided.  The comparison of appropriateness of the level of detail for data are reviewed by Diepen & Arnoldus [2003] and the main conclusions are:

- On the level of districts and neighbourhoods building form is leading and is provided a lot of attention. The higher aggregation level of municipalities shows a large differentiation of building form. Increasing the area seize reduces the homogeneity of building type within the area, while reducing the area seize increases the homogeneity of building type.
- Lower aggregation levels lack the cohesion of social characteristics, which are present at a larger aggregation level. Social characteristics are less spatially clustered at a lower aggregation level. Empirically there is no social-spatial distribution. Apparently there is a larger physical uniformity on the low scale level than there is on the social characteristics.

[12] Four digit postal code areas are of the form 2625, five digit postal code areas of the form 2625 A, and six digit postal code areas of the form 2625 AZ.

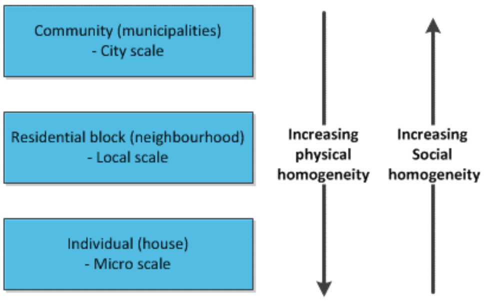



*Figure 21: Influence of level of detail for constructing residential environment typologies on the physical and social homogeneity.*

### *Summary*

To summarise, the construction of residential environment typologies is useful for reducing the amount of information and divide geographical areas into homogeneous areas. Typologies provide an aggregated approximation of geographical areas, which is easier to use compared to analysing the relevant variables of the area separately. The physical homogeneity increases with smaller topologies, while the social homogeneity increases with larger typologies. For the construction of relevant model districts the data availability is the key element.

## 4.2 Research choices for model district types

The theory of the previous section on the different ways in which living environment classifications are constructed is used to outline the discussion on the most appropriate classification for the segmentation of the operating area.

As described, model districts can be used to characterise the areas in their diversity and divide them into discrete types, which simplifies the large amount of information [Diepen & Arnoldus, 2003]. The residential environment consist of physical characteristics as well as sociological characteristics. This section discusses the main research choices concerning the construction of these discrete types of areas for the purpose of electricity network calculations. The following aspects are discussed: main criteria categories, hard or soft criteria, size of the areas, level of detail, and the data availability.

### *Research choice – criteria category*

Typologies divide areas into living environments on the basis of certain criteria. There are three types of criteria divisions: singular, monothematic, or multi-thematic. The criteria category needs to encapsulate the variables that can be used to predict, or estimate, the electricity demand, heat demand, PV deployment and heat pump deployment. A singular division, on e.g. building year, cannot provide enough insight into the different deployment rates of PV and heat pumps in a service area of a MV/LV-transformer. In other words, the singular division lacks the power to create uniquely identifiable and substantial differences between model districts since the differentiation based on e.g. building year only partially explains the variation of the electricity demand in different building types (see e.g. [DHPA, 2013]), or the differentiation of PV and heat pump deployment.

To enable an approximation of the electricity demand for dwellings the building year and the building type are required. The multi-thematic division including both physical and social criteria seems most appropriate since income and education are likely to influence the adoption rate of PV and heat pump systems. However, social correlations between deployment rates of PV and heat pumps are only investigated in literature to a small extend[13][Bleumink, 2013]. The physical criteria can provide insights into the maximum of surface area for PV and the likelihood of implementing a heat pump at a certain building type. Therefore, although the multi-thematic division is preferable, the monothematic division will be used.

***Research choice – Size and data availability***

Small model districts with a limited number of buildings allow for a more detailed characterisation and increases the physical homogeneity within the district. Therefore the optimum scale is a small area for model districts, but larger than the scale of reference buildings alone.

Using the six-digit postal areas will result between approximately 5 and 50 buildings in its deployment range. This allows for a detailed analysis with homogenous postal areas to draw precise conclusions. The six-digit postal area is available at the 'Kadaster' (central registration organisation in the Netherlands), but it is restricted due to privacy concerns[14] and requires a long and detailed approval procedure [Nieboer, 2015]. The same holds for the PC5 areas. Therefore the next-best is to use the four-digit postal code areas, for which it is important to realise that the method is an approach, rather than the real distribution. Each four-digit postal area (PC4) has between approximately 10 and 11.000 buildings, and thus results in a larger spread of buildings per postal code area compared to a PC6 or PC5 distribution.

Additionally the implication of using the PC4 areas is a reduced homogeneity for the classification of model districts. It is possible that within one PC4 area a multitude of model district classifications exists. With current approach the most dominant type of model district is used to classify the PC4 area, and thus discarding the less dominant model district types. The impact of this approach is elaborated upon in chapter 9.

***Research choice – hard/soft criteria***

The initial division is based on the hard criteria since these values are better to obtain and are readily available with a high degree of accuracy. Soft criteria values are likely to change faster and are harder to obtain. The drawback of the soft criteria segmentation performed for the client (see 4.1) is the division on the basis of above average properties. This implies that districts in which e.g. the largest percentage of building types are terraced houses, the consumer type is still characterised as living in an apartment since the relative percentage of apartments is high. This makes the analysis not usable as main divider. However, the soft criteria can provide insights in the willingness to install PV and heat pumps and can therefore provide an indicator for deployment rates for typologies with hard criteria. Initially the categorization is performed on the basis of hard criteria, but inclusion of soft criteria can be performed in future research.

***Research choice – level of detail***

By using model districts that can be visualised, or imagined by the policy department of DNOs the ability to gain insight into the trade-offs is increased compared to using houses on the micro-scale. Additionally the physical characteristics are most important for providing insights into the future development of PV and heat pumps. The social homogeneity is equally important, but the analysis lacks the in-depth data on the four-digit postal areas and its internal homogeneity. Therefore the

[13] A literature research has been performed to identify any studies that study correlations between social characteristics and the adoption rates of PV and heat pumps in the Netherlands. No relevant studies have been found. A former intern at the client performed a statistical analysis to identify possible correlations, but no reliable correlations have been found [Bleumink, 2013]

[14] The six-digit postal categorisation contains information of a limited set of households (sometimes as few as 5 households) which makes it possible to redirect information about individual households.

deployment of future measures to reduce the peak demand best fits with the local scale detail level which represents districts.

### *Conclusion*

The division into residential environment typologies in this research is on the basis of a monothematic division, with hard criteria, on four-digit postal code areas, for the residential blocks or neighbourhood. The next section describes the different classifications as applied in the literature.

## 4.3 Overview of hard typologies currently being used

Now that the main research choices are made regarding the residential environment typologies, this section describes the currently applied hard typologies on the basis of monothematic criteria. The international application is described first, after which an overview of hard typologies applied in the Netherlands is provided.

### *International hard typology development*

An analysis about the relationship between human behaviour, the building stock and the energy consumption has been performed for two case study areas, and concludes that there is a relationship between the parcel size, setback, the number of floors and the energy consumption [Soltani, Mehraein, & Sharifi, 2012]. This analysis used reference buildings, but no typology for the district. Also [Aksoezen, Daniel, Hassler, & Kohler, 2015] performed an analysis using reference buildings to determine if the building age can be used as an indicator for energy consumption (answer is yes). To determine the total percentage of houses which can be retrofitted/upgraded, Marique & Reiter [2012] used a characterisation of detached, semi-detached and terraced buildings in combination with building year. This approach was also used by Caputo, Gaia, & Zanotto [2013] to create a standard set of electricity profiles to use for energy simulations in the built environment. All papers describe a building focussed approach to perform energy analysis. No research on the level of districts or neighbourhoods has been found in the scientific literature. An interview conducted with Nieboer [2015] confirms that residential environment typologies are mainly applied in the Netherlands probably due to lack of detailed data in other countries. The Netherlands is thus a front runner of application of residential environment typologies.

### *Hard typologies in the Netherlands*

From the 4000 PC4 areas (four-digit postal code) in the Netherlands approximately 1000 are urban areas and 3000 are rural areas. The categorisation of regions can be done by using living environment classifications that categorise on the basis of building stock, the function, the building period, but also on the character of neighbourhoods. Different typologies have been constructed, of which four are further elaborated upon (see Table 6).

The typology of RIGO [1995] focusses on the area characteristics and determined the living environment and the social economic developments for urban areas in order to identify ‘problem areas’ in cities. In VROM [1997] this urban typology was expanded with living environments constructed after 1995 and rural areas, resulting in 19 typologies (see Table 6).

This led to a large degree of detail, which resulted in a large degree of variables that were required to perform the analysis on postal code areas. Additionally for the organisation of VROM it was important to include desires of residents in the typology, rather than just identify in which area people were living [VROM, 2006]. In the ‘Nota Wonen’ in 2000 the number of typologies was therefore reduced to 5 living environments, but with addition of social and soft variables

[Wassenberg, 2004]. The most important difference with previous typologies was that building year or building characteristics were not included.

The division was largely criticised due to the global character of the typology [Wassenberg, 2004]. Therefore the approach of ABF research with a further specification was used more frequently. Initially they constructed a 10 division, which was adapted and resulted in the 13 division of living environments.

*Table 6: Overview categories of hard residential environment typologies applied in the Netherlands*

| # | [RIGO, 1995, 1997] | [Ministerie van VROM, 1997] | [VROM, 2001] | [ABF Research, 1998] |
|---|---|---|---|---|
| 1 | Historic city-centre | Historic city-centre | Centrum urban | Centrum urban plus |
| 2 | Large city-district (renewal) | Large city-district (renewal) | Outside centrum | Centrum urban |
| 3 | Large city-district (renewed) | Large city-district (renewed) | Green-urban | Urban pre-war |
| 4 | Ageing 'tuindorp' district | Ageing 'tuindorp' district | Centrum village | Urban after-war compact |
| 5 | Ring '20 – '40 | Ring '20 – '40 | Rural living | Urban after-war groundbased |
| 6 | Park district | Park district | | Green urban |
| 7 | Private house and garden | Private house and garden | | Centrum small urban |
| 8 | Low-maintenance low-rise | Low-maintenance low-rise | | Green small urban |
| 9 | Ageing porch district | Ageing porch district | | Small urban |
| 10 | Atrophied porch district | Atrophied porch district | | Centrum village |
| 11 | Recent high-rise district | Recent high-rise district | | Village |
| 12 | Recent low-rise family | Recent low-rise family district | | Rural accessible |
| 13 | Prosperous low-rise district | Prosperous low-rise district | | Rural peripheral |
| 14 | Central after-war terraced | Central early-after-war terraced | | |
| 15 | Average after-war district | Average after-war district | | |
| 16 | Remaining (mixed districts) | Remaining (mixed districts) | | |
| 17 | Recent districts 1980-1994 | Recent districts 1980-1994 | | |
| 18 | | Rural districts | | |
| 19 | | Newly build >1995 | | |

### *Hard typologies in the energy sector*

There are two known examples of using the living environment typology in research for the energy sector. The most known application in which the district typologies are applied are used in the 'Meeks district' [Lumig & Uytterhoeven, 2009]. The aim of that research was to construct model districts that could be used as a representative district in electricity network calculations. This approach led to 2 model districts, which were used to provide example calculations rather than calculations for the entire operating area. In this approach the 13 division of ABF Research was used (see Table 6).

The second example is a model of CE Delft in which districts are divided on the basis of building year and the degree of urban density [Rooijers, 2014]. It has been used to determine the impact of the energy transition on the provision of heat by natural gas, heat pumps, or district heating.

## 4.4 Description of applied model districts

Even though different typologies are constructed in the last 20 years, most of these stem from the same basis and the differences are only created by adjustments throughout the years. The distribution deemed most reliable and recent is those from ABF Research [1998]. The distribution of [Rooijers, 2014] can also be applied. However, the names of the districts in ABF are preferred by the client over the distribution of CE Delft. Both are possible, but the ABF distribution of 13 types is used in the remainder of this research. Future research is desirable on comparing possible differences between the two categorisation methods.

The operating area is thus divided into 13 types of districts. The types range from completely urban, to completely rural. The construction and definition of the 13 residential living environment typologies from ABF as used in this research are described in Table 7. Additional information is available at the publisher of the typology [ABF Research, 1998].

*Table 7: Description of living environment typologies.*

| Residential living environment typology | Description on categorising postal areas |
|---|---|
| **City (*most urban*)** | **Areas with at least 27.500 households are classified as cities** |
| 1. Centrum-urban Plus | Within the group of cities the 6 largest municipalities (Amsterdam, Rotterdam, The Hague, Utrecht, Eindhoven and Groningen) are a distinct group. These 6 municipalities have a special urban centrum which is not present in smaller cities |
| 2. Centrum-urban | This category contains centres of cities, but also a number of districts that are closely located just outside of the centre. Initially in each location of a city the centre postal code of the centre is determined first. Additionally a number of other districts is also classified as centrum-urban based on the distance to the city centre, the percentage of employment in the hotel and catering industry, merchandise and small businesses, the density, the presence of multi-family houses and the presence of (large)urban services (cinema, theatre, museum). |
| **City (outside-centre)** | **After distinguishing the city centres the remaining districts are categorised in urban districts and green-urban districts. Districts with a high density are classified as urban, while the low density districts are classified as green-urban** |
| 3. Urban <1940 | District constructed predominantly before the second World War, are classified as urban pre-war |
| 4. Urban >1940 compact | Districts constructed predominantly after the second World War, are distinguished in the category of districts with a large degree of multi-family houses (urban after war compact)… |
| 5. Urban >1940 groundbased | … and in districts with predominantly ground based dwellings (urban afterwar groundbased) |
| 6. Green-urban | Districts with a low density and relatively high degree of green provide the 6th type of classification. |
| **Small urban** | **Small cities are those areas with a) more than 13.000 households and a density of more than 20 dwelling per acre; b) more than 10.000 households and a density of more than 20 dwellings per acre, or with a percentage of multi-family houses large than 10%, or with a density of the centre with more than 20 dwellings per acre.** |
| 7. Centrum-small urban | This category contains centres of small cities. In each small urban area one postal code area is classified as centre. |
| 8. Green-small urban | Of the remaining small urban districts the districts with a low density and a large degree of green are classified as the 8th environment |
| 9. Small urban | The remaining districts are the small urban districts |
| **Village and rural (*most rural*)** | **The remaining districts are part of the villages and rural areas** |
| 10. Centrum-village | Within the villages a distinction is made with areas with a high degree of services… |
| 11. Village | …and areas with a relatively small degree of services. |
| 12. Rural accessible | The rural accessible areas are within 20 minutes travel distance from a centrum urban environment |
| 13. Rural peripheral | The rural peripheral areas have a travel distance from a centrum urban environment longer than 20 minutes. |

The build environment is thus divided by a hard typology based on the definitions as constructed by ABF Research. This makes use of the physical characteristics of the areas, like density, building types, and building periods. Additionally the environments are constructed by using the geographical criteria, using location of the environment in a city or in a region. Both physical and geographical criteria are thus included. Points of departure that are excluded from the classification are criteria categories stemming from the economic, social, or user perception and behaviour characteristics.

## 4.5 Theory on different building types

The living environment classification of ABF Research uses building type to construct the different categories, as shown by the 'compact' and 'groundbased' suffixes. However, the distribution of different types of buildings is not reported upon. Including the types of building in the living environment classification differentiates the districts on the electricity demand, heat demand, roof surfaces and other variables. Further specifying the living environments with the different types of buildings creates a better fit to the load profile of the districts.

This section therefore describes the different types of residential buildings in the building stock. Commercial buildings are not further specified by type due to the time constraint, and data limitations of this research. It is suggested that the diversification of the commercial building type is included in future research. The model districts are a combination of the living environment classification and the types of reference buildings (see Figure 22).

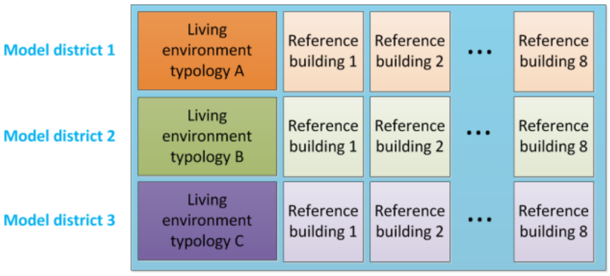



*Figure 22: Model districts are formed by a combination of living environment typologies and reference buildings.*

This section describes the reference buildings that can be used to represent the residential building stock. A literature review of the European reference buildings application is performed, after which the Dutch reference buildings are discussed. These reference buildings are the smallest building block of the analysis, and will be used to construct realistic and representative residential environment typologies for Dutch districts.

### 4.5.1 Literature review: reference buildings in Europe

Standard types of dwellings can be used for large scale prognoses of energy efficiency potential, housing stock analysis, or other large scale analysis in which grouping of houses is useful. Before 2008 these reference buildings, or model dwelling types, had only been defined in Germany and the Netherlands and to a lesser extent in Austria and the United Kingdom [Itard & Meijer, 2008]. Only in the Netherlands these model dwelling types have been used extensively for analysis in the residential building stock, especially for (costs) studies on energy efficiency.

The European Commission constructed an action plan for energy efficiency which emphasised the demand for energy efficiency and the potential for cost-effective energy savings in the build environment in combination with the “20-20-20 plan” [European Commission, 2011]. This led to a revision of the Directive for Energy Performance of Buildings (EPBD) 2010/31/EU by which member states are required to characterise the building stock and then establish reference buildings which represent the stock [Brandão de Vasconcelos et al., 2015]. This resulted in the construction of the EPISCOPE project (Energy Performance Indicator Tracking Schemes for the Continuous Optimisation of Refurbishment Processes in European Housing Stocks). The Directive resulted in a sharp increase in reference building construction for individual member states [BPIE, 2011; Brandão de Vasconcelos et al., 2015; Loga et al., 2012].

On the EU and international level several projects are started to define reference buildings. The Intelligent Energy Europe (IEE) programme started two major projects. The TABULA (Typology Approach for Building Stock Energy Assessment) created a uniform structure for European Building Typologies [Loga et al., 2012], and the ASIEPI (Assessment and Improvement of the EPBD Impact) tries to compare minimum energy performance requirements for reference buildings [ASIEPI, 2010]. Furthermore, the BPIE (Buildings Performance Institute Europe) reviewed the building stock of member states and the policies in place [BPIE, 2011]. An overview of different reference buildings in Europe is available at www.epsicope.eu.

### 4.5.2 Literature review: reference buildings in the Netherlands

The Dutch reference buildings have been developed by the Netherlands Enterprise Agency ("Rijksdienst voor Ondernemend Nederland") and the predecessors Agentschap NL and SenterNovem on the basis of an analysis existing representative buildings of the Dutch housing sector, which provide an extensive and complete overview of the building stock [Agentschap NL, 2011]. These standard types are used in (policy) studies on groups of dwellings.

The EPISCOPE project has led to a uniform classification of reference building types. It is the authors' expectation that this integration will become increasingly important for future deployment of reference buildings. Three variables are considered crucial by the TABULA, ASIEPI and BPIE projects for the construction of reference buildings, namely building function type, building location, and construction period [Brandão de Vasconcelos et al., 2015].

Since the climatic conditions in the Netherlands are roughly similar throughout the country the building location is deemed insignificant. The building function type and construction period should both be included. The Dutch residential building typology is often classified by single-family houses, terraced houses, multi-family houses and apartment blocks [Agentschap NL, 2011, 2013; Lumig & Uytterhoeven, 2009]. These categories are further specified (see below). The Dutch translation is included since translation is difficult to include due to the regional specifics of dwelling names

- Single-family house
    - Detached (*vrijstaand*)
    - Semi-detached (*twee-onder-één-kap*)
- Terraced house (*rijwoning*)
    - Middle row (*tussenwoning*)
    - End house (*hoekwoning*)
- Multi-family house
    - Apartment block
        - Common staircase and galleries (*galerijflat*)
        - Common staircase, no galleries (*portiekflat*)
        - Maisonettes (*maisonetteflat*)
    - Other apartments

These reference buildings are representative for the Dutch housing stock. Indicative pictures of each type of building are included in Figure 24. Dividing the residential area into the reference building class results in 26% of single-family houses, 42% of terraced houses, and 32% of multi-family houses [CBS, 2013b]. Additional division into a lower aggregation level of reference buildings is presented in Figure 23, but for the category of terraced houses no additional subdivision data is available. Most of the building stock is relatively old, with 39% constructed before 1964, 19% between 1965 – 1974, 26% between 1975 – 1991, and 16% between 1992 – 2005 [Agentschap NL, 2011].

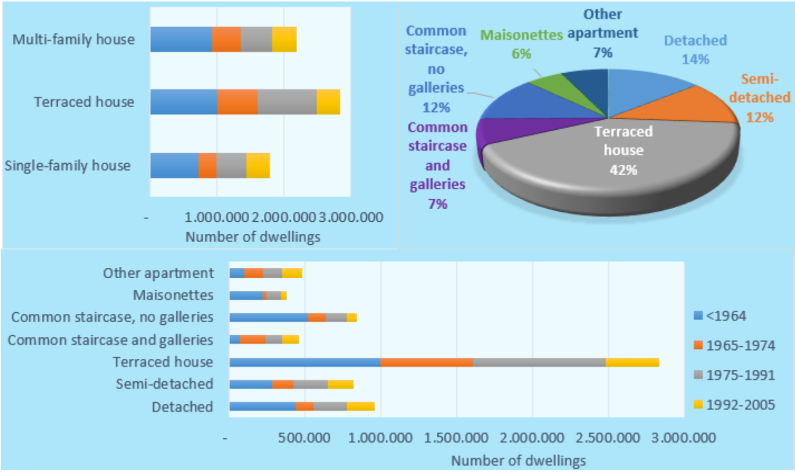



*Figure 23: Distribution of reference buildings in the Netherlands. Data sources: [Agentschap NL, 2011, 2013].*

### 4.5.3 Reference buildings to specify living environments

As described, different reference buildings can be distinguished based on the aggregation level of interest. The purpose of further dividing the living environments is to create a larger differentiation between the environments in order to determine the electricity and heat demand, and the deployment rates of PV and heat pumps. The electricity and heat demands are reported for the reference buildings detached, semi-detached, terraced dwelling, common staircase and galleries, Common staircase no galleries, maisonette and other apartments by [Agentschap NL, 2011]. Other research also uses these types to indicate the available roof surface on which PV can be applied [PBL & DNV GL, 2014], and the technical potential of heat pumps [DHPA, 2013]. Therefore these types of residential buildings are used to further specify the living environments in chapter 6.

## 4.6 Conclusion

The approach of this research is to determine the residential living environment for each PC4 area by using the 13 typologies of ABF. However, the typologies are constructed with a focus on residential buildings. This means commercial buildings are included, but without diversification on the type of commercial buildings. In chapter 6 the number of residential and commercial buildings are therefore determined for each residential living environment typology, which results in the model districts. However, there is no classification included for predominantly commercial building areas since the PC4 areas include multiple district types within which the business parks are too small to identify individually.

Besides the number of buildings the area size of use is the PC4 area. This creates less homogeneity within the area since multiple living environment typologies could apply within the smaller districts. Additionally, the model districts are provided with electricity by certain MV/LV-transformers. The transformers are located within a certain PC4 area, and are assumed to provide electricity to consumers within that PC4 area. However, in reality the connected users can also be located in a different PC4 area. Since the average number of transformers is approximately 30 per PC4 area (see chapter 7), the differences are expected to be small. We return to this point in the discussion in chapter 9.


*Figure 24: Overview of real building related to the reference building types in the Netherlands. Source: [Agentschap NL, 2011].*

Overall, the operating area is segmented by using 13 different living environment typologies, ranging from urban to rural districts. Research about the socio-demographic variables influencing deployment rates of renewable energy technologies, and characterising districts are lacking in the scientific literature. Therefore the analysis is performed by using physical characteristics of districts. Since the demographic and structural data about the districts is not available on PC6 or PC5 areas, the district size is determined by the PC4 areas. This will result in less diversified model districts.

# 5. Future energy scenarios

In the previous chapter the model districts have been defined by using 13 different types of living environments, 7 types of residential buildings, and 1 type of commercial building. This provides merely physical model districts that can be used to divide the operating area. However, the quantification of the net-energy demand[15] of the districts requires additional information about the consumption patterns and technologies of the connected users.

This chapter focusses on the future energy scenarios that can be used to explore the different pathways that the energy system might follow in the future. To do this a literature review is performed on different theoretical types and practical examples of scenarios for the energy sector. The scenarios need to be in the boundaries as determined earlier, meaning applicable to a long-term time period (outlook to 2040), sufficiently detailed for regional differentiation, include PV and heat pumps, and allow to be coupled to the model districts and reference buildings of the previous chapter.

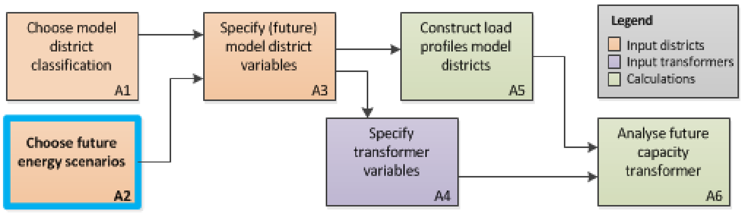



*Figure 25: Overview general approach of this research. This chapter focusses on the future energy scenarios.*

The theoretic foundations on construction of scenarios are briefly discussed in section 5.1, after which a select few existing scenarios that are within the boundaries as prescribed are described in 5.2. The qualitative description of the chosen scenarios is included in section 5.3, after which the quantitative description for the Netherlands (5.4), and for the operating area of Stedin (5.5) are included. These scenarios form the basis for the specification of the model district variables for determining the load profiles and peak demands.

## 5.1 Theory on scenario construction

Scenarios are used to explore the future through deploying what-if analysis with a number of internally consistent feasible futures [Chappin, 2011]. The most applied method is to describe the current conditions and then extrapolate expectancies for the future conditions. Scenario construction is a (group) process to determine the key issues in the external and internal environment of the topic of interest. Many different approaches for construction of energy scenarios can be identified (see Figure 26), and these approaches can also be combined.

[15] The prefix 'net-' is used to identify the overall energy or electricity demand of a specific region, combining all electricity demands and supplies of the connected users in that region. If the net-electricity demand is negative this means that there is actually an electricity supply in the district.

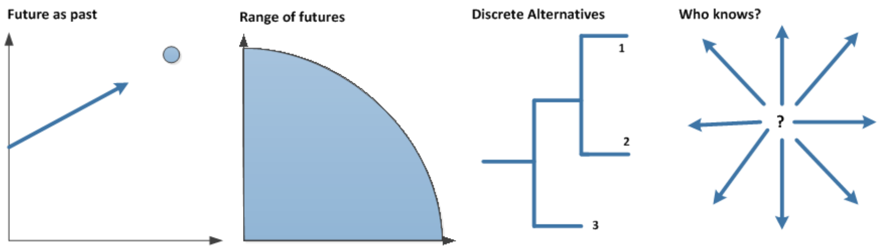



*Figure 26: Different approaches for construction of future energy scenarios. Additional background information is provided in [Mai, Logan, Blair, Sullivan, & Bazilian, 2013]*

Both qualitative and quantitative methods are deployed in scenario analysis [Mai et al., 2013]. The qualitative scenarios are often narratives of social, technological and economic trends, while quantitative scenarios typically use spreadsheets with static relationships between parameters with limited mathematical formulation [Chappin, 2011]. Additional information about differences in constructing and using scenarios can be found in [Mai et al., 2013], and a widely applied methodology for constructing scenarios is described in [Schwartz, 1996]. This methodology involves the following steps:

- Start by identifying a focal issue, starting with a specific decision and expanding this view.
- Determine the key forces in the local environment (micro-environment).
- Identify the driving forces (macro-environment). These are the major trends in the macro-environment on the social, political, environmental, economic, and technological aspects.
- Categorise the key forces and driving forces on importance and uncertainty.
- Create a scenario narrative based on combinations of only a few scenario drivers.
- Expand the scenario narrative by including all key forces and driving forces.
- Determine the implications by returning to the focal issue and think about the vulnerabilities, robustness, and improvements.
- Select the leading indicators that allow to follow the developments in reality. By monitoring these indicators and coupling them to the scenarios the market developments can be followed and the (at that time) most applicable scenario is known.

Analysing this process reveals that the focal issue is of main importance. The focal issue depends on the point of view of the developer, which is most likely influenced by the activities that are performed by the actor. Scenarios are therefore always perception dependent.

## 5.2 Overview of existing future energy scenarios

The energy system is a socio-technical system consisting of technology and stakeholders, and operating under uncertainties of the economy, social believes, and technological developments. Many different variables that influence the development of the future energy system can therefore be identified. Due to the qualitative manner of the initial construction of future energy scenarios (with the social believes of the developer, influenced by the point of view on the energy sector) in which the developer works or for whom the scenarios are being constructed, the focal issue needs to coalign for effective use of the scenarios.

Therefore it is not surprising to see that a multitude of scenarios have been constructed. A select few have been chosen which align best with this research, and these are described to identify the main differences on PV and heat pump deployment (see Table 8).

The Nationale Energieverkenning [2014] is deployed to provide a factual overview of the Dutch energy system in order to allow policy makers to use this information as a starting point. Two policy projections up until the year 2030 are deployed: a scenario for 'current policy' extrapolation, and a scenario for 'expected policy'. The focus of these scenarios are on the developments of the macro-environment, and since this was the first report the scenario description is more qualitative than quantitative.

Multiple studies have been performed by Dutch actors in the energy sector, for which Laborelec [2012] performed an analysis to identify the similarities and differences of 7 studies. All studies use a best and worst case situation in which PV and/or heat pump deployment is either 0% or 100%. Studies are performed by the organisations of Stedin, Rendo, Enexis, Nuon, and Laborelec. The data is, however, not readily available due to confidentiality of the specific numbers. Exception is the Stedin investigation, but the focus point of this research lies on the electric vehicle developments.

A third set of scenarios are provided by Ecofys [2014] which are used to investigate the influence of smart grid solutions in the distribution grid by deploying two case studies. These cases studies are based on two districts that are classified as 'green-small urban' and 'urban accessible' with the same definition as used in chapter 4. Again, the data source is confidential and not reported upon in detail, while also excluding the commercial buildings.

The final set of scenarios to be discussed are the Eneco [2015] scenarios that are constructed by using macro-economic developments as the main driving force. A total of 191 variables are quantified for three scenarios during the time period between 2020 and 2050. This includes a differentiation between residential and commercial variables, and the data is readily available at the client.

*Table 8: Different deployment rates for PV and heat pumps in future energy scenarios*

| Research | PV | Heat pumps | Assumptions/ comments |
|---|---|---|---|
| [Nationale Energieverkenning, 2014] | 49,9 PJ in 2030 | 26,3 PJ in 2030 | Based on current and intended policy in the Netherlands |
| [Laborelec, 2012] | 0,6 – 5,3 $kW_p$/dwelling in 2030 | 0,7 – 10 kVA/dwelling in 2030 | Overview multiple studies with extremes |
| [Eneco, 2015] | 1,38 – 6,72 $kW_p$/dwelling in 2040.<br>1,07 – 8,34 $kW_p$/small company in 2040. | 175 – 1454 kWh/dwelling in 2040.<br>601 – 3400 kWh/small company in 2040. | Based on expected economic growth rates. |
| [Ecofys, 2014] | 1,6 / 2,5 $kW_p$/dwelling in 2030/2050 | 10 / 35% dwellings with heat pump in 2030/2050 | Only investigates residential buildings. |

The public sources for the scenario descriptions do not include all information required to transpose the numbers into different units. Additionally it has been observed that many of the studies do not include commercial buildings in the research, or do not report on the numbers used in the scenarios. That information is, however, available at the Eneco scenarios. Also the focal point is based on the development of plausible scenarios rather than extreme types of scenarios. This aligns with the aim of this research to determine the impact of the energy transition on different regions in the operating area. Therefore it has been decided, in consultation with the client, to use the Eneco scenarios for the remainder of this research. During the verification/validation (Appendix F) the final results are compared with the other researches to determine deviations when deploying a different set of scenarios.

## 5.3 Qualitative description scenarios

The previous section briefly described the future energy scenarios of Eneco, which are used in the organisation of Stedin, and chosen as the research scenarios of interest. This section describes the storyline of each of the three scenarios in a qualitative manner. There are three pathways included in the scenarios, named **Paces**, **Tides** and **Circles**[16]. The main driving force are the economic developments, followed by interconnected developments in key parameters. The scenarios are a combination of the 'Discrete alternatives' and 'Who knows?' scenario types (see paragraph 5.1). The descriptions and figures are adapted from several internal documents in the organisations of Stedin and Eneco.

### 5.3.1 Economic developments in scenarios

Initial starting point of the scenarios is the speed of economic developments on the worldwide scale. The first scenario (**Paces**) assumes a world of two **Paces**, in which Europe stays behind and remains in a long-lasting recession, while the economic growth in the rest of the world speeds up. The exploitation of shale gas[17] in Southern-Europe is the turning point that initiates the renewed growth of the European economy.

Global volatility and cyclic movements are the key in the **Tides** scenario. After an initial recovery of the world economy, the collapse of the Chinese financial system is the beginning of another deep recession. Partially caused by the clean coal technology an unusual economic revitalisation is abruptly ended by a fossil fuel crisis.

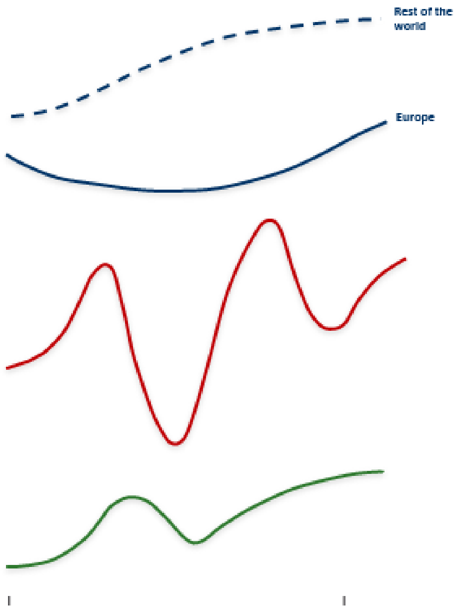


*Figure 27: Economic developments as assumed in the three Eneco scenarios.*

The fast expansion of renewable energy technologies creates a world of abundance in the **Circles** scenario, in which worldwide shortages of water and food disappear. This causes a steady growth of a mainly virtual world economy that is only interrupted by the definitive downfall of companies from the old economic paradigm.

### 5.3.2 Key parameters in scenarios

The key parameters are further specified while keeping in mind the assumptions about the development of the economy. This involves the scenario construction step that expands the scenario narrative by including all key forces and driving forces. The main results are included in Table 9.

[16] In the remainder of this research this colouring code is used when referring to the scenarios.
[17] Shale gas is a natural gas that is located in porous rock formations. In recent years there has been an uptake in the production volume of shale gas, especially in the United States.

Table 9: Interconnected key parameters as assumed in the Eneco scenarios

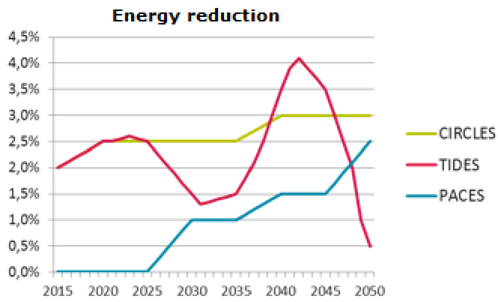
| Dimension | Paces | Tides | Circles |
|---|---|---|---|
| Character | Europe in recession, global strong growth | Cyclic economic growth | World of abundance without scarcity |
| Worldview in Europe | Recovery, survival | Liberal paternalism | Cooperative and sustainable |
| Economic growth EU | Slow | Changing | Large |
| Orientation in Europe | Fragmentation and nationalism | Europe follows global growth and stagnation | No boundaries |
| Technological innovation EU | Unable to match global economic growth | On specific markets only | Disrupted established systems |
| Energy sources | Growth of new fossil fuels | Old fossil fuels dominate | Renewable energy flourishes |
| Scarcity | Energy, food and water | Acute shortages during economic booms | No scarcity |
| Role government | Strong national | Retreating | Virtual and local |

## 5.4 Quantitative description scenarios - The Netherlands

Based on the narrative of the three scenarios the main variables are quantified. The most important variables for this research are briefly explained, namely the residential and commercial energy reduction, electricity demand, heat pumps, and installed PV capacity. Other variables (a total of 191) are included in Appendix B (page 134). This version of the scenarios are of May 2015.

### *Energy reduction residential/commercial*

The worldviews with economic prosperity result in a higher replacement rate of old electrical appliances for newer and more efficient appliances. In **Paces** the lack of spending power causes a delay of energy-efficient appliances and the energy bill is responsible for a large portion of total spending's. This results in a gradual increase in efforts to achieve energy reductions.




### *Electricity demand residential*

The electricity demand of household appliances includes household appliances but excludes electrical appliances related to heating or mobility demands. It is based on the correlation between economic growths, with the reduction in demand due to electricity reductions. The figure indicates the total electricity demand of residential buildings in the Netherlands.

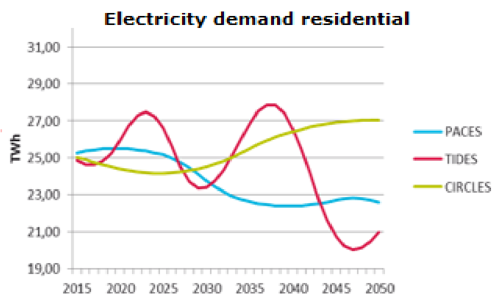



*Figure 28: (**top**) Energy reduction for the entire demand in the Netherlands, including residential and commercial buildings. (**bottom**) Residential electricity demand*

### *Residential heat pumps*

In the **Circles** scenario the number of heat pumps in being applied for the provision of heat quickly increases as a result of diminishing investment costs as well as the reduced costs of electricity. The cost-effectiveness of residential heat pumps increases in the **Circles** scenario due to its deployment to reduce peaks and valleys in the electricity production.

### *Commercial heat pumps*

Similar to the residential heat pumps, the commercial heat pumps increase significantly in the **Circles** scenarios due to increasing cost-effectiveness.

### *Installed PV capacity*

In **Circles** the exponential growth of installed PV capacity continues to hold on in the coming years due to a continuing decline in investment costs. The efficiency of solar panels continues to be improved in all scenarios. An average solar panel in 2015 had an efficiency of 16%, which in 2040 increases untill 27% in **Paces**, 29% in **Tides**, and 40% in **Circles**. After 2025 mobile PV is expected to increase and provide a part of the electricity demand of appliances which are not connected to the electricity network.

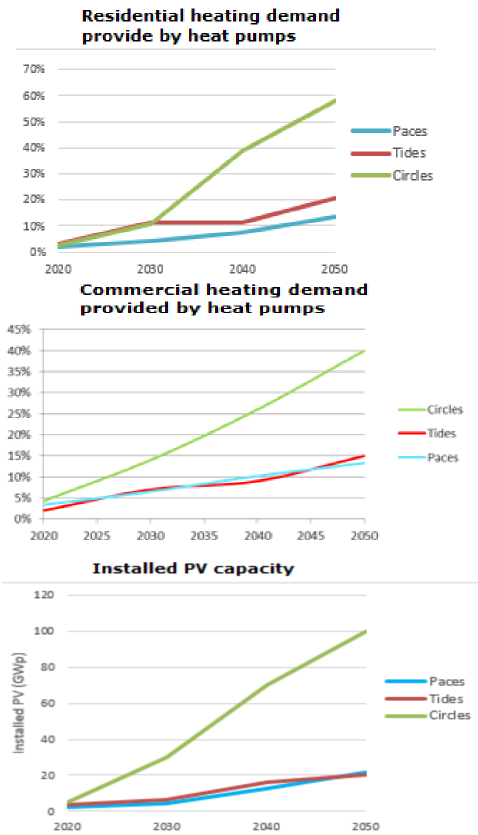



*Figure 29: Heat pump and PV deployments in the Netherlands until the year 2050.*

## 5.5 Quantitative description scenarios - Operating area

The numbers as specified in the national scenarios have been transposed into specific number for the operating area of Stedin. The national numbers are linearly transposed on the basis of number of residential and commercial buildings. In Table 10 the main variables for the residential and commercial connections in the operating area of the client are included.

*Table 10: Future energy scenarios operating area Stedin. Transposed from the national scenarios of Eneco. Version of May 2015.*

| STEDIN.NET | | | Reference | Paces | | | | Tides | | | | Circles | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 2012 | 2020 | 2030 | 2040 | 2050 | 2020 | 2030 | 2040 | 2050 | 2020 | 2030 | 2040 | 2050 |
| Residential | | | | | | | | | | | | | | | |
| **Demographics** | Residential connections | # mln | 1,85 | 1,96 | 2,06 | 2,09 | 2,09 | 1,96 | 2,06 | 2,09 | 2,09 | 1,96 | 2,06 | 2,09 | 2,09 |
| **Electricity demand** | Total electricity demand appliances | TWh | 5,9 | 6,14 | 5,26 | 5,31 | 5,73 | 6,52 | 6,27 | 6,57 | 6,62 | 5,73 | 5,80 | 6,22 | 6,81 |
| **Gas demand** | Total gas demand (heating) | mln m3 | 2710 | 2.619 | 2.501 | 2.296 | 1.969 | 2.725 | 2.800 | 2.756 | 2.526 | 2.836 | 2.893 | 2.478 | 982 |
| | Total gas demand (heating) | TWh | 26,47 | 25,58 | 24,43 | 22,43 | 19,24 | 26,62 | 27,35 | 26,92 | 24,68 | 27,71 | 28,26 | 24,21 | 9,60 |
| | Gas connections | # mln | 1,84 | 1,95 | 2,02 | 2,00 | 1,85 | 1,93 | 1,92 | 1,95 | 1,72 | 1,93 | 1,90 | 1,43 | 1,02 |
| **Heat pumps** | Heat pumps | #x1000 | 20 | 49 | 128 | 185 | 274 | 71 | 286 | 286 | 420 | 62 | 254 | 806 | 1.121 |
| | of which hybric | #x1000 | 10 | 35 | 92 | 92 | 32 | 35 | 143 | 143 | 50 | 35 | 92 | 149 | 52 |
| | of which full electric | #x1000 | 10 | 14 | 36 | 93 | 242 | 35 | 143 | 143 | 370 | 26 | 162 | 657 | 1.069 |
| | Total electricity demand heat pumps | TWh | 0,04 | 0,07 | 0,18 | 0,36 | 0,77 | 0,16 | 0,64 | 0,64 | 1,42 | 0,13 | 0,76 | 3,04 | 4,96 |
| **PV** | Connections with PV | #x1000 | 74 | 111 | 166 | 412 | 610 | 177 | 240 | 507 | 554 | 222 | 915 | 1.755 | 1.848 |
| | Total installed PV capacity | GWp | 0,22 | 0,55 | 1,00 | 2,88 | 4,88 | 0,89 | 1,44 | 3,55 | 4,43 | 1,11 | 6,40 | 14,04 | 18,48 |
| | Total generated electricity PV | TWh | 0,19 | 0,47 | 0,85 | 2,45 | 4,15 | 0,75 | 1,22 | 3,02 | 3,77 | 0,94 | 5,44 | 11,94 | 15,70 |
| Commercial | | | | | | | | | | | | | | | |
| **Demographics** | Small commercial connections | #x1000 | 158 | 159 | 150 | 176 | 227 | 192 | 211 | 265 | 275 | 177 | 218 | 277 | 338 |
| **Electricity demand** | Average electricity demand | Mwh | 20 | 20,00 | 19,42 | 17,39 | 15,55 | 18,27 | 14,02 | 13,52 | 10,14 | 17,68 | 14,51 | 12,77 | 11,44 |
| | Total electricity demand | TWh | 3,2 | 3,18 | 2,92 | 3,05 | 3,53 | 3,51 | 2,95 | 3,59 | 2,78 | 3,13 | 3,17 | 3,53 | 3,87 |
| **Gas demand** | Total gas demand (heating) | TWh | 13 | 11,42 | 7,90 | 7,44 | 7,94 | 14,35 | 11,43 | 11,47 | 10,78 | 10,67 | 9,09 | 8,49 | 7,09 |
| | Average gas demand per connection | MWh | 80,6 | 71,88 | 52,52 | 42,37 | 34,94 | 74,68 | 54,31 | 43,26 | 39,24 | 60,29 | 41,64 | 30,67 | 20,96 |
| | Average gas demand per connection | M3 | 8251 | 7358 | 5376 | 4337 | 3576 | 7644 | 5560 | 4428 | 4017 | 6171 | 4262 | 3140 | 2145 |
| **Heat pumps** | Heat pumps | #x1000 | 18 | 30 | 41 | 69 | 108 | 18 | 69 | 91 | 163 | 35 | 122 | 257 | 454 |
| | Total electricity demand heat pumps | TWh | 0,3 | 0,49 | 0,80 | 1,26 | 1,86 | 0,32 | 1,12 | 1,50 | 2,53 | 0,60 | 1,97 | 3,91 | 6,59 |
| **PV** | Connections with PV | #x1000 | 0,89 | 1,33 | 2,00 | 4,95 | 7,32 | 2,13 | 2,89 | 6,09 | 6,66 | 2,66 | 15,22 | 43,28 | 66,58 |
| | Installed capacity PV | GWp | 0,02 | 0,04 | 0,08 | 0,23 | 0,39 | 0,07 | 0,12 | 0,28 | 0,36 | 0,09 | 0,71 | 2,31 | 4,44 |
| | Total generated electricity PV | TWh | 0,02 | 0,04 | 0,07 | 0,20 | 0,33 | 0,06 | 0,10 | 0,24 | 0,30 | 0,08 | 0,60 | 1,96 | 3,77 |

## 5.6 Conclusion

In this chapter the theoretical types of scenarios are briefly discussed, followed by a description of multiple scenarios currently in use. Important notion is the focal point that is used in the development of the scenarios, which is developer dependent due to the qualitative nature and uncertainty of the future developments. Thus, the aim and purpose of the scenario construction need to coalign with the aim of the research.

While many scenarios are available, only few have the same focus and starting point. However, the main difficulty is the data acquisition of the scenarios which is often not possible due to confidentiality. A possible explanation for this sensitivity of the figures are the required assumptions about the market developments, which is related to the policy or strategy of an institution and therefore sensitive for the eyes of the competitors. However, the internally developed future energy scenarios of Eneco and Stedin are readily available. The discrete and explorative national future energy scenarios of Eneco are converted into the scenarios for the operating area of the client.

In the previous chapters several boundaries have been discussed that need to apply on the scenarios. The PV and heat pump deployment rates are specified for the outlook until 2050 with 10 year intervals. Most variables are coupled to the number of (residential and commercial) buildings and can therefore be coupled to the individual model districts and reference buildings. However, the differentiation for the regional differences in e.g. PV and heat pump deployment rates, or electricity demand for different locations, are not specified in the scenarios.

In the chapter that follows, the variables as specified in the future energy scenarios of the operating area of the client are divided between the different model districts. Additional information is required about the differentiation between the 7 reference buildings since this data is not included in the scenarios.

# 6. Specification model districts

The categories of the model districts and the types of reference buildings are defined in chapter 4, and the previous chapter discussed the future energy scenarios for the exploration of future developments in the operating area. These scenarios are mostly diversified by using the number of buildings, and thus allows for a differentiation over the model districts, which is the aim for this chapter. Information about the differences for PV and heat pump deployment, and heat and electricity demands between the reference buildings is still lacking.

Therefore, in this chapter each postal code area (PC4) is categorised with the appropriate model district from chapter 4 to divide the operating area. Also, the deployment rates of PV and heat pumps as specified in the future energy scenarios (chapter 5) for the operating area are converted into deployment rates per model district. Specific analysis are performed to determine the technical potential of heat pumps, and PV deployment per reference building. Therefore the total number of residential and commercial buildings are determined first for each model district, after which the distribution of reference buildings within each district is determined.

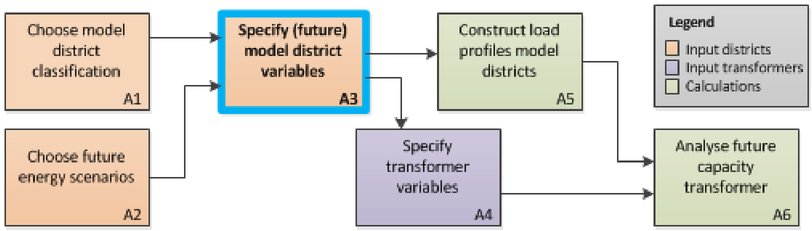



*Figure 30: Overview general approach of this research. This chapter focusses on the specification of the model district variables.*

This chapter thus starts with dividing the operating area into model districts, and determining the number and types of buildings within each model district (6.1). In section 6.2 the load profiles are used to determine the basic electricity demand of appliances and lighting, the electricity demand of heat pumps, and the PV supply for an individual connection or installation. By combining the load profiles with the annual demand, or supply, and with the number of residential and commercial buildings, the net-electricity demand per district can be determined. This chapter provides a brief description of the most important elements, and additional background can be found in Appendix A and Appendix B.

## 6.1 Dividing the operating area into model districts

### 6.1.1 Distribution of living environments in operating area

The model districts from chapter 4 are used to divide the operating area into model district types. To determine the postal codes that are operated by Stedin the location (or postal codes) of the distribution transformers are used. Each postal code in which a transformer of the client is located is considered a region operated by Stedin. Since the postal codes are relatively large, there will be certain areas at the edge of the operating area of which a small part is actually outside of the operating area. Due to the large number of PC4 areas, namely 668 PC4 areas, the influence of this assumption is expected to be small. Thus, for each postal code (4 digit) in the operating area the living environment typology has been set by using all PC4 areas in which transformers are located, and classify each PC4 area with the living environment that accompanies it according to the data of ABF Research (see Figure 31).

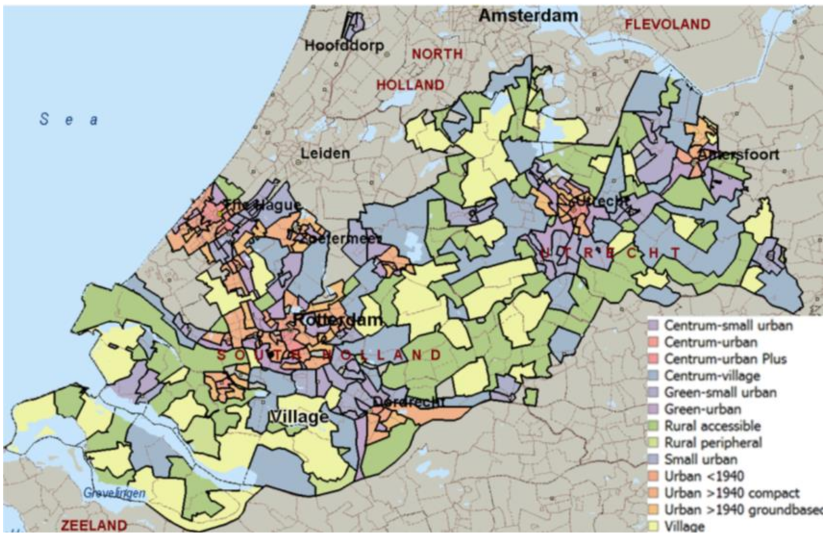



*Figure 31: Distribution of model districts in the operating area of Stedin. The grey lines demarcate the four digit postal code areas, and the coloured parts are operated by the client.*

The operating area of Stedin for the electricity network is located in the provinces of North-Holland, South-Holland and Utrecht. The rural accessible (17%), urban >1940 compact (14%), small urban (13%) and centrum-village (13%) model districts are most present in the operating area, and when combined represent 57% of the entire area (see Table 11).

The Central Bureau for Statistics (CBS) in the Netherlands reports on the number of residential and commercial buildings, as well as other demographic variables. By using the PC4 code the living environment data is coupled to the CBS data. An overview of the living environments, residential buildings and commercial buildings in the operating area is provided in Table 11. The operating region consists of 668 PC4 areas, while the Netherlands has a total of 3.865 PC4 areas [CBS, 2013b], meaning that 17% of all the PC4 areas are operated by Stedin. When looking at the buildings, the operating area consists of 2.039.098 buildings, while there are a total of 8.539.005 buildings in the Netherlands [CBS, 2013b][18], meaning that 24% of the buildings in the Netherlands are operated by Stedin. The total number of small consumer connections in the operating area of Stedin was 1.992.033 in 2013 [Stedin Netbeheer B.V., 2014]. This is slightly lower than the total number of buildings provided by the CBS, which can be explained by the fact that certain buildings do not have an electricity connection.

Overall it can be concluded that the current division of buildings in the operating area by means of the living environments on the PC4 area is accurate when considered for the entire operating area. Also the number of buildings is similar to the number of small consumer connections. This is already the first validation of the approach, concluding that the number of buildings as obtained by the CBS data combine to nearly the same number of small user connections in the operating area of Stedin, in which the CBS data adds up to a 2% larger building stock than the registered number of connections.

[18] The number in of buildings provided by the CBS exclude the buildings in the sectors of government, education and healthcare due to uncertainty in the numbers, which means the actual numbers are slightly higher, but the distribution is likely to remain the same.

*Table 11: Overview of living environment distributions in the operating area*

| Living environment | Number in operating area | Distribution in operating area | Residential buildings | Distribution residential buildings | Commercial buildings | Distribution commercial buildings |
|---|---|---|---|---|---|---|
| Centrum-urban Plus | 29 | 4% | 115.743 | 6% | 15.215 | 10% |
| Centrum-urban | 9 | 1% | 44.523 | 2% | 4.903 | 3% |
| Urban <1940 | 48 | 7% | 203.358 | 11% | 14.453 | 9% |
| Urban >1940 compact | 93 | 14% | 423.699 | 23% | 21.463 | 14% |
| Urban >1940 groundbased | 45 | 7% | 179.858 | 10% | 12.940 | 8% |
| Green-urban | 46 | 7% | 76.393 | 4% | 8.605 | 5% |
| Centrum-small urban | 26 | 4% | 91.488 | 5% | 8.828 | 6% |
| Small urban | 87 | 13% | 261.361 | 14% | 19.223 | 12% |
| Green-small urban | 32 | 5% | 57.194 | 3% | 6.113 | 4% |
| Centrum-village | 84 | 13% | 277.286 | 15% | 26.150 | 17% |
| Village | 50 | 7% | 95.947 | 5% | 10.238 | 6% |
| Rural accessible | 114 | 17% | 53.724 | 3% | 7.330 | 5% |
| Rural peripheral | 2 | 0,3% | 1.004 | 0,1% | 98 | 0,1% |
| *No data available* | *3* | *0,4%* | *#N/A* | *#N/A* | *1.965* | *1%* |
| **Total sum** | **668** | **100,0%** | **1.881.578** | **100,0%** | **157.520** | **100,0%** |

## 6.1.2 Number of buildings in each model district

The next step is to determine the number of residential and commercial buildings in each model district. The current distribution of residential and commercial buildings is analysed by grouping the living environment categories together. The rural peripheral typology has been excluded since the dataset is too small, resulting in a loss of 0.3% of the PC4 areas in the entire operating area.

***Residential buildings***

It can be observed that the number of dwellings are rather dispersed for the PC4 areas within each living environment category (see Figure 32). Some of the living environments are nearly normally distributed, while others show clear peaks in the distribution (e.g. green-urban). In general there are either one or two peaks within the distributions. Therefore each typology class is divided into either one peak or two peaks, depending on the shape of the histogram. Two peaks are identified at 6 living environment histogram: urban <1940, urban >1940 groundbased, green-urban, centrum-small urban, small urban and green-small urban typologies.

The aim of this research is to create model districts that are representative for the operating area. Using the average number of buildings results in average districts, but as observed with for example the green-urban typology, using the average can be misleading. Therefore for each peak area the mode is determined. For example, the histogram for the PC4 areas classified with the urban <1940 living environment is split into two parts; those PC4 areas with less than 5000 residential buildings and those with more than 5000 residential buildings. Next the modes of the two areas are determined, resulting in a mode of 4250 for the first peak area, and a mode of 5750 residential buildings in the second peak area. A more elaborate explanation per living environment type is included in Appendix A.4.

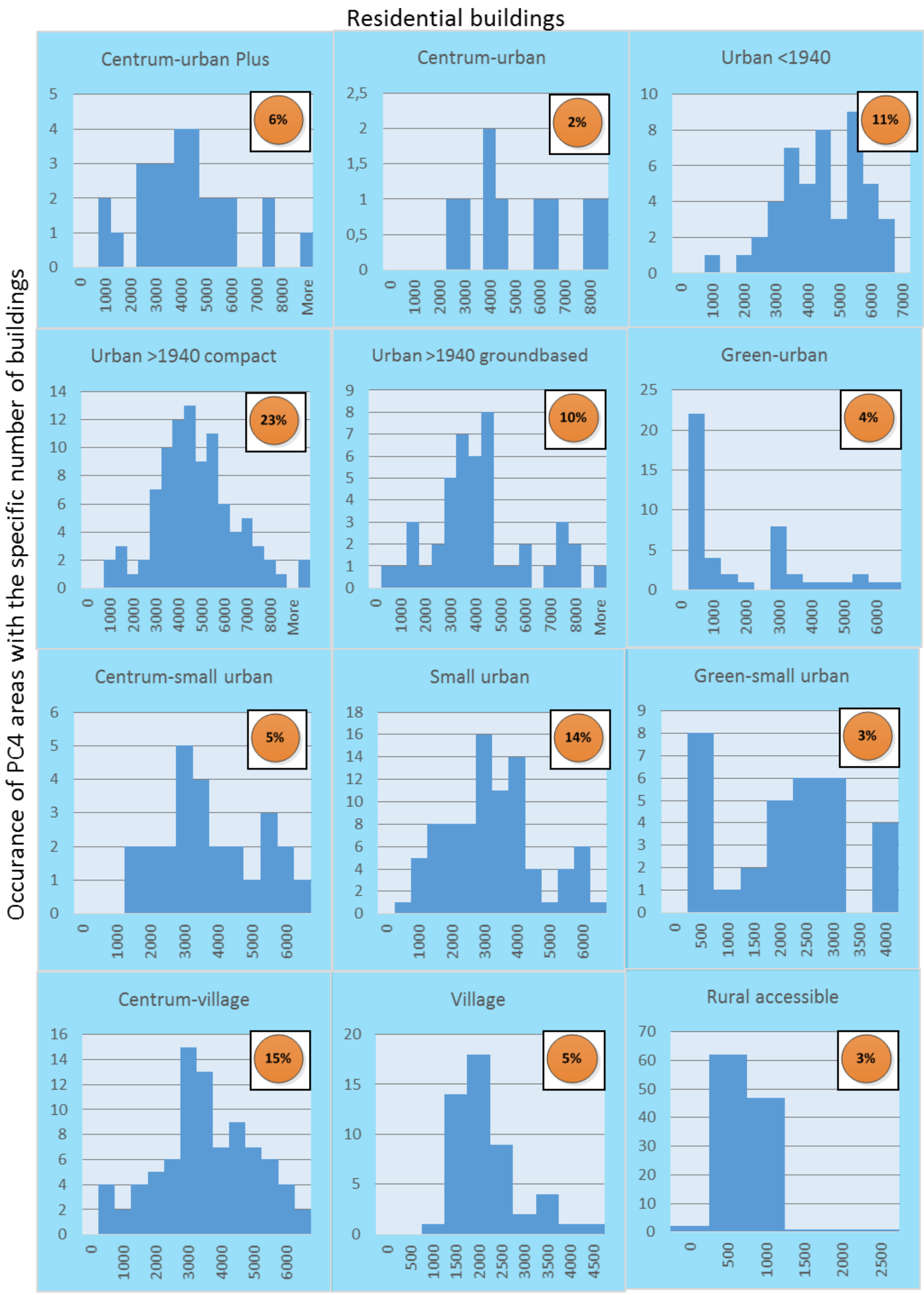



*Figure 32: Histograms of the number of residential buildings per postal code area classified with a particular living environment. Constructed with fixed bin sizes of 500, ranging from 0 until 9000 buildings. In case there are more than 9000 buildings the area falls into the 'more' category. Only the bins with at least 1 value are included. The top right circles indicate the percentage of residential buildings of the entire operating area that are located in that living environment.*

### *Commercial buildings*

Histograms are also constructed for the commercial buildings distribution, and these are included in the appendix on page 123. The number of residential buildings per model district have already been set. Since there can be a correlation between the number of residential and commercial building within a specific region, the dataset of the commercial buildings is split in accordance with the peak areas of the residential buildings. Two histograms are constructed, one for each peak, after which the number of commercial buildings is determined by using the average, or the mode, depending on the distribution.

For example, the number of residential buildings in al PC4 areas classified as urban <1940 environments, with less than 5000 residential buildings are the first group to analyse the number of commercial buildings (left side picture in Figure 33). The same is done for the PC4 areas with more than 5000 residential buildings (right side). Although the distribution is different, there is no general relation between the number of commercial buildings and the number of residential buildings within this living environment category. The number of commercial buildings in each of the two distributions is therefore set to 340 commercial buildings.

The same approach is deployed for the living environments with two peaks in the number of residential buildings, while for the environments with one peak the dataset has not been split, and either the average or the mode of the dataset are used for the number of commercial buildings. Additional information about these procedures are included in Appendix A.4. The number of buildings within a PC4 area can be as low as 13 or as high as 11.000. This is a large spread, which could be related to the large size of the PC4 areas, which is further discussed in chapter 9.

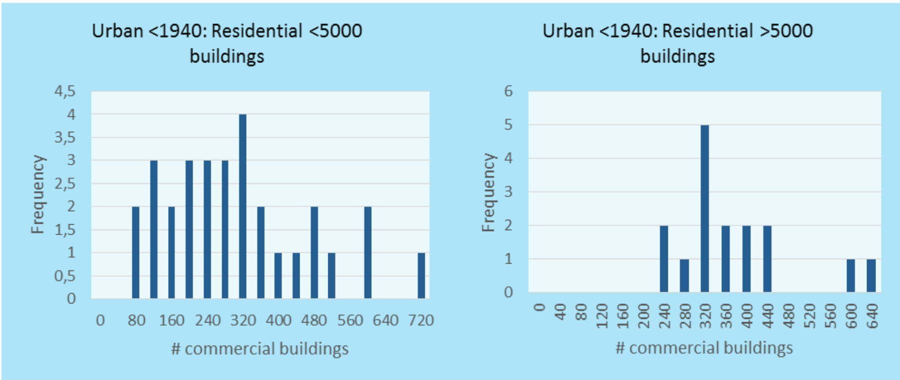



*Figure 33: Number of commercial buildings for PC4 areas classified with peak 1 (left) of the residential buildings, or peak 2 (right) of the residential buildings for the living environment Urban <1940.*

### Conclusion

Overall there are now 12 model districts, with 6 model districts that have two values for the number of buildings, resulting in 18 model districts. The number of residential and commercial buildings per model district are provided in Table 12.

*Table 12: Number of residential and commercial buildings per model district. The ratio is determined by dividing the number of commercial buildings by the number of residential buildings, indicating the number of commercial buildings per residential building.*

| Nr. | Model district | Number in operating area | Number of residential buildings | Number of commercial buildings | Ratio commercial and residential buildings |
|---|---|---|---|---|---|
| 1 | Centrum-urban Plus | 29 | 4250 | 580 | 0,14 |
| 2 | Centrum-urban | 9 | 4250 | 497 | 0,12 |
| 3 | Urban <1940 - Peak 1 | 29 | 4250 | 340 | 0,08 |
| 4 | Urban <1940 - Peak 2 | 19 | 5750 | 340 | 0,06 |
| 5 | Urban >1940 compact | 93 | 4750 | 340 | 0,07 |
| 6 | Urban >1940 groundbased - Peak 1 | 38 | 4750 | 260 | 0,05 |
| 7 | Urban >1940 groundbased - Peak 2 | 7 | 7750 | 501 | 0,06 |
| 8 | Green urban - Peak 1 | 29 | 750 | 140 | 0,19 |
| 9 | Green urban - Peak 2 | 17 | 3250 | 378 | 0,12 |
| 10 | Centrum-small urban - Peak 1 | 19 | 3250 | 300 | 0,09 |
| 11 | Centrum-small urban - Peak 2 | 7 | 5750 | 555 | 0,10 |
| 12 | Small urban - Peak 1 | 75 | 3250 | 260 | 0,08 |
| 13 | Small urban - Peak 2 | 12 | 6250 | 413 | 0,07 |
| 14 | Green-small urban - Peak 1 | 9 | 750 | 100 | 0,13 |
| 15 | Green-small urban - Peak 2 | 23 | 3000 | 231 | 0,08 |
| 16 | Centrum-village | 87 | 3250 | 260 | 0,08 |
| 17 | Village | 50 | 2250 | 220 | 0,10 |
| 18 | Rural accessible | 114 | 750 | 100 | 0,13 |

### 6.1.3 Reference buildings per model district

Now that the number of buildings per model district are set, the next step is to determine the distribution of reference buildings within each model district. As discussed in chapter 4, there are 7 reference buildings for residential buildings and only 1 reference building for commercial buildings.

Data about the different types of houses within a postal code area is only available after purchasing. Therefore an approximation is constructed by using the reference buildings (constructed by Agentschap NL [2011]), the general distribution of reference buildings in the Netherlands [Agentschap NL, 2011, ABF Research, 2014], the number of single-, and multi-family houses of CBS [2013b], and reports that have reported about the types of houses within a certain area who did purchase the data. These data sources are used to construct a qualitative table about the distribution of reference buildings for each of the model districts (see Figure 34), after which quantities (percentage of total houses in the model district represented by the reference building) are assigned. The more detailed explanation of the approach is included in Appendix A.5.

The distribution of the occurrence of the reference buildings within a model district, are combined with the total number of households within the model district, resulting in the number of reference buildings for each of the 7 types within a model district.

This approach is surrounded with uncertainty since the actual data is not available and the approximation is based on multiple sources. Therefore an additional check is performed, and the calculated number of reference buildings in the operating area are compared to the number of single-family and multi-family buildings for which the data is available [CBS, 2013b]. Single-family houses include the reference buildings detached, semi-detached and terraced houses. Multi-family houses include the reference buildings common staircase and galleries, common staircase no galleries, maisonettes, and other apartments.

| Type of reference building | | Detached | Semi-detached | Terraced hosue | Maisonette | Common staircase and galleries | Common staircase no galleries | Other apartments |
|---|---|---|---|---|---|---|---|---|
| **Distribution in the Netherlands** | <1964 | 441.000 | 285.000 | 1001000 | 226.000 | 69.000 | 523.000 | 99000 |
| | 1965-1974 | 119.000 | 142.000 | 606000 | 22.000 | 174.000 | 112.000 | 125000 |
| | 1975-1991 | 221.000 | 224.000 | 879000 | 94.000 | 109.000 | 142.000 | 125000 |
| | 1992-2005 | 178.000 | 173.000 | 353000 | 40.000 | 113.000 | 70.000 | 136000 |
| | **Total** | 959.000 | 824.000 | 2.839.000 | 382.000 | 465.000 | 847.000 | 485.000 |
| | **% of total** | 14% | 12% | 42% | 6% | 7% | 12% | 7% |
| **Green-urban** | <1964 | -1 | -1 | -1 | -1 | -1 | -2 | -2 |
| | 1965-1974 | 0 | 1 | 1 | -1 | -2 | -2 | -2 |
| | 1975-1991 | 0 | 1 | 1 | -1 | -2 | -2 | -2 |
| | 1992-2005 | 0 | 1 | 1 | -1 | -2 | -2 | -2 |

| **Legend: This type of building in this building period is...** | |
|---|---|
| -2 | ... nearly non-existent in the living environment, exceptions not included. |
| -1 | ... available in the living environment, but is relatively small compared to other buildings. |
| 0 | ... approximately the same distributed as other buildings with '0'. |
| 1 | ... relatively abundant in numbers compared to other building types. |
| 2 | ... most present in this living environment, other building types are nearly non-existing. |

*Figure 34: Example of the qualitative constructed distribution of reference buildings within the green-urban model district.*

Large outliers are examined and adapted (see Appendix A.5), but differences remain between the calculated number of single- and multi-family buildings and the actual number of buildings as constructed from the CBS data (see Table 13). It should be noted that this causes differences in the results of the model districts, although the data is considered to be a sufficient approximation for this research. Improvements can be made by applying for the actual data on the geographical distribution of reference buildings (available at the Kadaster).

*Table 13: Difference in calculated and actual data about the distribution of single-family and multi-family buildings.*

| Model district | Sum single-fam. ABF | Sum multi-fam. ABF | Percentage single-fam. ABF | Sum single-fam. Calculated | Sum multi-fam. Calculated | Percentage single-fam. calculated | Difference calculated and ABF single-fam. | Difference calculated and ABF multi-fam. |
|---|---|---|---|---|---|---|---|---|
| Centrum-urban Plus | 18.386 | 97.357 | 16% | 9.887 | 105.856 | 9% | -7% | 7% |
| Centrum-urban | 14.531 | 29.992 | 33% | 14.877 | 29.646 | 33% | 1% | -1% |
| Urban <1940 | 48.167 | 155.191 | 24% | 82.993 | 120.365 | 41% | 17% | -17% |
| Urban >1940 compact | 125.109 | 298.590 | 30% | 171.003 | 252.696 | 40% | 11% | -11% |
| Urban >1940 groundbased | 121.785 | 58.073 | 68% | 121.282 | 58.576 | 67% | 0% | 0% |
| Green-urban | 31.527 | 44.866 | 41% | 42.176 | 34.217 | 55% | 14% | -14% |
| Centrum-small urban | 52.029 | 39.459 | 57% | 53.443 | 38.045 | 58% | 2% | -2% |
| Small urban | 166.861 | 94.500 | 64% | 174.642 | 86.719 | 67% | 3% | -3% |
| Green-small urban | 34.272 | 22.922 | 60% | 31.455 | 25.739 | 55% | -5% | 5% |
| Centrum-village | 212.877 | 64.409 | 77% | 238.900 | 38.386 | 86% | 9% | -9% |
| Village | 83.071 | 12.876 | 87% | 85.981 | 9.966 | 90% | 3% | -3% |
| Rural accessible | 48.749 | 4.975 | 91% | 48.840 | 4.884 | 91% | 0% | 0% |

Overall, there is enough confidence in the distribution of reference buildings within the model districts. The resulting distribution of reference buildings, as will be used in the remainder of the research, is presented in Figure 35. The model district are now specified with the occurrence of the 7 types of residential reference buildings, and 1 type of commercial building.

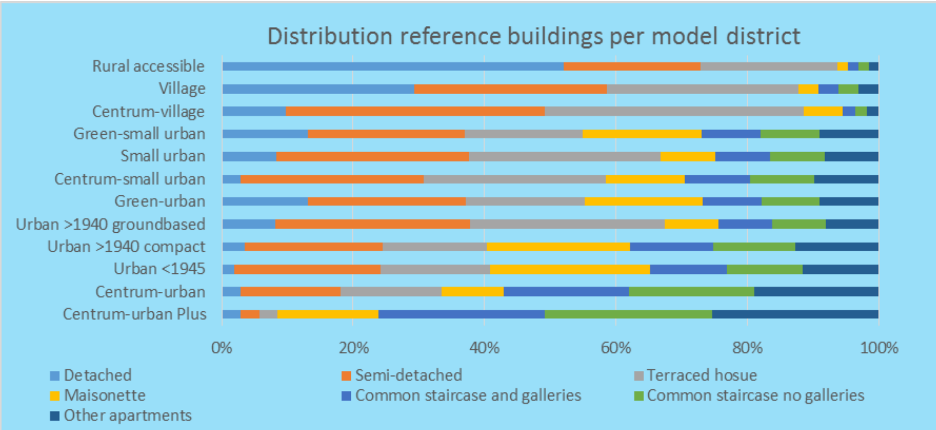



*Figure 35: Overview of distribution of reference buildings within the model districts*

## 6.2 Construction of load profiles

This section explains how the future load profiles of households and small commercial users are constructed. These consists of a basic electricity demand including the appliances and lighting, and of the expected change in demand caused by heat pumps and PV. The load profiles describe the average demand per household of a large group of households. The simultaneousness on the level of the individual households is therefore included in the profiles[19].

The reference buildings are used to determine the deployment rates of PV and heat pumps, as well as the electricity and heat demand. This is determined for each model district, and for each of the 3 future energy scenarios. Each scenario contains a total number of installed PV, heat pumps, and electricity demand increase for the operating area. It should however be known e.g. how much PV is installed in each model district in the years 2015, 2020, 2030 and 2040 for each of the scenarios.

[19] When considering individual consumers the use of appliances can cause large peaks during moments of operation. However, when looking at a group of consumers, not all consumers are using appliances at the same moment. This results in a lower average demand in the district, meaning that the individual consumer has a low simultaneousness (on average only a small number of consumers will have the same profile). Additional information about the simultaneousness is available in section 2.1.5.

Therefore the general number for the entire operating area are specified into the numbers per model district.

The general load profiles of the model districts are constructed by combining the following profiles:

- Basic electricity demand profile (lighting and appliances)
- PV supply profile
- Heat pump demand profile

These profiles are constructed for both residential and commercial connections. The profiles used are neutral, which means that the profiles require The technical potential of PV and heat pump implementation per reference building are determined using data from [PBL & DNV GL, 2014] and [DHPA, 2013] respectively.

### 6.2.1 Current basic load profile

The current demand profiles for the electricity demand are based on the standard profiles for electricity from EDSN[20]. The standard profiles provide the electricity demand as a fraction of the yearly demand. These fractions are between 0 and 1, which indicates the fraction of the yearly electricity demand as consumed in that specific hour (see Figure 36).

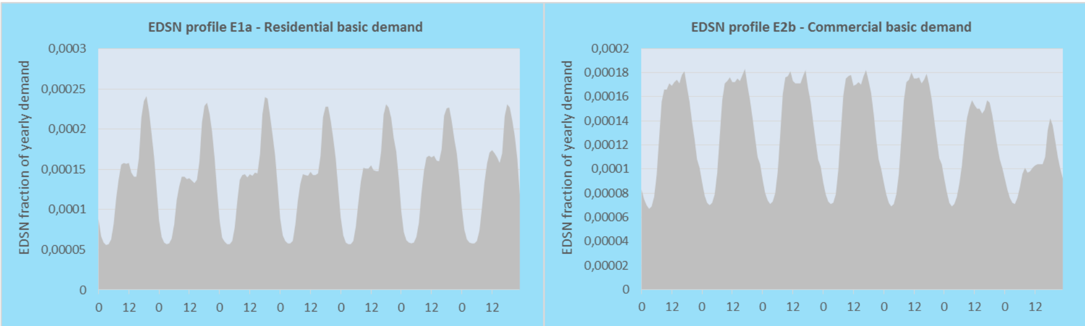



*Figure 36: EDSN profiles for the basic electricity demand for one week, between 7th January and 13th January. Left provides the residential profile E1a, and right provides the small commercial profile E2b. The residential demand is slightly higher during the weekend (last two days in the graph). The small commercial profile has a slightly lower demand during Saturday, and a substantially smaller demand at Sunday.*

The residential electricity demand profile is based on the EDSN profile E1a which represents the household profile. The commercial electricity demand is based on the EDSN profile E2b which represents the profile for stores and small commercial buildings. To determine the absolute demand per hour the EDSN fractions are multiplied with the yearly electricity demand. The yearly electricity demands are included in Table 14.

*Table 14: Assumptions electricity demand. Source Eneco scenarios, see section 5.5.*

| Description | Value |
|---|---|
| Yearly residential electricity demand | 3,5 MWh |
| Yearly commercial electricity demand | 20 MWh |

However, the residential electricity demand differs between different reference buildings (and therefore also between model districts). The deviation from the average residential electricity demand per reference buildings in included in Table 15. The number of reference buildings (per type) per model district are multiplied with the yearly deviation, which in turn is multiplied with the current average yearly electricity demand. This results in the average electricity demand per household for each of the model districts, in the current situation.

[20] EDSN (2013) Profielen Elektriciteit, available at www.edsn.nl/verbruiksprofielen.

*Table 15: Deviation electricity demand per residential reference building*

| Reference buildings | Deviation from average electricity demand |
|---|---|
| Detached | 142% |
| Semi-detached | 121% |
| Terraced house | 151% |
| Maisonette | 91% |
| Common staircase and galleries | 50% |
| Common staircase no galleries | 70% |
| Other apartments | 75% |
| Source: | [Agentschap NL, 2011] |

## 6.2.2 Future basic electricity demand

To determine the future electricity demand the current demand profile is scaled on the yearly growth of the electricity demand (see section 5.4). It has been assumed that the load profiles remains similar in shape. The growth rates include the economic growth and efficiency increases. Each scenario contains different assumptions about the growth rate of the electricity demand, resulting in three different demands per model district. Additionally, the distribution of reference buildings differs between the model districts, resulting in a deviation of the average electricity demand.

The resulting yearly electricity demand per household in the year 2040 is depicted in Figure 37, as well as the electricity demand for commercial buildings for which no differentiation between districts is applied (see section 4.5). Combining the annual electricity demand with the EDSN profiles results in the future load profile for the basic electricity demand.

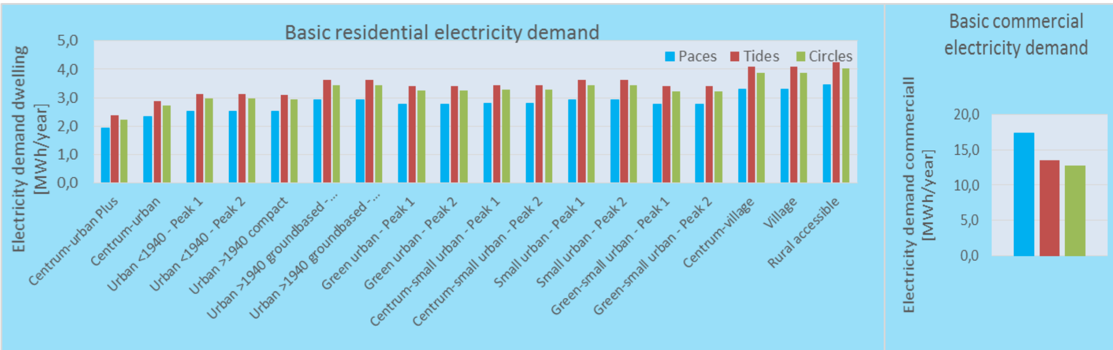



*Figure 37: The average yearly electricity demand per consumer type in the year 2040. Left provides an overview of the average yearly electricity demand of a household, which differs between the model districts.*

## 6.2.3 PV load profile

The supply profile of the PV installations is determined by combining the installed capacity ($kW_p$), the annual production per installed capacity (in $kWh/kW_p$), and the weather conditions, with the supply profile of a reference PV installation. This section contains the brief explanation of the approach and assumptions, and additional information is provided in Appendix B. The interest of this study is on the extreme situations that can occur, meaning that every day is assumed to be sunny. The installed PV capacity per model district is specified using the following formula.

*Installed PV capacity per model district ($W_p$) = Available roof surface PV ($m^2$) x PV covered roof surface (%) x PV efficiency per $m^2$ ($W_p/m^2$) x Chance PV per district (%)*

- Total available roof surface PV for residential buildings is 256 $km^2$, and 152 $km^2$ for utility buildings [PBL & DNV GL, 2014]. This represents the technical potential of PV, meaning the maximum of roof integrated PV that can be applied. Per residential building the average available roof surface equals 34 $m^2$ [PBL & DNV GL, 2014], and 137 $m^2$ per utility building [Eneco scenarios, 2015]. For residential buildings the available roof surface for PV is calculated by using

the roof surface available for each of the 7 reference buildings (ranging from 13 up until 62 $m^2$), while the utility buildings are assumed to all have the same roof surface.
- The PV covered roof surface is expressed as the percentage of (commercial or residential) roof surface covered by PV based on the national installed PV capacity in the operating area and the number of buildings, meaning that a linear relation is used from the national scenarios[21]. The total installed capacity of PV in 2014 is set to 1 $GW_p$, and rises to a capacity between 13 and 70 $GW_p$ in 2040 (see scenarios on page 134).
- The PV efficiency is equal to the national scenarios, ranging from 160 $W_p/m^2$ in 2014 up until 270 to 350 $W_p/m^2$ in 2040 due to technical innovations. There is no differentiation between model districts.

After constructing the installed PV capacity based on the technical potential in the different model districts, and the covered roof surface as obtained from the national scenarios, some differentiation between the model districts is achieved. However, when comparing the current deployment rates of the installed PV capacity as registered in the Product Installation Register (PIR)[22] the differences between the model districts are too small. Therefore an additional variable is included in the formula called the 'Chance PV per district', which compares the current deployment rates as obtained by the technical potential and covered roof surface per model district, with the registered installed capacity in the PIR database for each model district type. An extensive explanation and analysis of this chance variable is available in appendix B.3.2.

- Differentiation of PV deployment between different model districts (named the 'Chance PV per district (%)') in 2014, is based on the weighted percentage deviation from the average installed capacity (per residential or commercial building) in the Netherlands in 2012. Since future changes are unsure, the percentages are assumed to convert linearly to 100% in 2050, meaning that each model district installs exactly the amount of PV as specified on the national scale in 2050.

Overall, there is a differentiation of the installed capacity between model districts on the basis of the differing available roof surfaces, and the current and future differences in deployment rates of PV in districts based on the chance variable. Additional assumptions:

- All of the PV capacity is installed on roofs of utility and residential buildings, meaning only building integrated PV (BIPV) are included and ground based PV (GBPV) are excluded. Also novel technologies like PV cells integrated in windows or in clothes are excluded.
- The PV load profile is based the maximum irradiation measured over the last 14 years in the KNMI weather station of Rotterdam. Using the NEN7120:2011 the solar irradiance (measured as J/cm2/hour) is converted to the kW supply of the installation, resulting in the extreme day profile for each month with hourly intervals.
- The orientation of the PV panels are assumed to be mixed, as well as the angle of inclination. An installation oriented east or west has approximately a 10% lower peak supply compared to a fully south facing installation [Bogerd, 2015].
- All PV installations are assumed to be fully in the sun, without shadows of surrounding objects. The average profile would result in a yearly supply of 853 $kWh/kW_p$, while the maximum profile with only sunny days provides 1640 $kWh/kW_p$ [CE Delft, 2014].

[21] The national scenarios are converted into the scenarios that are applicable on the operating area of Stedin by using the number of residential and commercial consumers. Therefore the numbers of the national scenarios and the scenarios of the operating area are linearly scaled. Thus, the numbers of the national and operating area scenarios result in the same outcome.

[22] The Product Installation Register (PIR) contains the installed PV capacity per postal code area. Registration is voluntary, and estimates of the completeness of the database range from 60 – 80% [Bleumink, 2013].

### *Load profile PV reference installation*

CE Delft [2014] has constructed the PV profile by using the highest solar irradiation that has been measured during each hour of the month, for all 12 months, for the last 14 years at the KNMI measuring station of Rotterdam. Using the NEN7120:2011 the solar irradiance (measured as J/cm2/hour) is converted to the kW supply of the installation, resulting in the extreme day profile for each month, with hourly intervals. A mix of orientations and angles has been used for an ideal situation without losses (e.g. shadows). Using the average kWh/kW$_p$ electricity supply for this system would result in a yearly yield of 853 kWh/kW$_p$, but since the interest is on the extreme supply profile the actual electricity supply of 1640 kWh/kW$_p$ is much higher.

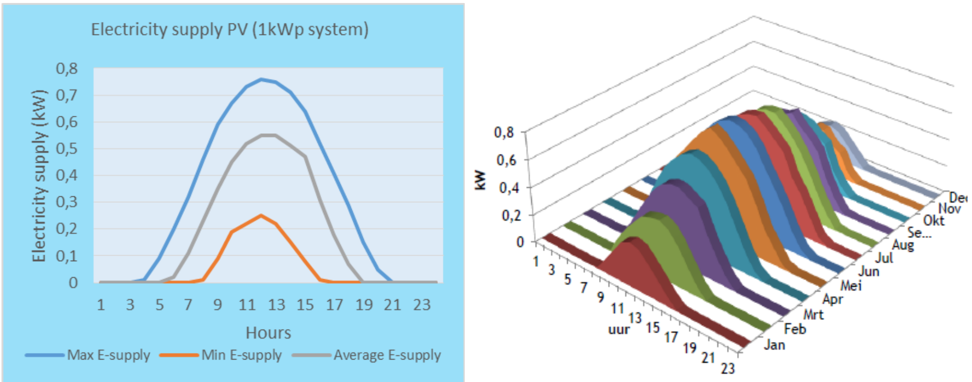



*Figure 38: (**left**) Minimum, maximum and average electricity supply per 1kW$_p$ PV system per day. (**right**) Day profiles PV for a 1 kW$_p$ installation for each month of the year; source [CE Delft, 2014].*

### *Input variables*

Based on the approach, the installed PV capacity for each of the model districts in the year 2040 is determined for each of the future energy scenarios (see Figure 39). This is a combination of the residential and commercial installed PV capacity. The large differences between the model distritcs are largely caused by the different number of buildings per model district (different size, and density of buildings). Combining the installed capacity with the supply profile results in the electriciy supply profile for the model districts.

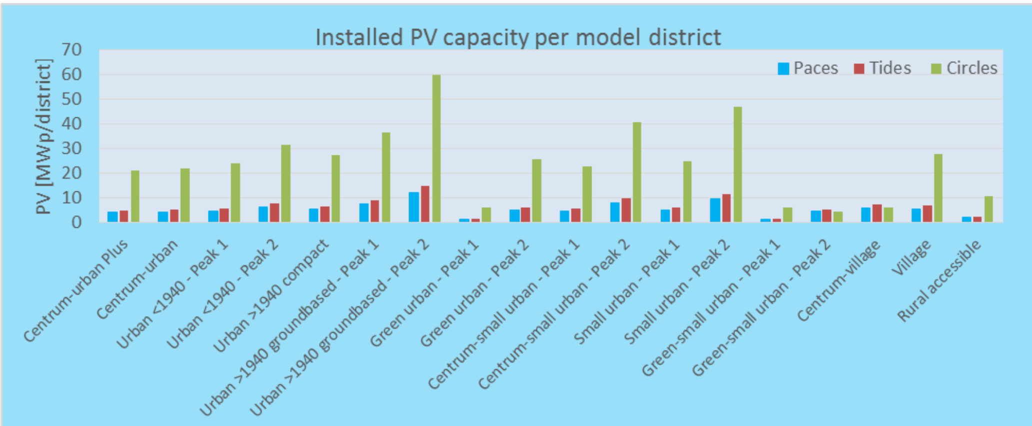



*Figure 39: Installed PV capacity per model district, for each of the three Eneco scenarios in the year 2040.*

## 6.2.4 Load profile residential heat pumps

This section describes the approach to construct the demand load profiles of the residential heat pumps. Construction of the load profiles is based on the number of residential heat pumps, the heating demand, and the technical efficiency of the heat pump.

### *Number of residential heat pumps*

The number of residential heat pumps per model district are specified using the following formula. Additional information is provided in Appendix B.

*Number of residential heat pumps (#/district) = [Number of dwellings suitable for heat pumps (#/district) / [Number of residential buildings (# NL) x Percentage of residential buildings suitable for heat pumps (% NL)]] x Number of residential heat pumps (# NL)*

- Within each model district the number of reference buildings for each of the 7 types are multiplied with the technical potential each of these reference buildings has for application of (full electric or hybrid) heat pumps [see DHPA, 2013]. This results in the total number of dwellings suitable for heat pump deployment for each model district, which ranges between 53% and 86% of the dwellings.
- The percentage of residential buildings in the Netherlands that are suitable for heat pumps are determined by multiplying the number of dwellings in the Netherlands for each of the 7 reference buildings with the technical potential of these reference buildings. In 74% of the total stock of Dutch dwellings heat pumps are technically feasible.
- The number of residential heat pumps are determined in the national future energy scenarios[23] and range from 80.000 in 2014 up until 0,6 to 3,2 million in 2040 (see scenarios on page 134).

Overall, there is a differentiation of the number of residential heat pumps between model districts on the basis of the differing technical potential.

### *Load profile*

The load profile of heat pumps is strongly related to the capacity of the heat pumps. In this study it is assumed that one heat pump provides the full heat demand of the residential or commercial building. In reality it is common practice to have less capacity installed than actually required due to the high investment costs [Ecofys, 2014]. However, data about the installed capacity is not available and therefore the assumption is made that the heat demand of each residential building is fully supplied by the heat pump. During moments that the installed capacity is insufficient additional back-up generation is applied. This study uses two types of heat pumps: full electric and hybrid heat pumps. For full electric heat pump less nominal capacity than the required heat demand can cause comfort problems during cold days [Ecofys, 2014]. For hybrid heat pumps the natural gas heater is applied during moments of insufficient heating capacity.

The load profiles of the two types of heat pump is the same during normal operation. When approaching the critical heat supply that can be provided, the full electric heat pump will run at full capacity. The hybrid heat pump, however, switches to an additional heating element using a natural gas burner. This results in a reduced electricity demand, during peak moments. Hybrid heat pumps thus require a connection to the natural gas network. In the Netherlands there is the ambition to have a completely energy neutral build environment in 2050, which reduces the certainty of a gas network on the long term [PBL, 2014a]. On the long term the Eneco scenarios therefore expect a large degree of the heat pumps to be fully electric, ranging from 93% to 97% of the entire stock to be full electric in 2050 (see page 134).

In this study only a profile for full electric heat pumps is used since a profile for the hybrid heat pumps are not available, and the majority of the heat pumps are considered to be full electric. Therefore, the hybrid heat pumps are assumed to provide 50% of the heat through the heat pump, and 50% by

[23] The national scenarios are converted into the scenarios that are applicable on the operating area of Stedin by using the number of residential and commercial consumers. Therefore the numbers of the national scenarios and the scenarios of the operating area are linearly scaled. Thus, the numbers of the national and operating area scenarios result in the same outcome.

the natural gas boiler [Eneco scenario, 2015]. The input variable for heat pumps are therefore determined by the number of full electric heat pumps plus half the number of hybrid heat pumps. This results in a higher modelled peak demand than occurs in reality since the switch towards the natural gas burner is no longer included during peak moments.

The load profile is constructed by using the EDSN standard profiles for heat pumps. The total profile is constructed by using the meteorological data of the year 1963 of the KNMI. This was an extremely cold year, and therefore a good fit for the extreme profile.

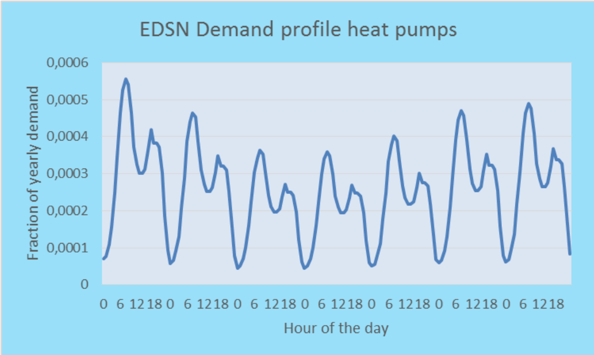



*Figure 40: EDSN profile for heat pump electrical demand.*

The final electrical load profile is constructed by dividing the heat demand of one residential building with the COP[24] that is applicable. For example, the yearly heating demand of a households is 60 GJ in an extremely cold year. The COP of the heat pump is 3, resulting in a yearly electrical demand of: 60GJ /3 COP/ 3,6 = 5,5 MWh/year.

### *Input variables*

The COP of full electric heat pumps is assumed to be 3.0, and for hybrid heat pumps 4,0 [Eneco scenarios, 2015]. Residential buildings deploy both types of heat pumps. For each model district the COP for residential buildings is therefore determined by the proportion of full electric and hybrid heat pumps.

The number of residential heat pumps per model district in 2040 for each scenario are depicted in Figure 41, which thus include all electric heat pumps and half of the hybrid heat pumps.

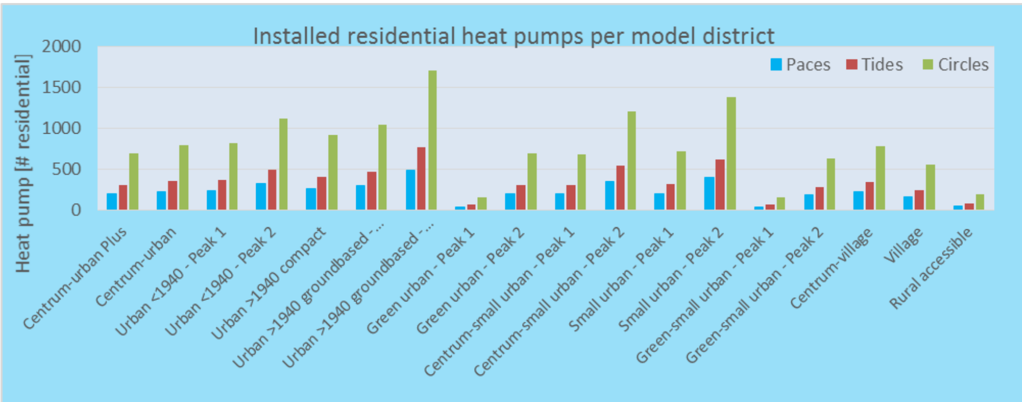



*Figure 41: Number of residential full electric heat pumps in the model districts in 2040. Hybrid heat pumps are included, but are assumed to provide half of the heating through natural gas, resulting in half the number for the input variables.*

[24] The Coefficient of Performance (COP) provides the efficiency of the heat pump. Dividing the heat demand (in joule) by the COP results in the electricity demand of the heat pump.

### *Residential heating demand*

The heating demand per model district depends on the types of dwellings. Similarly to the electricity demand the number of each type of reference building are determined per model district, after which these numbers are multiplied with the average heating demand, and the deviation from the heating demand as depicted in Table 16. Currently the average annual heating demand for households is 40 GJ, which turns to 32 GJ in the **Paces** scenario, 37 GJ in the **Tides** scenario, and 43 GJ in the **Circles** scenario in 2040 [Eneco scenarios, 2015].

*Table 16: Deviation heating demand per reference building*

| Reference building | Heating demand per dwelling |
|---|---|
| Detached | 169% |
| Semi-detached | 131% |
| Terraced house | 108% |
| Maisonette | 91% |
| Common staircase and galleries | 66% |
| Common staircase no galleries | 66% |
| Other apartments | 66% |
| Source: | [Agentschap NL, 2011] |

Additional assumptions:

- The average heating demand for residential buildings for each of the model districts is determined by multiplying the number of reference buildings with the heating demand for each of the 7 reference buildings as specified by [Agentschap NL, 2011].
- Residential heat pumps consists of full electric and hybrid heat pumps, of which the latter is assumed to provide 50% of the heat by means of natural gas [Eneco scenarios, 2015]. Therefore only the electric required heating demand is used as an input for the MKBINS model, since the load profile for heat pumps in that model is based on the electricity demand of the heat pump.
- The COP (Coefficient of Performance) of the residential heat pumps is calculated by the distribution of full electric and hybrid heat pumps. Full electric heat pumps have been assigned a COP of 3, and hybrid heat pumps a COP of 4 [Eneco scenarios, 2015]. Using the number of full and hybrid heat pumps in a model district results in the average COP of the district.
- The load profile for the residential heat pump is based on the electric heating demand for a cold winter year, for which the KNMI data for 1963 have been used [CE Delft, 2014]. During that year the heating demand was 58 GJ/year, which is 123% above the average residential heating demand. The same percentual increase is used for the commercial heating demand (see next section).

### 6.2.5 Commercial heat pump deployment in model districts

The approach to construct the load profiles for the commercial heat pumps is slightly different from the approach of the residential heat pumps. The number of commercial heat pumps per model district are specified using the following formula. Additional information is provided in Appendix B.

*Number of commercial heat pumps (#/district) = [Average commercial heating demand (MWh/company) * Number of commercial companies (# district) * Commercial heating demand provided by heat pumps (% NL)] / [Total commercial heating demand (MWh NL) / Number of commercial buildings (# NL)]*

- It is assumed that commercial buildings only install full electric heat pumps [Eneco scenarios, 2015].

- Since the aim is to provide extreme profiles the heating demand is increased with 123%, which is the same percentage as used in the residential heating demand for the extremely cold year of 1963 (see previous section).
- The electricity demand of these full electric heat pumps is determined by using a COP of 3 [Eneco scenarios, 2015], and the average heating demand per commercial building. *Electricity demand = average heating demand / COP.*

#### Load profile

The load profile of the commercial heat pumps is the same as for the residential heat pumps (see section 6.2.4). Commercial buildings only deploy full electric heat pumps, for which a COP of 3 is assumed [Eneco scenarios, 2015].

#### Input variables

Since only full electric heat pumps are deployed, the total number of commercial heat pumps do not need to be adapted for the hybrid heat pumps. The resulting number of commercial heat pumps per model district are included in Figure 42.

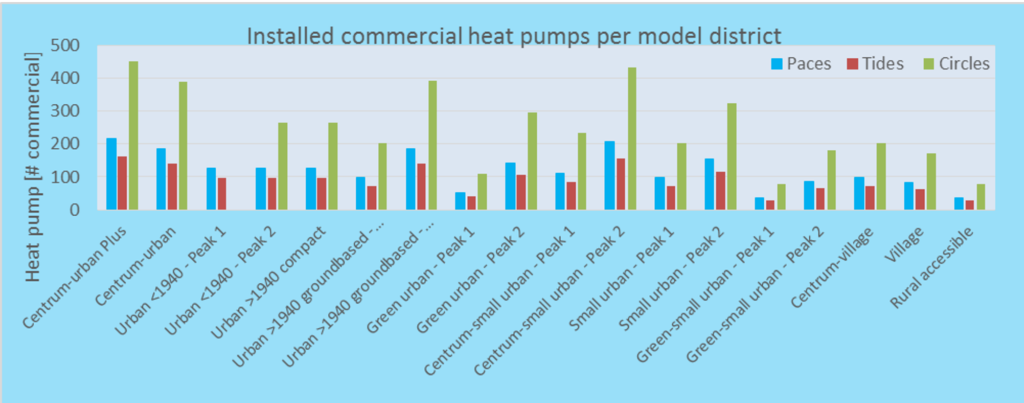



*Figure 42: Number of full electric commercial heat pumps in the model districts in 2040.*

#### Commercial heating demand

The average yearly heating demand of commercial buildings in 2040 is 63 GJ in scenario **Paces**, 49 GJ in scenario **Tides**, and 46 GJ in scenario **Circles** [Eneco scenarios, 2015]. Combining the EDSN profile for heat pumps, the heat demand, and the COP results in the electrical load profile for the commercial heat pumps.

## 6.3 Conclusion

This chapter focussed on the construction and specification of the model districts. The number of buildings within a PC4 area can be as low as 13 or as high as 11.000. The number of residential and commercial buildings are constructed by using the mode of the number of buildings as occur in reality. Data about the different types of houses within a postal code area is only available after purchasing. Therefore an approximation is constructed which is validated against the overarching categories of single- and multi-family buildings, in which the differences in the model districts are smaller than 17%. The reference buildings are key in specifying the scenarios for the model districts in the deployment rates of PV and heat pumps. A brief overview of the main differences between the scenarios in the specified model districts is included in Table 17. The final load profiles in the model districts are diversified on the basis of the number of buildings, the installed PV capacity and the installed heat pump capacity.  Additional differentiation is applied for the PV deployment in the different model districts on the basis of the current deployment rates, with a linear relation to an equal chance of deployment in all districts in the year 2050.

*Table 17: Comparison of the assumptions in the scenarios. The basic electricity demand is presented as the increase in demand compared to 2013. The PV and heat pump deployment are scaled in relation to the other scenarios, meaning each row adds up to 1.*

| Ratios between scenarios in 2040 | Paces | Tides | Circles |
|---|---|---|---|
| Residential electricity demand (compared to 2013) | 79% | 98% | 93% |
| Commercial electricity demand (compared to 2013) | 87% | 68% | 64% |
| PV deployment | 0,1 | 0,2 | 0,7 |
| Residential heat pumps | 0,2 | 0,3 | 0,6 |
| Commercial heat pumps | 0,3 | 0,2 | 0,5 |

The general load profiles of the model districts are constructed by combining the following profiles:

- Basic electricity demand profile (lighting and appliances)
- PV supply profile
- Heat pump demand profile

The combination of the residential and commercial profiles per model district results in the future load profile for each of the scenarios in 2040.

# 7. Specification distribution transformers

The geographical delineation of the build environment is provided by the model districts as specified in chapter 4. For each of these model districts the electricity load profiles are constructed in chapter 6 based on the Eneco future energy scenarios. However, the geographical delineation needs to be coupled to the electricity network, or more specifically to the distribution transformers that provide the model districts with the required electricity.

The aim of this chapter is therefore to create a connection between the model districts and the MV/LV-transformers. There are two ways to approach this: (1) by taking the model districts as a starting point and coupling certain standard types of transformers that apply to that specific model district, or (2) by starting from the transformer characteristics and coupling the relevant model district to the transformers. The first approach has the advantage that a small number of transformers can be used which can be extrapolated to the impact for the entire operating area. However, this requires strong relations since transformer characteristics differ significantly.

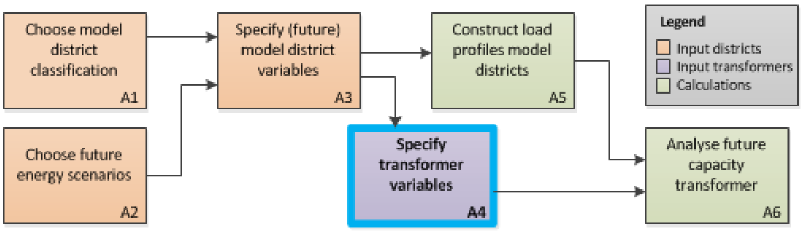



*Figure 43: Overview general approach of this research. This chapter focusses on the specification of distribution transformers.*

This chapter therefore starts by analysing the current stock of transformers for the entire operating area (section 7.1). Section 7.2 aims to look for relations between the stock of transformers and the type of model districts. The other approach, by taking the electricity network as a starting point and connect the model districts to the transformers, is explored in section 7.3. This chapter ends with a concluding on the results of this chapter and the best applicable approach for connecting the model districts to the electricity network.

## 7.1 Description current stock of transformers

The operating area of Stedin consists of 22.285 MV/LV-transformers in the year 2014. To provide insight into the general characteristics of the transformer stock the nominal capacity, current loading and building year of the distribution transformers are discussed.

### 7.1.1 Nominal capacity

The installed nominal capacity of the transformers depends on the required (future) capacity for the connections located in the service area. There are some standard sizes (or standard capacities) for transformers, which can be distinguished by the horizontal lines in Figure 44. Utilities often deploy standard size transformers since the manufacturers and DNOs have the advantage of economies of scale and it also reduces the requirements for spare parts. The most applied nominal capacities range between 100 kVA, and 1000 kVA. Especially the 630 kVA and 400 kVA transformers are often deployed.

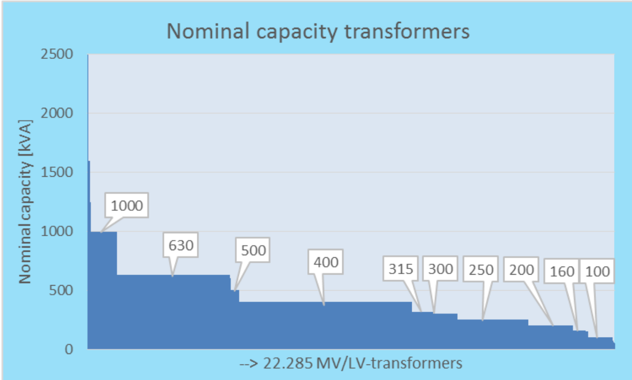



*Figure 44: Nominal capacity of MV/LV-transformers in operating area of Stedin in the year 2014.*

### 7.1.2 Current loading

The current loading of all MV/LV-transformers in 2013 are provided in Figure 45. The figure indicates the loading rate as a percentage of the nominal capacity of the transformer. During operation the MV/LV-transformers can be loaded until 120% of the nominal capacity before the lifetime is shortened due to damages in the equipment, and overloading mechanisms to prevent damages come to work[25]. The maximum loading rate are measured by manually reading the indicator of each transformer that measures the highest load since the last reading moment of the indicator.

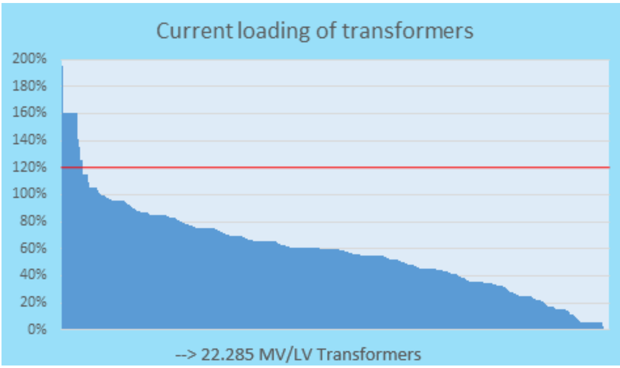



*Figure 45: Current loading rate of MV/LV-transformers in Stedin operating area in 2014*

The average loading rate of the transformers in the operating area is 60%. Currently, 817 transformers have a maximum loading rate above 120%, which is 3,7% of the total stock. Only the highest loading rate is registered, meaning no information is provided about the number of times the transformer is overloaded, or the duration of the individual overloading's. Therefore asset management divisions of DNOs perform additional analysis for transformers that have a registered overloading to determine if the peak demand is structural or accidental, and whether refurbishment, replacement or addition of a new transformer is deemed necessary to maintain the high reliability of the electricity supply.

### 7.1.3 Building year

The building year of the MV/LV-transformers is depicted in Figure 46. Transformers have a lifetime that mainly depends on the number of, and duration of (over)loadings, and the maintenance performed on it [Kulkarni & Khaparde, 2013]. By retro-fitting the transformers an average lifetime of 70 years is not unlikely according to a manufacturer of distribution transformers [SGB Smit, 2015]. However, as obtained from the current stock of transformers the oldest transformer in the operating area is already 90 years old. The average lifetime is used as an indicator for which transformers are

[25] Additional information is provided in section 2.1.5.

likely to be replaced by the year 2040, which are thus the transformer build before the year (2040-70= ) 1970. A total of 5105 transformers is built before 1970, which is 22,9% of the total stock.

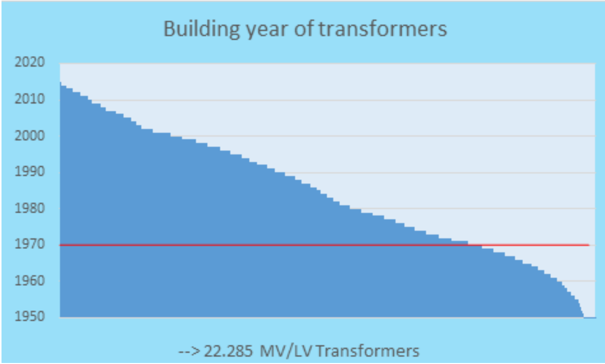



*Figure 46: Building year of MV/LV-transformers*

### 7.1.4 Discussion on current stock of transformers

Jongen [2012] performed a statistical lifetime study on the stock of distribution transformers of the Dutch DNO Liander, and reported a mean lifetime of 71 years, with a 90% confidence interval between 60 and 84 years. This is comparable with the stock of the client.

Additionally the loading rates of the distribution transformers is low in most cases, with an average loading rate of 60%. A low loading rate means that much unused capacity is installed, which reduces the economic efficiency of the transformer. Why is this loading rate so low?

This is partly due to the network design procedures. First of all, as observed in the distribution of the nominal capacity of the transformers, the transformer capacities are (currently) standardised in 250 kVA, 400 kVA, 630 kVA, 1000 kVA, and 1600 kVA at the client, resulting in a certain margin in the design. For example, if a connection of 55 kVA is requested by a customer (or calculated to be required for a district), a transformer of 250 kVA is installed which continues to have a low loading rated throughout its lifetime. Secondly, the policy in the asset management division is that at initial operation no more than 85% of the installed capacity may be used in order to allow for future increases in demand. Thirdly, commercial entities are required to request the capacity that they expect to use. More often than not the initially requested capacity is not fully used, resulting in unused transformer capacity.

## 7.2 Grouping transformers per model district

This section investigates if there is a relation between the model districts and the transformers, based on the categorisation by using the model districts. The main parameters of the model districts are the type of district, and the number of (residential and commercial) buildings per district type. The main parameters of the transformers are the number of transformers, building year, nominal capacity and current loading of the nominal capacity. These parameters are used in combination to look for relevant relations between the model districts and the transformers, as specified in Table 18. The relations that are deemed most important and that are investigated are included in the green cells[26].

[26] Additional research can be performed on the remaining relations in the table. However, in consultation with the client the currently investigated relations are expected to be most significant. Due to time (and data) limitations only these three relations are investigated.

*Table 18: Variables for analysing the relation between model districts and the transformers located in the model districts.*

| Model district characteristics / Transformer characteristics | District type | Number of buildings per district type | Number of commercial buildings per district type | Number of residential buildings per district type |
|---|---|---|---|---|
| Number of transformers | # of transformers per district type | # of buildings per transformer per district type | # of commercial buildings/transformer per district type | # of residential buildings/transformer per district type |
| Building year | Building year per district type | # of buildings per building year | *Not possible to execute since the transformer data does not include the capacity per connection, making the analysis results unreliable due to possible large users in the PC4 areas.* | |
| Nominal capacity | Nominal capacity per district type | Nominal capacity per building | | |
| Current loading of nominal capacity | Loading per district type | Loading per building | | |

### 7.2.1 Number of transformers per district type

The number of transformers per postal code (PC4) area differs greatly. Some PC4 areas contain 1 transformer, while other areas contain up until 180 transformers per PC4 area. The number of transformers per model district areas are plotted in Figure 47. Several general conclusions are drawn for the number of transformers per district type:

- There is a large spread[27] between the number of transformers per district type for different postal code areas, although the spread size depends on the district type. The largest spread is observed for the green-urban (spread 172), followed by the centrum-small urban (spread 171). The smallest spread is observed for the village (spread 75), the rural accessible (spread 90) and the small urban (spread 90) districts. In all cases the spread is too large to use an average number of transformers per model district.
- Many model districts contain one especially large number of transformers per PC4 area, for which the causes are unsure. However, this substantially influences the spread for each district type. Removing the largest number of transformers per district type, and recalculating the spread, results in the spread as provided in Figure 48. Substantially above average are the centrum-urban plus, green-urban, and centrum-village districts. Substantially below average are the urban <1940, village, and rural accessible districts.
- On average, the largest number of transformers per PC4 area are located in the centrum-urban plus and centrum-urban districts, which are also the districts with the highest urban density (see page 119). The smallest number of transformers per PC4 area are in the rural accessible districts, which is the district with the smallest urban density[28].

Within the model districts a large variation of the number of buildings per PC4 area are observed (see section 6.1.2), which could explain the large spread in the number of transformers in the model districts. However, the urban >1940 compact and groundbased districts have the largest spread in the number of buildings per PC4 area, while these are districts with an average spread in the number of transformers (see Figure 48). The spread of the transformers can thus not be explained by the variance in the number of buildings (only). However, additional analysis of the number of buildings per transformers might provide additional insights. This is the focus of the next section.

Overall, there is no general relation between the number of transformers per PC4 area, and the model district types. The spread of the number of transformers within the model districts is too large

[27] The spread is defined as the difference between the largest number of transformers per PC4 area, and the smallest number of transformers per PC4 area, for each of the model district types.
[28] The urban density factor is not a predictive variable for the number of transformers per PC4 area since e.g. the urban <1940 districts have the third highest urban density factor, while being the district with the second smallest number of transformers per PC4 area on average.

to set one number of transformers per model district. Therefore it is concluded that there is no usable relation between the model districts and the number of transformers.

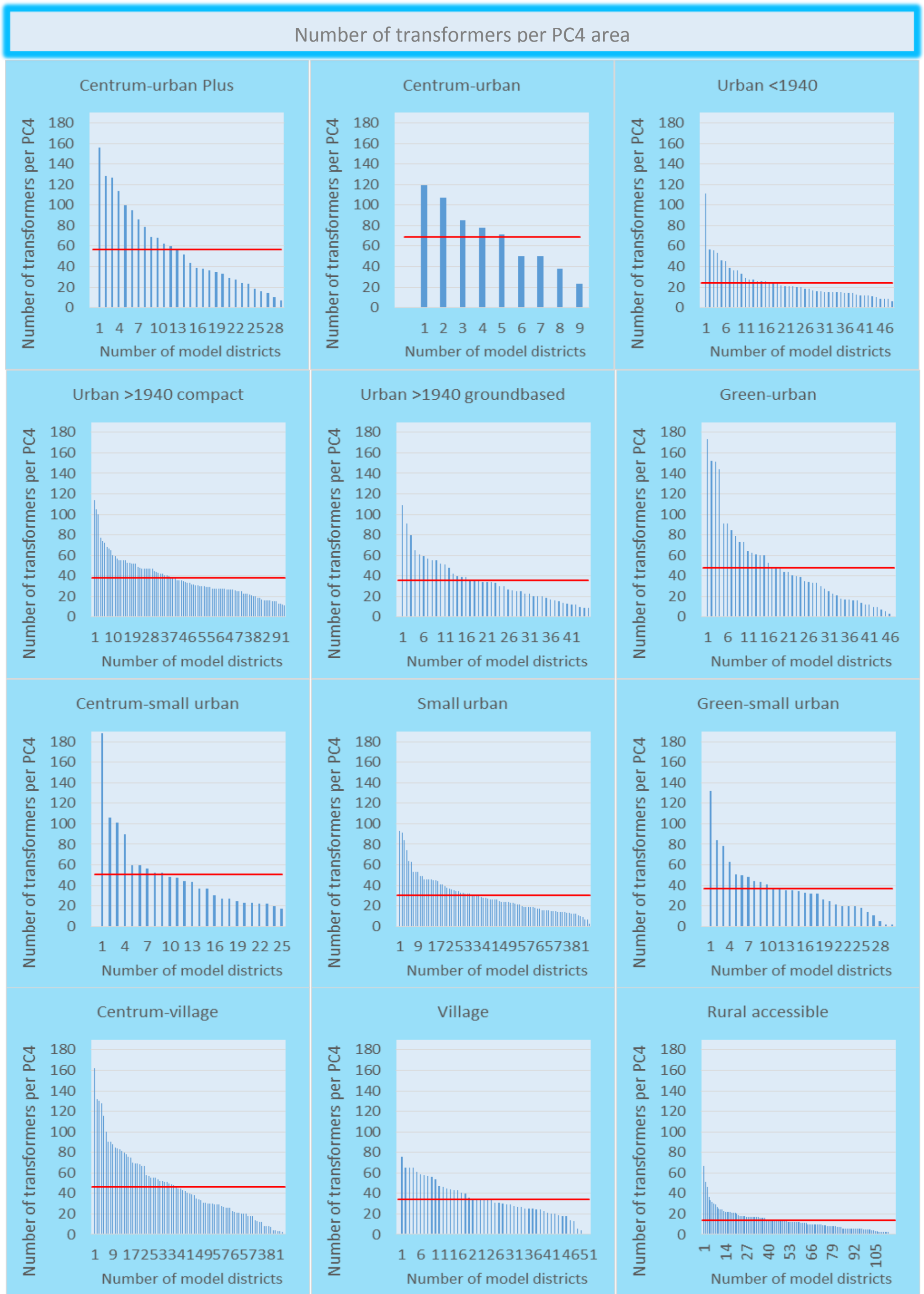



*Figure 47: For each PC4 area the model district is determined, and for each group of model districts the number of transformers per four digit postal code are plotted. The red line represents the average number of transformers per four digit postal code area.*

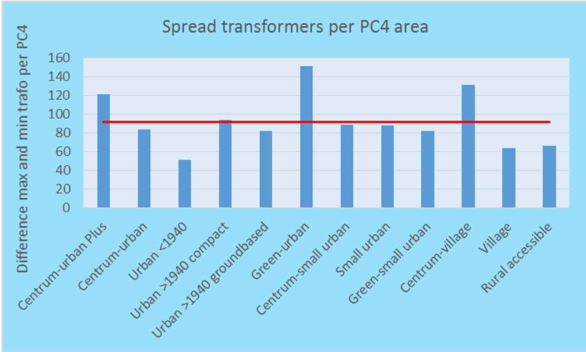



*Figure 48: Difference between maximum and minimum number of transformers (the spread) per PC4 area for each of the model districts. The PC4 area with the largest number of transformers is removed from the dataset.*

### 7.2.2 Number of buildings per transformer per district type

Each transformer provides a certain number of residential and commercial buildings of electricity. Perhaps when including the number of buildings per transformer, plotted for each of the model districts, a relation is revealed between the model districts and the transformers. The total number of buildings (both residential and commercial) are determined for each postal code area, as well as the total number of transformers per PC4 area. By dividing the total number of buildings by the total number of transformers, the number of buildings per transformer are determined. The results are provided in Figure 50.

Several general conclusions are drawn for the number of buildings per transformer per district type:

- Each transformer provides between 1 and 400 buildings of electricity (both residential and commercial).
- There is a large spread for the number of buildings per transformer for all of the model districts. The smallest spread is observed for the transformer in the centrum-urban districts, and the largest spread in the urban <1940 and urban >1940 ground based districts.
- A smaller number of buildings per PC4 area results in a smaller number of buildings per transformer, and vice versa (see Figure 49).

| Model district | Average number of buildings per trafo | Number of buildings per PC4 |
|---|---|---|
| Centrum-urban Plus | 112 | 4830 |
| Centrum-urban | 89 | 4670 |
| Urban <1940 | 224 | 6090 |
| Urban >1940 compact | 148 | 4930 |
| Urban >1940 groundbased | 145 | 5010 |
| Green-urban | 45 | 890 |
| Centrum-small urban | 92 | 3550 |
| Small urban | 131 | 3510 |
| Green-small urban | 74 | 1090 |
| Centrum-village | 95 | 3510 |
| Village | 75 | 2470 |
| Rural accessible | 48 | 850 |

*Figure 49: Average number of buildings per PC4 area for the 12 model districts, as well as the average number of buildings per distribution transformer.*


*Figure 50: Number of buildings (residential and commercial) per transformer per four digit postal code area.*

The analysis shows that the larger the number of buildings per PC4 area, the larger the number of buildings per transformer. Two hypothesis are formulated that could explain this result:

1. The larger the number of buildings in a PC4 area, the larger the required capacity for the entire district since the nominal capacity per building remains the same, and the transformers thus have a larger nominal capacity.
2. Districts with a large number of buildings require a smaller nominal capacity per building, meaning that the nominal capacity of transformers in districts with a large number of buildings is not higher than the nominal capacity of transformers in districts with a small number of buildings.

In Figure 51 the average number of buildings per PC4 area are compared with the average transformer capacity located in the PC4 area. In general there seems to be a rough relation supporting the first hypothesis. However, there are some clear outliers such as the urban <1940, and the green-urban districts. Therefore, with the relatively small research effort, there is no quantitative relation to support the fist hypothesis. Additionally, the second hypothesis seems reasonable since areas with large number of buildings contain dwelling types that have a lower basic electricity demand (see Figure 37 on page 56), meaning that a smaller nominal capacity per dwelling is required. Most likely, the combination of the two hypothesis can explain how a larger number of buildings results in a larger number of buildings per transformer, although additional research is required.

| Model district | Number of buildings per PC4 | Average trafo capacity per PC4 (kVA) |
|---|---|---|
| Centrum-urban Plus | 4830 | 26365 |
| Centrum-urban | 4670 | 32507 |
| Urban <1940 | 6090 | 10007 |
| Urban >1940 compact | 4930 | 15648 |
| Urban >1940 groundbased | 5010 | 16070 |
| Green-urban | 890 | 23439 |
| Centrum-small urban | 3550 | 22823 |
| Small urban | 3510 | 12577 |
| Green-small urban | 1090 | 16346 |
| Centrum-village | 3510 | 18185 |
| Village | 2470 | 11105 |
| Rural accessible | 850 | 4534 |

*Figure 51: Comparison of the number of buildings per PC4 area, and the average transformer capacity per PC4 area.*

Overall, there is no clear quantitative relation between the number of buildings per transformer and the model district type. However, additional research is suggested since there seems to be a qualitative relation in which the larger the number of buildings in a postal code area, the larger the number of buildings per individual transformer.

### 7.2.3 Nominal capacity per building

Each transformer has a certain nominal capacity, which is used for the provision of electricity to a certain number of buildings. For a large number of buildings, with the same electricity demand, a high transformer capacity is required, which can be achieved by installing one transformer with a very high nominal capacity, or by placing multiple transformers with lower nominal capacity. Perhaps a relation between the nominal capacity per building can be observed when plotted for each of the model districts. The nominal capacity per PC4 area is determined by taking the sum of nominal capacity of all transformers located in that PC4 area. The number of buildings per PC4 area is constructed by adding the number of commercial and residential buildings.

The electricity demand of households and commercial buildings is not the same. Data about the electricity demand per dwelling or commercial building per transformer is not available. Therefore an assumption is made about the nominal capacity attributed to dwellings and commercial buildings. The annual electricity demand per dwelling in 2013 is assumed to be 3.333 kWh, and for a commercial building 21.992 kWh/year (see Chapter 5). Therefore commercial buildings are assigned a factor 6,6 compared to dwellings in the attribution of nominal capacity per building. The resulting nominal capacity per building is included in Figure 52.

Several general conclusions can be drawn:

- The capacity per building is smallest for the urban pre-war and after-war districts, followed by the small urban districts[29].

[29] Possible explanation: these are the oldest electricity networks with the smallest transformers?

- The capacity per building is highest for the green-urban districts[30]
- The 7 remaining districts (centrum-urban plus, centrum-urban, centrum-small urban, green-small urban, centrum-village, village, and rural accessible) all have an average nominal capacity per building of approximately 4 kVA.
- The ratio households and companies per PC4 area influences the average nominal capacity per building. The outliers with high nominal capacity (>100 kVA per building) are all areas with more companies than households.

Besides these general conclusions, no usable relation between the model district and the nominal capacity per building is found. It is however remarkable that many of the districts have an average nominal capacity of 4 kVA per building. To place this in perspective, in newly build areas the general rule of thumb is to assign 1,1 kVA to each household during initial network design [Asare-Bediako et al., 2014]. The top-down analysis with the nominal capacity as a starting point thus results in approximately 4 kVA per building, while in the bottom-up a nominal capacity of 1,1 kVA per household is used. The large difference can be partially explained by the fact that the current loading of the transformers in the operating area is 60% (see section 7.1.2), meaning unused capacity is available at the transformers. Apparently the installed nominal capacity is substantially higher than the strictly required nominal capacity at most of the transformers. The remainder of the difference is explained by the higher nominal capacity assigned to commercial buildings. For commercial buildings the capacity is determined based on the peak demand. Additional investigation on the reserve capacity is recommended.

[30] Possible explanation: relatively large distance between buildings, which results in more transformers, which results in a higher capacity per building?

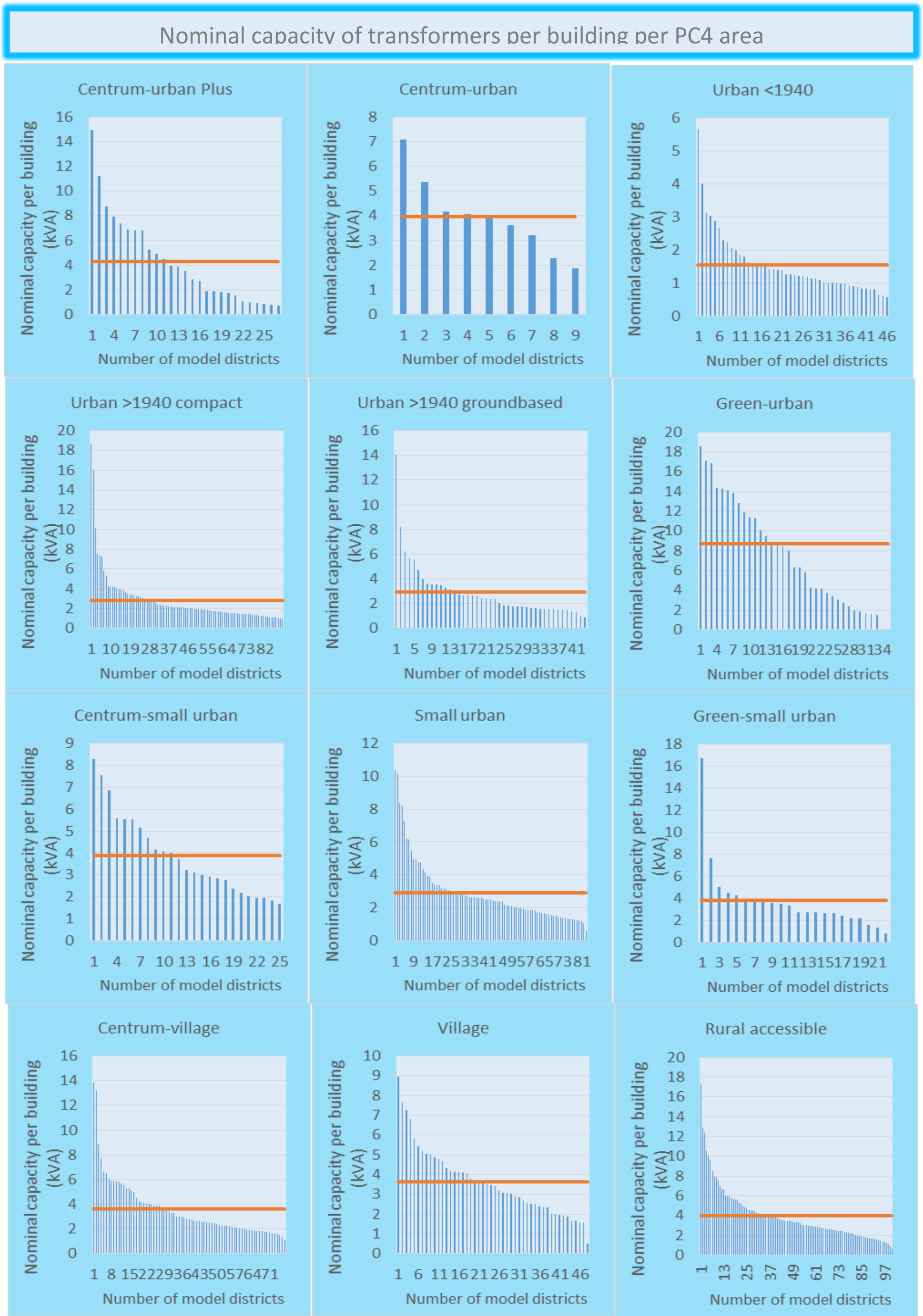



*Figure 52: Nominal capacity per building per PC4 area.*

### 7.2.4 Relationship urban density and transformer capacity

During this research multiple discussions resulted in the assumption that rural areas contain small transformers (with a small nominal capacity), and urban areas contain large transformers. Also Asare-Bediako et al. [2014a] assume a high transformer capacity in dense urban areas, and small transformer capacities in rural areas (see Table 19).

*Table 19: Relation distribution transformers and connected households in the Netherlands according to* [Asare-Bediako et al., 2014]

| Transformer capacity | Number of connected households | Locations |
|---|---|---|
| 630 kVA | 300 – 350 | Highly dense areas |
| 400 kVA | 200 – 250 | Normal cities |
| 250 kVA | 100 – 150 | Cities and towns |
| 100 kVA | 40 – 60 | Rural areas |

Therefore the relation between the model districts and the distribution of different transformer capacities is investigated (see Figure 53). 100 kVA transformers are indeed mainly located in the more rural areas. However, for the remaining transformer capacities there is no clear relation. Therefore the assumption that rural areas contain small capacity transformers and urban areas contain large capacity transformers is not valid[31].

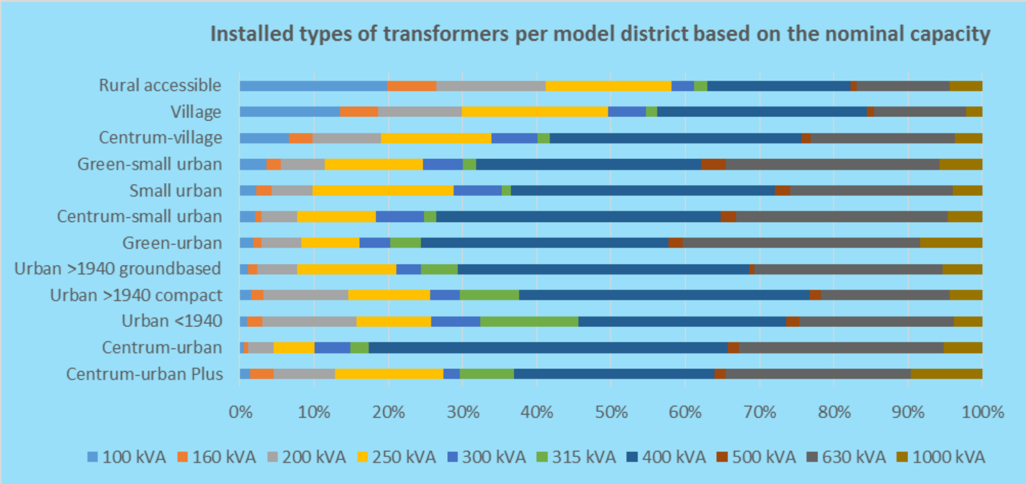



*Figure 53: Distribution of transformer capacities per model district in the operating area of Stedin.*

## 7.3 Individual transformers coupled to model districts

The previous approach, as explained in section 7.2, tried to construct model transformers that accompany model districts by using the model districts as a starting point. In this section no grouping or segmenting of transformers is applied, but rather an approach to use the individual transformer data and try to determine the future loading rate of these transformers.

The total network load consists of the net-load of residential and commercial buildings combined. To determine the future loading of MV/LV-transformers the percentual increase between the current and future peak demands are determined for each model district by calculating the current peak demand and the peak demand in 2040. This increase is added to the current percentual loading rate of the transformers to obtain the future loading rate. This thus requires data about the location (postal code) and the current loading rate as a percentage of the nominal capacity of the MV/LV-transformers.

[31] The distribution of transformer capacity categories in the different model districts is based on the PC4 areas. Therefore the figure can be misleading since each PC4 area contains multiple transformers, but only one model district type is applied. It could be that when applying smaller model districts the distributions of the transformer types changes, and the conclusion could change as well.

Two databases have been coupled to obtain the postal code of the transformer and the current maximum loading rate. The increase in peak demand per model district is also available (see section 8.3). Therefore, this approach is used in the remainder of this research.

***Data availability current loading rate transformers***

The databases are, however, not complete. The total stock of distribution transformers consists of 22.286 transformers. For the region of Utrecht the current load demand are estimated rather than determined for each of the transformers. Therefore the location of the specific load demand is unknown, making it impossible to provide a load demand for the individual transformers. As a result, the 6.525 transformers in the region of Utrecht are not included in the remainder of this research, which is 29% of the entire transformer stock.

The transformer loading rate is registered by manually noting down the ID of the transformer and the current loading rate. These results can be coupled to the other characteristics of the transformers, such as the nominal capacity or building year, by using the ID of the transformer and relating them to the ID of the junction used for the distribution buildings of the transformers. However, not all junction ID's are available in the database, which resulted in the inability to couple the postal code location to 842 transformers, which is 4% of the entire stock. Unfortunately these transformers are also excluded from the analysis. A large degree of these transformers were located in the region of Delft and Gouda.

Overall, the current load demand and the location of 14.919 transformers are available. This represents 67% of the total stock of distribution transformers.

## 7.4 Conclusion

To conclude, the number of transformers per postal code (PC4) area ranges between 1 and 180 transformers. The number of buildings per transformer ranges between 1 and 400 buildings, and the nominal capacity per building ranges between 1 and 18 kVA per building. The most striking relation is that a smaller number of buildings per PC4 area results in a smaller number of buildings per transformer, and vice versa. However, no usable relation was found between the model districts and the transformers when analysing the different model districts for the number of transformers, the number of buildings per transformer, and the nominal capacity per building. Therefore it is not possible to couple model types of transformers to the model districts.

Grouping or segmenting of the transformers is not possible, and therefore the future load demand of the transformers is determined by analysing the individual transformers. The transformers are used as a starting point, after which the model district type is determined for each of the transformers, and the percentual increase in peak demand (between 2013 and 2040) is added to the current maximum loading rate (in 2013) of the individual transformers. This results in the future loading rate for each of the transformers in 2040.

# 8. Results

In the previous chapters the model districts have been specified by attributing a proportion of the future energy scenario to each of the model districts. Additionally the relation between the model districts and the electricity grid is investigated, but it is concluded that there is no clear relation by which standard types of transformers can be assigned to the model districts.

This chapter combines the load profiles of the individual demand and supply profiles to construct the net-electricity demand profiles of the model districts. The resulting (future) peak demand is used to calculate the future load demand of the individual distribution transformers.

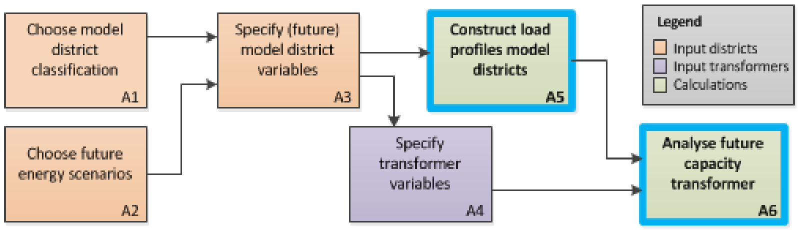



*Figure 54: Overview general approach of this research. This chapter focusses on the results of the load profiles and the future loading of the distribution transformers.*

This chapter starts with the description of the load profiles of the model districts during the summer and winter (section 8.1). The highest annual net-electricity demand in the load profiles represents the peak demand, which are discussed per residential and commercial building (section 8.3), followed by the overall increase in peak demand for the entire districts between 2013 and 2040 (section 8.4). This increase in peak demand is used to determine the future load demand of the distribution transformers in section 8.5, followed by a discussion of the results (8.6), and the conclusion (8.7).

## 8.1 Load profile per model district

The load demand of the model districts are constructed for an entire year on an hourly interval. These are based on the three scenarios of **Paces**, **Tides**, and **Circles**, for which the year of interest is the year 2040. Other years that can be chosen as year of interest are 2020, 2030, and 2050. For each model district, in each of the scenarios, the hour with the highest net-electricity demand of the year is the day that represents the extreme winter day. The day in which the hour with the highest net-electricity supply of the year is located, is the extreme summer day.

The load profile of a district consists of the basic electricity demand, the heat pump demand, and the PV supply for both residential and commercial buildings. Combined, these load profiles result in the net-electricity demand[32] of the district. The basic residential demand has a significant peak during the evening, while the basic commercial demand is high during the day and reduces during the night. The electrical demand of the residential and commercial heat pumps are similar in shape, causing a

[32] The load profiles are presented as a stacked graph. This means some caution is advised in interpreting the profiles.

Figure 55 shows the stacked graph, as well as the net-electricity demand of the centrum-urban plus district. The PV supply is subtracted from the total demand of buildings and heat pumps, which means the bottom of the PV supply presents the net-electricity demand of the district.

high demand in the morning, and an increase in demand during the evening. The PV supply is highest during the middle of the day, for both residential and commercial supply. The PV profile is negative since it represents a supply profile instead of a demand profile, and the PV profile does not contain fluctuations since it is assumed to be sunny throughout the year to simulate extreme situations (see section 6.2.3). These observations can be used in future research to identify suitable methods to reduce the peak demand, by means of Demand Side Management (DSM) (see e.g. [Luo et al., 2010]).

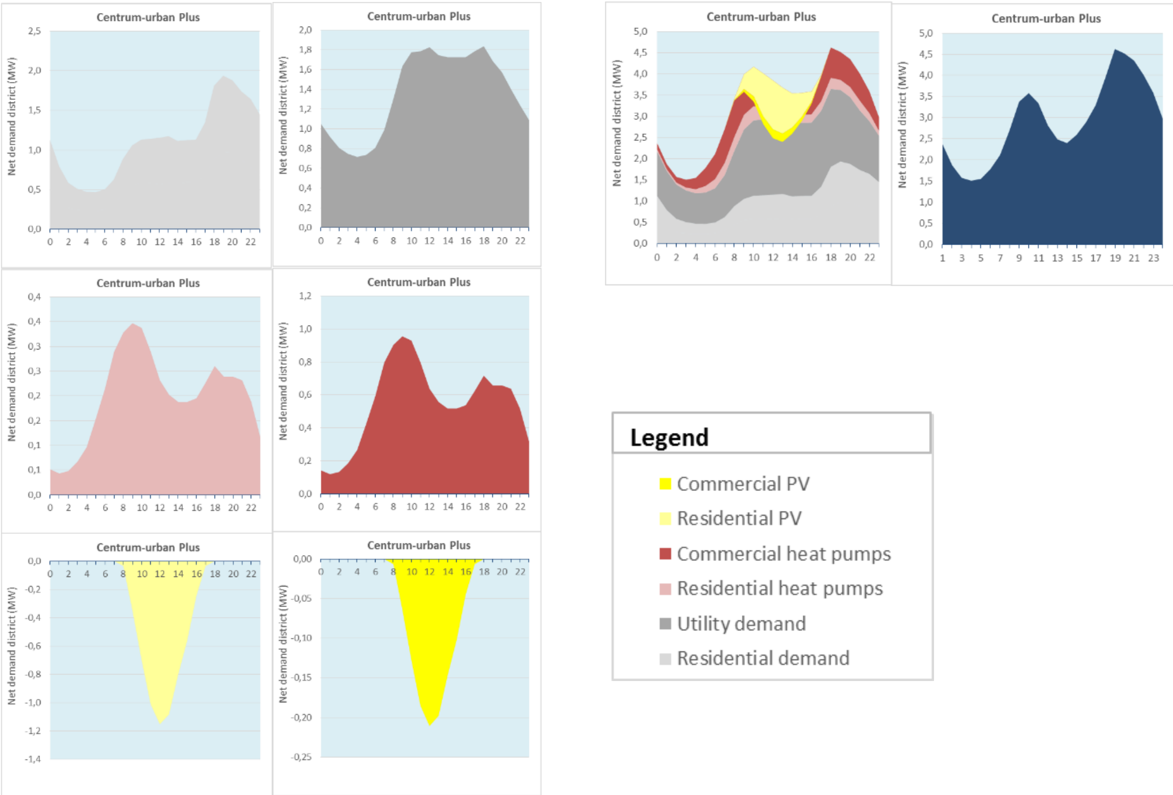



*Figure 55: Load profiles of centrum-urban plus district in **Paces** 2040. The example shows that the combined stacked graphs (right) are less easily interpretable than the individual load demand profiles of the demands and supplies (left). The net-electricity demand of the model district is provided by the blue area in the top-right graph.*

The load profile is constructed for each of the model districts. Since there is a large overlap in the general structure of the load profiles just 4 model district load profiles are visualised. These are the centrum-urban plus, urban >1940 compact, small urban, and rural accessible districts. Those districts are chosen because the first is the most urban, and the last is the most rural, while the urban >1940 compact, and the small urban districts have a large share of the number of buildings in the operating area. This results in the most extreme types of districts, while also maintaining a good representation of the operating area.

### 8.1.1 Load profiles extreme winter day

This section describes the load profiles of the extreme winter situation. The load profiles of the 4 model districts for the year 2040 are provided in Figure 56. High level observations of the results are:

- During the day there are two peaks, and two valleys for all districts. The first peak demand is during the morning (between 7:00 and 10:00 hours), followed by a valley (between 10:00 and 15:00 hours), followed by the second peak demand during the evening (between 15:00 hours and 21:00 hours), after which the night demand drops (creating a valley between 21:00 hours and 7:00 hours).

- The PV supply reduces the height of the morning peak in all scenarios and for all districts. During the evening peak there is no PV supply.
- The **Paces** and **Tides** scenarios are roughly similar in the net-electricity demand, and the highest peak demand is during the evening peak. This peak is caused by the basic electricity demand, and the heat pump demand of residential and commercial buildings. In the **Circles** scenario the evening peaks are still dominant, although the morning peaks are also high. For the rural accessible and village districts the PV supply peak is higher than the (evening) demand peak.
- For most districts in the **Paces** scenarios the largest fluctuations in daily electricity demand are caused by the basic electricity demand, followed by the PV supply. The village and rural accessible are the exception since in these districts the PV supply causes the largest fluctuations during the day, followed by the basic electricity demand. The largest fluctuations in the urban districts for the **Tides** scenario are also caused by the basic electricity demand, but for the rural districts the PV supply causes the largest fluctuations. In the **Circles** scenario the largest fluctuations are all caused by PV supply, followed by electricity demand of heat pumps.

Generally speaking, the load profiles indicate that in the **Paces** and **Tides** scenarios all districts have the highest demand during the evening. Approximately ¾ of this demand is caused by the basic electricity demand, and ¼ by the electrical demand of heat pumps. For most districts in the **Paces** scenario, and the urban districts in the **Tides** scenario, the largest fluctuations in demand are caused by the basic electricity demand, followed by the PV supply. In the rural districts of the **Tides** scenario, and the rural accessible and village districts in the **Paces** scenario, the largest fluctuations are caused by the PV supply, followed by the basic electricity demand. The **Circles** scenario shows substantially different load profiles, in which the morning and evening peaks are closer together. In all (Circle) districts the PV supply is the dominant factor in the fluctuations, followed by the electricity demand of heat pumps.

In this modelling approach the assumption is made that each day is a sunny day with maximum PV electricity production. Would the results be different if there is a cloudy day during the winter, with only limited PV supply? In the **Paces** and **Tides** scenarios the net-peak demand of the districts would remain during the evening. The morning peak would become higher, but the fluctuations in demand would become smaller, especially in the village and rural accessible districts. In the **Circles** scenario the net-peak demand of the village and rural accessible districts would reduce since the PV supply is responsible for the largest supply peak. For all districts in the **Circles** scenario the morning peak would become nearly as high as the evening peak, and the fluctuations in demand would reduce significantly.

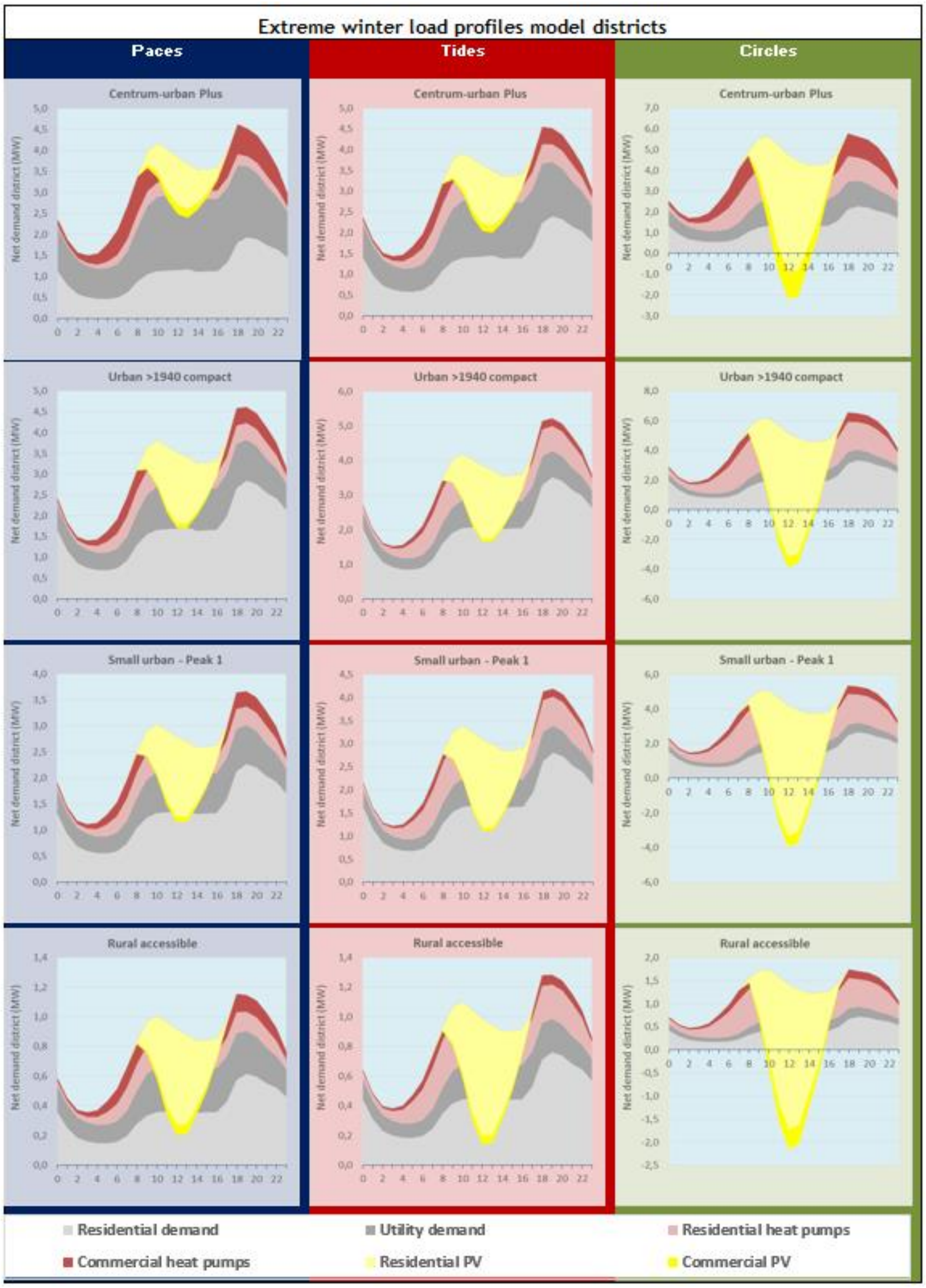



*Figure 56: Extreme winter-day load profiles of selected model districts for the year 2040, based on the 3 scenarios.*

### 8.1.2 Load profiles extreme summer day

The extreme summer load profiles of the 4 model districts for the year 2040 are provided in Figure 57. High level observations of scenarios:

- The PV supply largely influence the load profile of the districts for all scenarios. This is mainly residential PV supply.
- There is nearly no electricity demand of the heat pumps.
- The highest peak demand is during the late evening around 22:00 hours.
- The highest net-peak demand is caused by the basic electricity demand in the urban **Paces** districts, and the centrum-urban plus district in the **Tides** scenario. In all other cases the highest net-peak demand is caused by the PV supply peak, followed by the basic electricity demand.

During the extreme summer days the PV supply is clearly dominant in the load profile. The PV supply is responsible for the largest net-peak demand, and for the largest fluctuations in the daily electricity demand in most districts. Only the rural districts in the **Paces** scenario and the centrum-urban plus district in the **Circles** scenario have a net-peak demand caused by the basic electricity demand. Looking at the net-demand of the districts it is remarkable to observe a late demand peak during the evening (during which no PV supply is available).

What would be the influence of a cloudy day? The highest peak demand would shift from the late evening (22:00 hours) towards the beginning of the evening (18:00 hours), and become slightly higher. The highest net-peak demand of the district would reduce without the supply peak of PV, and the daily demand fluctuations would reduce significantly. However, in the urban districts in the **Paces** scenario and the centrum-urban plus district in the **Tides** scenario the highest net-peak demand remains to be caused by the basic electricity demand and heat pump demand. The peak shifts from the late evening towards the beginning of the evening, and would become slightly higher.

### 8.1.3 Yearly observations

The extreme summer and winter days have been discussed in isolation, although there are also some observations when combining the two, or considering the entire year load profiles.

Overall observations:

- The yearly net-electricity demand in the **Circles** scenario is negative for all districts, meaning that the PV supply is higher than the yearly electricity demand of the districts.
- The winter load profiles show diversified results for the model districts. The heat pumps and the basic electricity demand generally cause the highest peak demand during the beginning of the evening.
- The summer load profiles are dominated by the PV supply. The PV supply peak is responsible for the highest net-peak demand for all districts in the **Circles** scenario, all districts except for the centrum-urban plus district in the **Tides** scenario, and the rural districts in the **Tides** scenario. In the remaining districts the basic electricity demand causes the highest net-peak demand.

Many more conclusions can be drawn for the individual model districts for the different scenarios. The load profiles are especially useful for determining the best approach to reduce the peak demands, and the feasibility of peak reduction measures like demand response, storage, or expansion of the network capacity. However, the aim of this research is to investigate the impact of the load demands of the districts on the distribution transformers. Therefore the next sections focus specifically on the peak demands, and the impact on the distribution transformers.

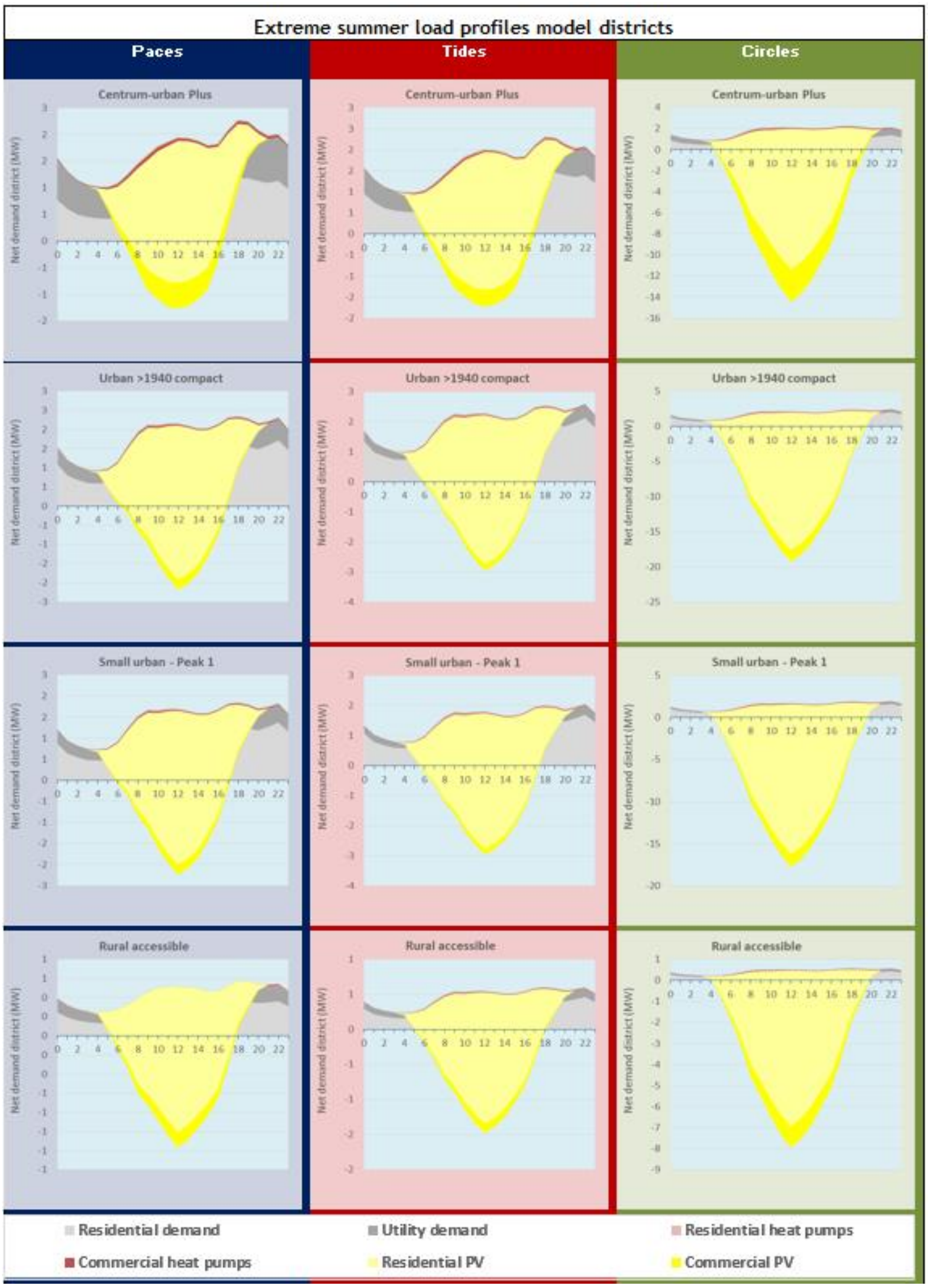



*Figure 57: Extreme summer-day load profiles of selected model districts for the year 2040, based on the 3 scenarios.*

## 8.2 Developments throughout the years

The sight year is 2040, but other years provide insight into the developments and tipping points in the developments throughout the years. Therefore the load profiles of the centrum-urban plus district are used as an example to indicate the changing demand in the years 2020, 2030, 2040 and 2050 (see also section 5.4 for the trends in the scenarios). Winter load profiles are included in Figure 58, and the summer load profiles in Figure 59.

In the winter and summer load profiles the difference between the scenarios are clearly visualised. In the **Paces** scenario the basic electricity demand declines throughout the years, while in the **Tides** scenario a wave of initial increase is observed until 2020, followed by a substantial decrease in 2030, after which the demand increases again until 2040. The **Circles** scenario assume a parabolic increase in basic electricity demand until 2050.

The deployment rates of residential and commercial heat pumps follows the same (linear) upward trend throughout the years, while in the **Tides** scenario the deployment of residential heat pumps are is higher than in the **Paces** scenario. The **Circles** scenario has the highest deployment of heat pumps compared to the other scenarios.

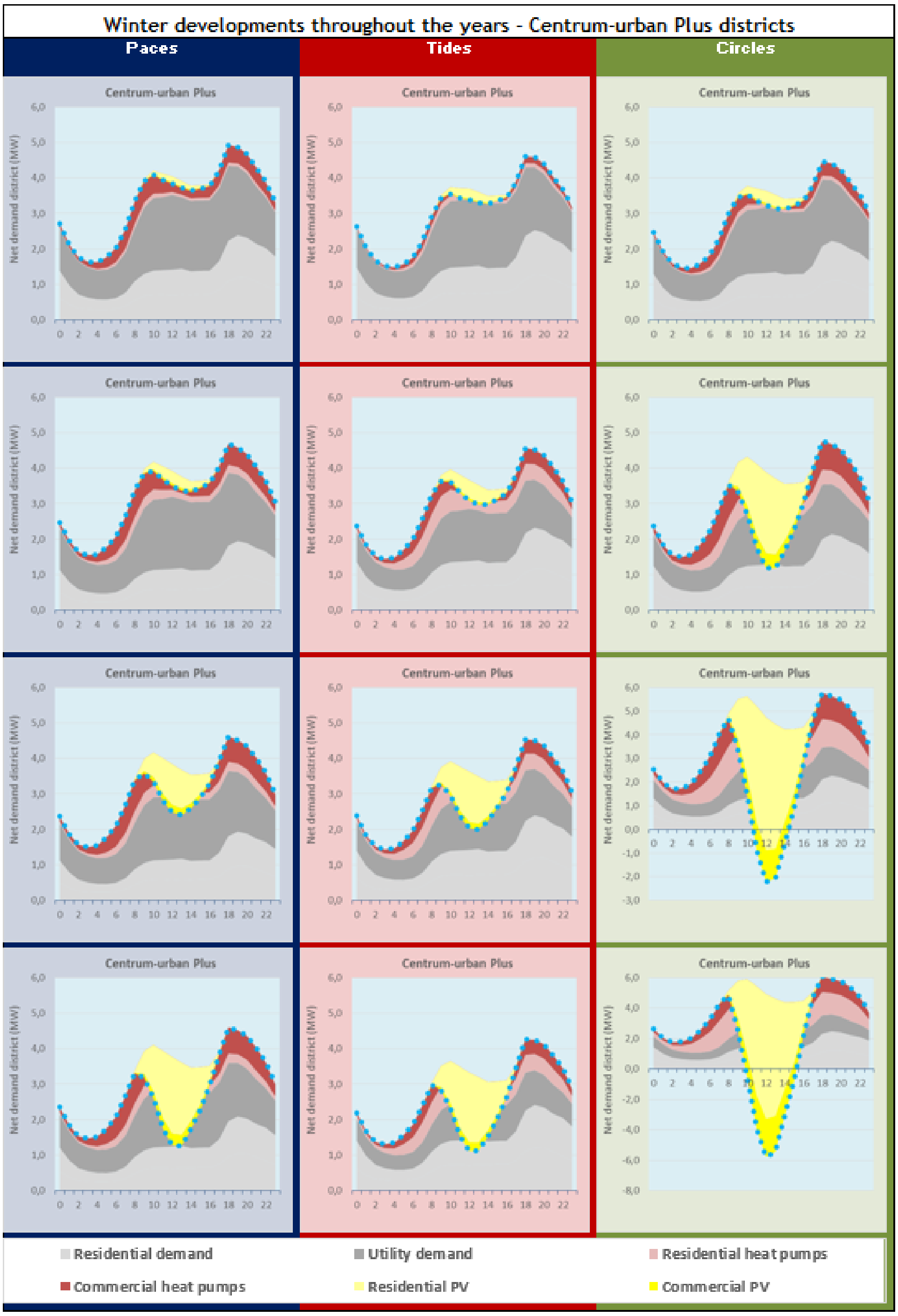



*Figure 58: Winter load profile of the centrum-urban plus districts throughout the years for the three scenarios.*

The PV deployment is similar to the heat pump deployment trends in the three scenarios. The **Paces** and **Tides** scenario have a nearly similar installed capacity throughout the years, while the **Circles** scenario assume a substantially larger deployment rate of PV compared to the other districts.

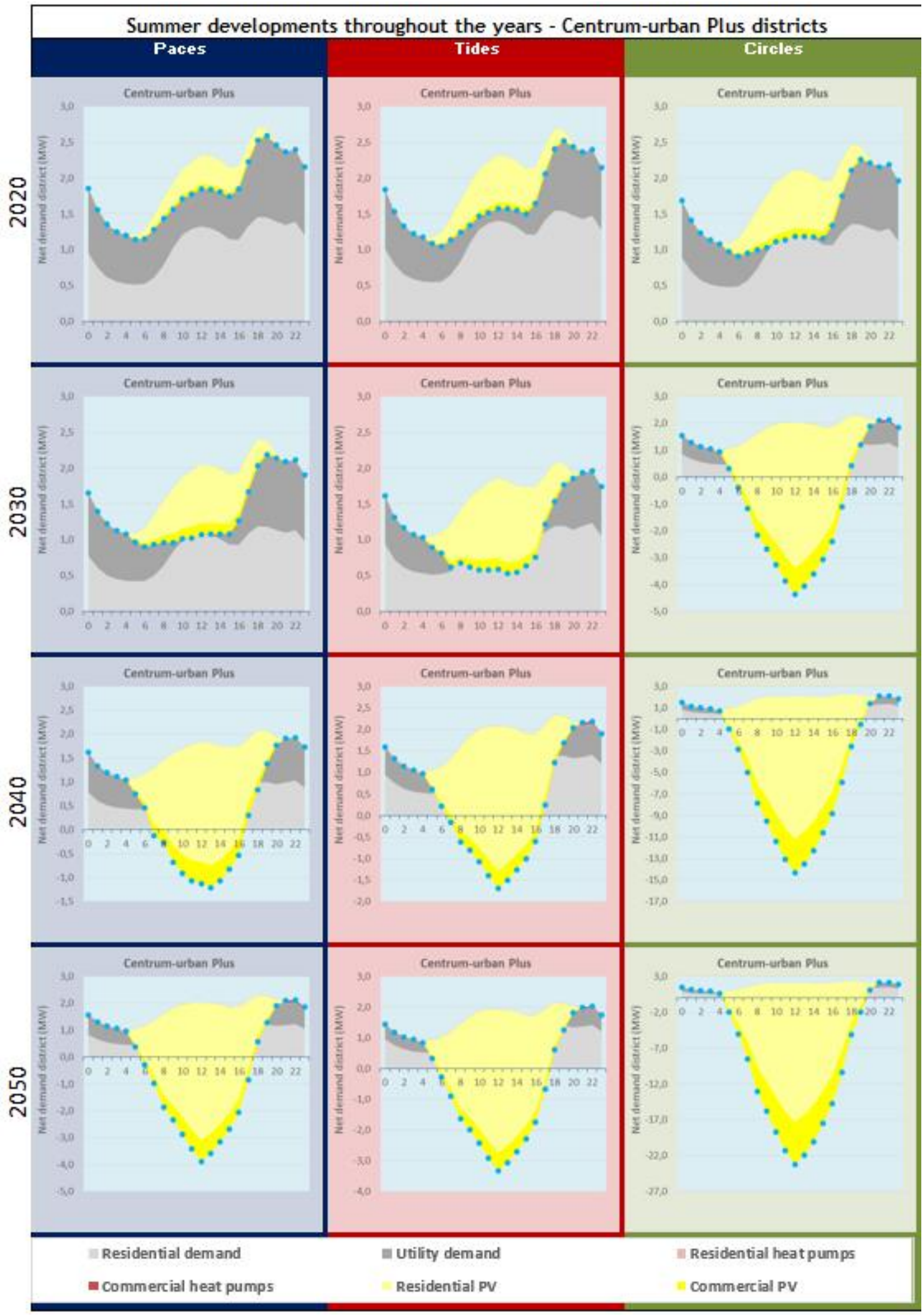



*Figure 59: Summer load profile of the centrum-urban plus districts throughout the years for the three scenarios.*

## 8.3 Peak demand per model district

There are roughly 3 categories in which the model districts can be divided when looking at the peak demand per dwelling (see Figure 60). The most urban districts (first 5) have a relatively low peak demand, the most rural districts (last 3) have a relatively high peak demand, and the intermediate districts have a relatively intermediate peak demand. Generally speaking, the more rural a district is, the higher the peak demand per dwelling.

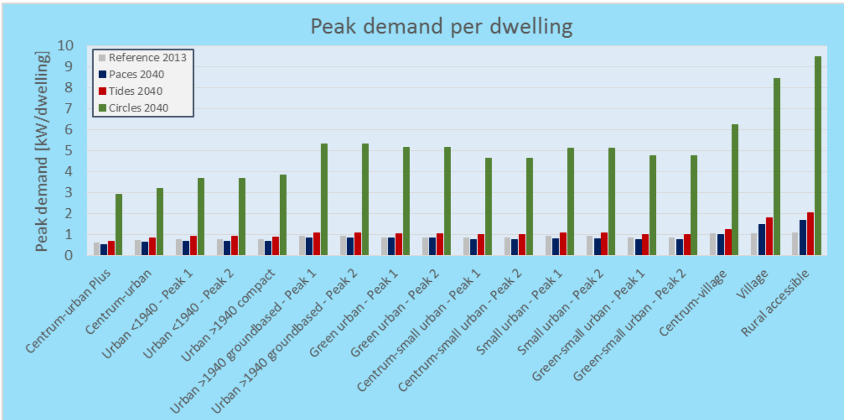



*Figure 60: Peak demand per dwelling per model district.*

Looking at the peak demand per utility building reveals a large similarity in the peak demands of districts (see Figure 61). This is due to the modelling approach in which there is no differentiation between the types of commercial buildings in the different model districts. There is, however, a large increase in peak demand per utility building in the last 5 (or most rural) districts in the **Circles** scenario due to the high penetration rate of PV capacity. This is the only variable that differs for the commercial buildings in the different model districts.

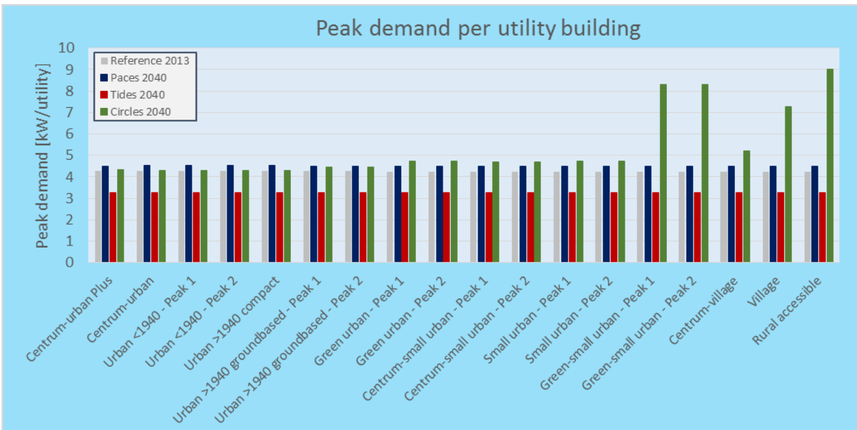



*Figure 61: Peak demand per commercial building per model district.*

## 8.4 Increase in peak demand

This section discusses the increase in peak demand within the model districts between 2013 and 2040. The peak demand is useful in itself to understand the causes of the increase in demand in the model districts, and is required to determine the future load demand of the distribution transformers (see Chapter 7). The percentual increase of the peak demand per model is provided in Table 21. To explain the differences between the peak demands in the scenarios the differences in the assumptions between the scenarios are included in Table 20.

*Table 20: Comparison of the assumptions in the scenarios. The basic electricity demand is presented as the increase in demand compared to 2013. The PV and heat pump deployment are scaled in relation to the other scenarios, meaning each row adds up to 1.*

| Ratios beteen scenarios in 2040 | Paces | Tides | Circles |
|---|---|---|---|
| Residential electricity demand (compared to 2013) | 79% | 98% | 93% |
| Commercial electricity demand (compared to 2013) | 87% | 68% | 64% |
| PV deployment | 0,1 | 0,2 | 0,7 |
| Heat pump deployment - Residential | 0,2 | 0,3 | 0,6 |
| Heat pump deployment - Commercial | 0,3 | 0,2 | 0,5 |

The **Paces** scenario has the lowest increase in peak demand compared to the other scenarios, and even results in a reduction of the peak demand for most districts. This is caused by the reduced basic electricity demand for both residential and commercial buildings[33], and a relatively small deployment of PV and residential heat pumps. The village and rural accessible districts have a higher proportion of the PV deployment due to the additional differentiation factor for the geographical differences in deployment based on the current deployment and expected future deployment (see 6.2.3), which is higher for the more rural districts (see Table 21). For the 3 most urban districts the highest annual peak demand occurs during the summer, while for the remaining districts the peak occurs during the winter.

For most model districts in the **Tides** scenario there is a moderate increase in peak demand. The centrum-urban plus district has a decrease in peak demand caused by the relatively high share of commercial buildings (see Table 12 on page 52), of which the basic electricity demand is low (68% compared to 2040), as is the commercial heat pump deployment (lowest of all districts). The urban >1940 districts have a substantial increase in peak demand, caused by the relatively high share of residential buildings with a relatively high basic electricity demand. Based on the ratio between residential and commercial buildings, the basic electricity demand, and the proportion of PV assigned to the model districts, the peak demands of the other model districts can also be explained in a similar line of reasoning. The 2 most urban districts have a peak demand during the summer, while the remaining districts have a highest annual peak demand during the winter.

All model districts have a significant increase in peak demand for the **Circles** scenario, ranging from 231% up until 600% increase in the peak demand compared to 2013. This peak demand occurs during the summer and is caused by the supply peak of PV. Since the **Circles** scenario assumes a substantially higher deployment rate of PV compared to the other two scenarios, the resulting peak demand is also substantially higher[34]. Within the **Paces** and **Tides** scenarios the village and rural accessible have a relatively high proportion of the overall installed capacity in the operating area, which also results in a summer supply peak for these districts which is substantially higher than the winter demand peak as occurs in the other districts. Overall, the village and rural accessible districts have the highest peak demand increase for all 3 scenarios.

[33] In **Paces** the residential electricity demand is 79% in 2040 compared to the demand in 2040, and for commercial buildings 87%.

[34] In 2040 the overall PV deployment in the operating area is 3,1 GWp in **Paces**, 3,8 GWp in **Tides**, and 16,4 GWp in **Circles**. The installed capacity of PV in the **Circles** scenario is thus approximately 4 till 5 times higher than in the other scenarios.

*Table 21: Peak demand per model district per scenario. The increase in peak demand is the increase compared to 2013 and for the whole district. The ration of commercial and residential buildings is determined by dividing the number of commercial buildings by the number of residential buildings.*

| | Increase peak demand compared to 2013 | | | Ratio commercial and residential buildings |
|---|---|---|---|---|
| | Paces | Tides | Circles | |
| Centrum-urban Plus | -2% | -4% | 231% | 0,14 |
| Centrum-urban | -4% | 0% | 233% | 0,12 |
| Urban <1940 - Peak 1 | -7% | 4% | 287% | 0,08 |
| Urban <1940 - Peak 2 | -8% | 6% | 308% | 0,06 |
| Urban >1940 compact | -7% | 13% | 293% | 0,07 |
| Urban >1940 groundbased - Peak 1 | -8% | 22% | 361% | 0,05 |
| Urban >1940 groundbased - Peak 2 | -8% | 9% | 406% | 0,06 |
| Green urban - Peak 1 | -1% | -1% | 302% | 0,19 |
| Green urban - Peak 2 | -4% | 4% | 359% | 0,12 |
| Centrum-small urban - Peak 1 | -6% | 4% | 337% | 0,09 |
| Centrum-small urban - Peak 2 | -6% | 4% | 333% | 0,10 |
| Small urban - Peak 1 | -7% | 7% | 376% | 0,08 |
| Small urban - Peak 2 | -7% | 8% | 390% | 0,07 |
| Green-small urban - Peak 1 | -3% | 2% | 354% | 0,13 |
| Green-small urban - Peak 2 | -7% | 7% | 393% | 0,08 |
| Centrum-village | -7% | 12% | 422% | 0,08 |
| Village | 21% | 49% | 577% | 0,10 |
| Rural accessible | 24% | 51% | 600% | 0,13 |

To conclude, the increase in peak demand can be explained by using the ratios between the scenarios (based on the underlying assumptions) in combination with the ratio of residential and commercial buildings within a model district. Substantial increases in the peak demand are mainly caused by the PV supply peak, which occurs at the village and rural accessible districts (for all scenarios), and for all districts in the **Circles** scenario.

## 8.5 Future load demand transformers

The increase in peak demand between 2013 and 2040 per model district (see Table 21) is used to determine the future load demand of the MV/LV-transformers. The following formula is applied:

*Future load demand (%) = Current loading (%) x [1 + Increase in peak demand in model district (%)]*

The resulting percentage of transformer that are overloaded, meaning a load demand higher than 120% of the nominal capacity, are included in Table 22. This is based on the single highest peak. The resulting load demands of the transformers lead to the following observations:

- Currently (in 2013), between 0% and 2% of the transformers in the model districts are overloaded (above 120% of the nominal capacity). The rural areas are slightly more overloaded than the urban areas.
- The **Paces** scenario increases the number of transformers that are overloaded in the village and rural accessible districts. The other districts either have a small decrease of the overloaded transformers, or a slight increase.
- The **Tides** scenario increases the transformers in the village and rural accessible districts to increase substantially (17% and 16% of the stock overloaded respectively). A relatively remarkable increase is observed for the urban >1940 groundbased peak 1 district, in which 9% of the transformers are overloaded. The remaining districts are comparable with the current situation and the **Paces** scenario.
- The **Circles** scenario causes nearly all transformers to be overloaded in all of the model districts. The percentage of transformers being overloaded above 120% ranges between 80% and 96%.

- The village and rural accessible districts have a significant increase in the number of transformers being overloaded for all three scenarios.

*Table 22: Percentage of transformers overloaded for each model district, with the current situation in 2013 and the future scenarios for 2040.*

| Model districts | Current | Paces | Tides | Circles |
|---|---|---|---|---|
| Centrum-urban Plus | 0% | 0% | 0% | 82% |
| Centrum-urban | 1% | 0% | 1% | 86% |
| Urban <1940 - Peak 1 | 0% | 0% | 0% | 91% |
| Urban <1940 - Peak 2 | 0% | 0% | 1% | 96% |
| Urban >1940 compact | 1% | 1% | 1% | 91% |
| Urban >1940 groundbased - Peak 1 | 1% | 1% | 9% | 92% |
| Urban >1940 groundbased - Peak 2 | 1% | 1% | 1% | 94% |
| Green urban - Peak 1 | 1% | 1% | 1% | 80% |
| Green urban - Peak 2 | 0% | 0% | 0% | 94% |
| Centrum-small urban - Peak 1 | 2% | 2% | 3% | 91% |
| Centrum-small urban - Peak 2 | 0% | 0% | 0% | 92% |
| Small urban - Peak 1 | 1% | 1% | 1% | 92% |
| Small urban - Peak 2 | 0% | 0% | 0% | 87% |
| Green-small urban - Peak 1 | 2% | 2% | 2% | 86% |
| Green-small urban - Peak 2 | 0% | 0% | 0% | 93% |
| Centrum-village | 1% | 1% | 3% | 91% |
| Village | 2% | 6% | 17% | 92% |
| Rural accessible | 1% | 5% | 16% | 92% |

The percentage of overloaded transformers does not indicate if the transformers are just barely overloaded, or highly overloaded. Also it is unclear what the maximum or average loading is of the districts without overloaded transformers. Therefore, in Appendix E the load demand of all transformers within the 18 model districts are plotted for the current situation (in 2013), and the future situation in 2040 for the scenarios **Paces**, **Tides** and **Circles**. However, these detailed images are hard to use in drawing conclusions, therefore the range of loading for the **Tides** scenario are provided in Figure 62.

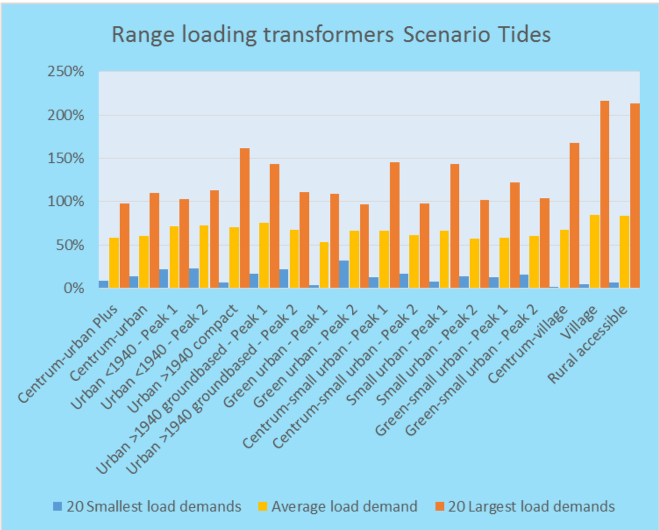



*Figure 62: Range of transformer loading for **Tides** scenario. For the smallest and largest load demands the average of the 20 smallest and largest values are used.*

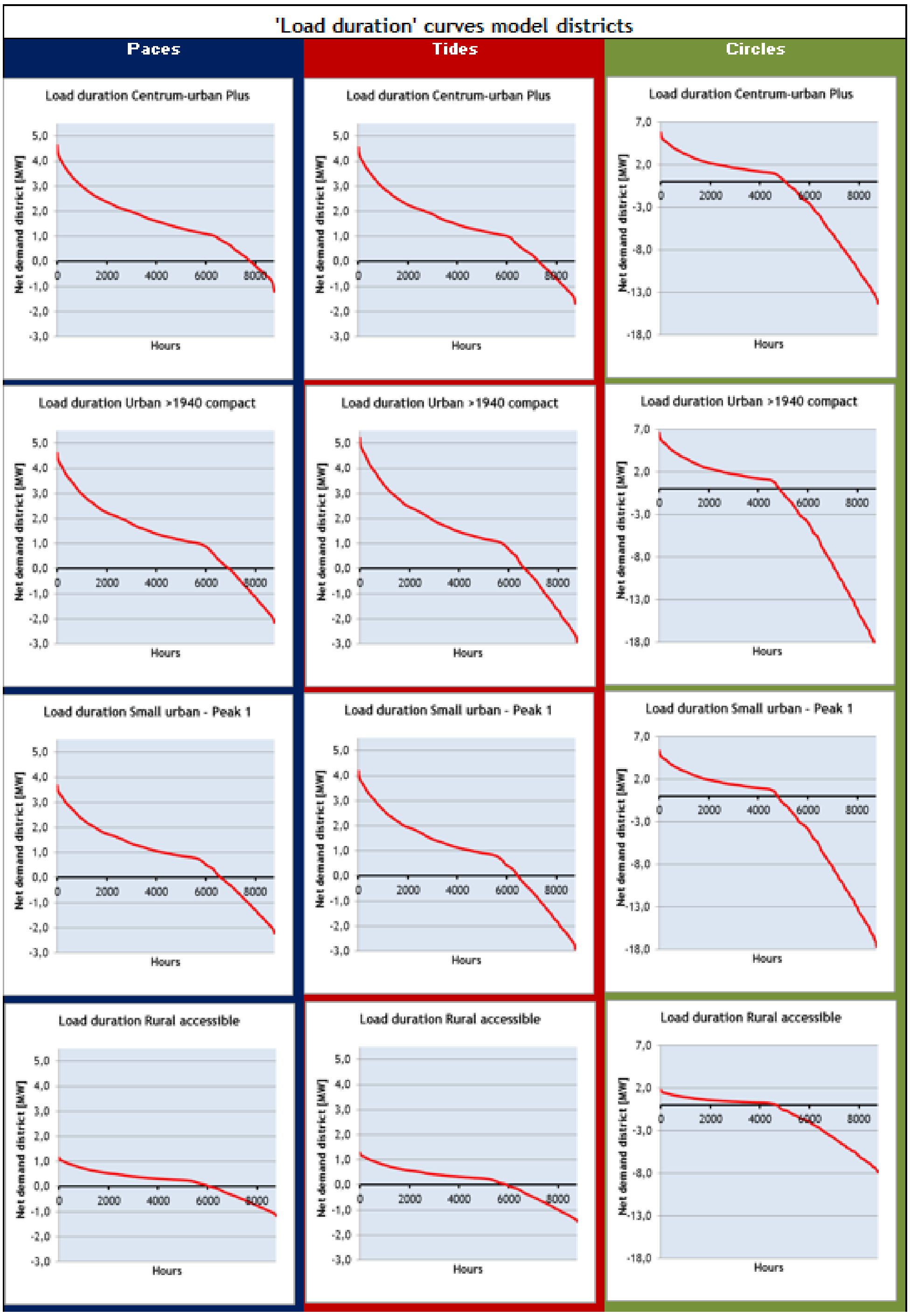



*Figure 63: 'Load duration' curves per model district for the year 2040, based on 3 scenarios. Normally load duration curves provide the absolute load demands, but since insight into the supply peak is valuable this adapted version is preferred by the client. The vertical axis of the* ***Paces*** *and* ***Tides*** *scenario are fixed on the same interval, while the graphs for the* ***Circles*** *scenario have its own fixed interval due to the large deviation that occurs at this scenario compared to the other two.*

The figure indicates the range of loading of the distribution transformers. The transformers in the green-urban peak 2 districts have the smallest range, meaning the difference between the largest loading rate and the smallest load demands is the smallest. The largest range is observed in the transformers located in the rural accessible districts. In this scenario the average transformer in each of the districts is below the maximum loading range of 120%. Similar results are observed in the other two scenarios.

Additionally the annual load duration curves provide insight into the distribution of the load demand in the model districts (see Figure 63). The load duration curves consists of two parts; the demand peaks and the supply peaks. The largest demand peaks quickly reduce to lower values, and an S-curve can be observed, while the supply peaks have a more linear shape in which the largest supply peaks have a less steep declination rate compared to the demand peaks.  As can be observed in the graphs of Figure 63 the supply peak is most influential in the **Circles** scenario.

## 8.6 Discussion of results

### *Load profiles*

The load profiles provide insights into the moment in which the peak demand occurs, the demand or supply that causes the peak demand, as well as the fluctuations in demand and supply. In the **Paces** and **Tides** scenarios most districts have the highest peak demand during the winter, for which the basic electricity demand is the largest cause, followed by the heat pump demand and the PV supply (see Table 23). Exceptions are the rural areas with the (centrum) village and rural accessible districts in which the highest peak demand is during the summer, and caused by the supply peak of PV, followed by the basic electricity demand. Also in the **Circles** scenario the summer PV peak supply is the largest influencer of the annual peak demand. In this scenario there are no exceptions, and in all districts the PV is largely responsible for the peak demand of the districts. In the **Circles** scenario the annual PV supply even exceeds the annual demand of the districts. This is due to the modelling approach in which an extreme PV profile is used with clear skies throughout the years to model extreme situations that the distribution transformers need to be designed for.

*Table 23: For each of the model districts the time at which the highest annual peak demand is registered, and identification of the main cause in the high demand with 1 being the highest. Categories are the basic electricity demand, PV supply, or heat pump demand.*

| Model district | Paces | Main cause | | | Tides | Main cause | | | Circles | Main cause | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Summer or winter peak? | Basic | PV | HP | Summer or winter peak? | Basic | PV | HP | Summer or winter peak? | Basic | PV | HP |
| Centrum-urban Plus | Winter | 1 | 3 | 2 | Winter | 1 | 3 | 2 | Summer | 2 | 1 | 3 |
| Centrum-urban | Winter | 1 | 3 | 2 | Winter | 1 | 3 | 2 | Summer | 2 | 1 | 3 |
| Urban <1940 - Peak 1 | Winter | 1 | 3 | 2 | Winter | 1 | 3 | 2 | Summer | 2 | 1 | 3 |
| Urban <1940 - Peak 2 | Winter | 1 | 3 | 2 | Winter | 1 | 3 | 2 | Summer | 2 | 1 | 3 |
| Urban >1940 compact | Winter | 1 | 3 | 2 | Winter | 1 | 3 | 2 | Summer | 2 | 1 | 3 |
| Urban >1940 groundbased - Peak 1 | Winter | 1 | 3 | 2 | Winter | 1 | 3 | 2 | Summer | 2 | 1 | 3 |
| Urban >1940 groundbased - Peak 2 | Winter | 1 | 3 | 2 | Winter | 1 | 3 | 2 | Summer | 2 | 1 | 3 |
| Green urban - Peak 1 | Winter | 1 | 3 | 2 | Winter | 1 | 3 | 2 | Summer | 2 | 1 | 3 |
| Green urban - Peak 2 | Winter | 1 | 3 | 2 | Winter | 1 | 3 | 2 | Summer | 2 | 1 | 3 |
| Centrum-small urban - Peak 1 | Winter | 1 | 3 | 2 | Winter | 1 | 3 | 2 | Summer | 2 | 1 | 3 |
| Centrum-small urban - Peak 2 | Winter | 1 | 3 | 2 | Winter | 1 | 3 | 2 | Summer | 2 | 1 | 3 |
| Small urban - Peak 1 | Winter | 1 | 3 | 2 | Winter | 1 | 3 | 2 | Summer | 2 | 1 | 3 |
| Small urban - Peak 2 | Winter | 1 | 3 | 2 | Winter | 1 | 3 | 2 | Summer | 2 | 1 | 3 |
| Green-small urban - Peak 1 | Winter | 1 | 3 | 2 | Winter | 1 | 3 | 2 | Summer | 2 | 1 | 3 |
| Green-small urban - Peak 2 | Winter | 1 | 3 | 2 | Winter | 1 | 3 | 2 | Summer | 2 | 1 | 3 |
| Centrum-village | Summer | 2 | 1 | 3 | Winter | 1 | 3 | 2 | Summer | 2 | 1 | 3 |
| Village | Summer | 2 | 1 | 3 | Summer | 2 | 1 | 3 | Summer | 2 | 1 | 3 |
| Rural accessible | Summer | 2 | 1 | 3 | Summer | 2 | 1 | 3 | Summer | 2 | 1 | 3 |

The winter peaks in the **Paces** and **Tides** scenarios are caused by the early evening peak during dinner time. For the **Circles** scenario the morning and evening demands are nearly the same, although the net-demand of the district is reduced during the morning by the PV supply. During the summer the evening demands are the largest. Depending on the district type the highest demand is either during the early evening (18:00 hours) or during the late evening (22:00 hours). However, due to the PV supply the net-demand of the district reduces during the early evening, making the late evening peak the moment in which the highest demand occurs. Looking at the net-electricity demand of the districts during the summer shows that the demand peak is responsible for the highest peak demand for the urban districts in the **Paces** scenario, and the centrum-urban plus districts in the **Tides** scenario. For all other districts, meaning the rural districts in the **Paces** scenario, nearly all districts in the **Tides** scenario, and all districts in the **Circles** scenario, the PV supply peak causes the largest peak demand during the summer.

#### *Peak demand*

Besides the shape of the load profile, the height of the demand is investigated. The increase in peak demand for the model districts differs within the scenarios, as well as between the scenarios. For the **Paces** and **Tides** scenarios the village and rural accessible show a substantial increase in peak demand between 2013 and 2040. Additionally all districts in the **Circles** scenario have a peak demand increase between 231% and 600% compared to 2013, which is caused by the increase in PV supply. The most urban districts (first 5) have a relatively low residential peak demand, the most rural districts (last 3) have a relatively high peak demand, and the intermediate districts have a relatively intermediate peak demand. Generally speaking, the more rural a district is, the higher the peak demand per dwelling. The commercial buildings have nearly the same peak demand due to the modelling approach without differentiation into different reference buildings. Exception are the commercial buildings in the most urban districts in the **Circles** scenario due to the large PV deployment. Overall there are differences between the peak demand increase of the model districts, especially for the village and rural accessible districts.

#### *Load duration*

Load duration only insight into the distribution of the load demand throughout the year. Additional research can be performed to identify the load demands that cause the transformers to be overloaded, as well as the duration of the loading. In this research the transformers being loaded above 120% of the nominal capacity are considered overloaded. This is the value at which asset management division start an investigation in the number of times, and the duration of the overloading of the specific distribution transformer.

## 8.7 Conclusion

Main conclusions on the peak demand of buildings are:

- The more rural a district is, the higher the nominal capacity per residential building
- The most urban districts have a substantially higher nominal capacity per commercial building. The PV deployment creates a tipping point as observed in the **Circles** scenario.

The peak demand in district results in:

- The increase in peak demand can be explained by using the ratios between the scenarios (based on the underlying assumptions) in combination with the ratio of residential and commercial buildings within a model district. Substantial increases in the peak demand are mainly caused by the PV supply peak, which occurs at the village and rural accessible districts (for all scenarios), and for all districts in the **Circles** scenario.
- The peak demand has a tipping point in which the supply peak becomes bigger than the demand peak, and shifts towards the summer due to increased PV deployment. PV peak is ‘sharper’ than the evening demand peak of the basic electricity demand and heat pumps, and therefore more sensitive to changes which can lead to substantial increases of the peak demand. Therefore it is advised to have a clear registration of PV and heat pumps, which allows to identify the districts that are close to the supply or demand peak demand tipping point.

Overloading of transformers:

- Is largest in the **Circles** scenario, in which more than 80% of the distribution transformers are overloaded.
- Is largest in the village and rural accessible districts within each of the scenarios.
- In comparison with the current situation the **Paces** and **Tides** scenario result in similar overloading rates, except for the village and rural accessible districts, and the urban >1940 groundbased peak 1 district in the **Tides** scenario.

A discussion on the certainty and implications of these results is included in the next chapter.

# 9. Discussion

This report has described the approach for the research based on the main research choices, and the results as obtained by performing the approach. This chapter zooms out and discusses the research approach and the implication of the results for the network planning and operation. This involves the following questions. What is the impact of making different choices in the approach? In retrospect, was this the best approach to perform the research? How does this research relate to other research in the field of load forecasting? How valid are the results and what main lessons are learned by performing the research?

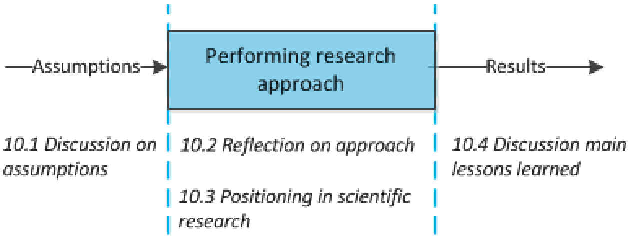



*Figure 64: Structure of this chapter and the relation between assumptions, research as conducted, and the results.*

This chapter starts by discussing the main assumptions underlying the research choices[35] are discussed (9.1). The research approach[36] as used in this research is reflected upon in 9.2, after which a discussion follows on the positioning of this research in relation to other scientific research[37] (9.3). The last section discusses the validity of the results and the main lessons learned during the research[38] (9.4).

## 9.1 Discussion on assumptions

Several assumptions are very influential in performing the research approach. These are the regional deployment of PV, heat pumps, and the temperature dependency in the heat pump load profile. The remaining assumptions are included in Appendix C.

### *Regional deployment of PV*

The current PV deployment in the different model districts is based on the current installed capacity as registered in the Product Installation Register (PIR), and the available roof surface in the specific district. The future deployment is assumed to become equal in each of the districts in the year 2050, with a linear increase from the current differentiation towards the equal deployment in the year 2050. Also the PIR is assumed to be complete, even though the database is estimated to contain approximately 80% of the installed capacity. Studies about the drivers of the (future) regional deployment are lacking, and the one small study performed by Bleumink [2013] did not find a clear relation between the PV deployment and socio-demographic characteristics. This is remarkable since in this study a clear relation is found between the model districts, since the PV deployment is higher in rural areas compared to urban areas. However, the development towards the future is unsure.

### *Regional deployment heat pumps*

[35] A full list of assumptions is included in Appendix C

[36] The research approach is described in chapters 4, 5, 6, and 7.

[37] Positioning of the research is based on the literature research in section 2.5.

[38] The main lessons learned are discussed by using the results of chapter 8, and the conclusions of the verification and validation of the research in Appendix F.

The regional deployment of heat pumps is based on the building types that are suitable for application of heat pumps (see DHPA, 2013). No additional differentiation is applied, resulting in a relatively similar deployment of heat pumps in the model districts when corrected for the number of buildings. To the best of our knowledge there are no studies on the regional deployment rates of heat pumps. The study of DHPA [2013] does make a reference to an increased deployment if the financial position of the consumer is better, but this is not substantiated with any arguments. The future deployment of heat pumps is based on the national scenarios with a factor of the technical potential of the buildings in the model districts since no other research is available. In order to be able to perform research on the drivers of future heat pump deployment it is desirable to have a database of the geographical installation rates of heat pumps, which is currently lacking.

***Load profile heat pumps***

In this research all heat pumps are assumed to be ground based. Therefore the Coefficient of Performance (COP) is not temperature dependent since the ground temperature is relatively stable. However, air-source heat pumps do require a temperature dependent COP. During an expert meeting performed at the client, the expectation was that most heat pumps are expected to become ground based, or hybrid (see Appendix F). Additionally, a sensitivity analysis is performed in which the sensitivity in changes in the COP has a small impact on the resulting peak demand. However, tipping points can exist. Therefore it is concluded that the impact of the assumption is unsure and requires additional research.

## 9.2 Reflection on approach

Three main elements of the approach are discussed: the size of the model districts, the use of model districts in relation to individual district analysis, and the consideration of the districts in isolation.

### 9.2.1 Size of the model districts

To construct the model districts a certain delineation is required on which the statistical analysis can be performed to make distinctions between the different districts. In this research a geographical segmentation is used by using the four digit postal code (PC4) areas. This negatively affects the research due to the large size of the PC4 areas, with an average of 2.412 buildings per PC4 area. Differences between the main variables when using a smaller area size, such as the PC5 or PC6 areas, are included in Table 24.

*Table 24: Differences between PC4, PC5, and PC6 area sizes.*

| | PC4 | PC5 | PC6 |
|---|---|---|---|
| Number in the Netherlands | 4.046 | 32.869 | 453.575 |
| Average number of buildings | 2.412 | 297 | 22 |
| Average number of transformers | 33 | 4,1 | 0,3 |

More specifically, smaller areas result in a:

- Smaller spread in the number of buildings, and therefore in in a more accurate representation of reality by using the model districts since the difference between the average number of buildings in the model districts and as occur in reality is smaller.
- A larger physical homogeneity, meaning the types of buildings in the model districts are more uniform and results in a more accurate determination of the basic electricity demand, and PV/heat pump deployment (see Figure 65).
- More accurate segmentation of the operating area into the model districts due to the increased physical and spatial homogeneity of the districts.

- A more accurate load demand estimation of distribution transformers serving a small number of consumers since the simultaneous factor reduces, resulting in an increase in the fluctuations, and therefore in the peak demand of the service area.
- For each transformer the relevant model district type is determined based on the geographical location. The certainty that the district type represents reality is smaller when using larger model districts. All transformers in the PC4 area of Figure 65 would be considered located in the 'blue' district, while in reality a different classification is more accurate for the transformer.

Smaller model districts thus provide more accurate results. The PC4 areas are used due to data availability issues. Geographical datasets about the number of buildings, and types of buildings are available on PC5 and PC6 level, but not publicly (see databases of e.g. Kadaster, LISA, CBS microdata, BAG). If available, the approach can be used since data on distribution transformers is registered at the PC6 level.

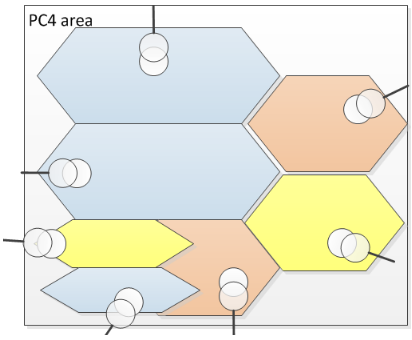



*Figure 65: Internal division within a PC4 area. Smaller areas represent PC5 or PC6 areas, and the two rounds represent the distribution transformers that feed the different areas. The colours identify different types of model districts. The figure indicates that classifying the PC4 area with one model district is a simplification of reality since multiple model district types can be identified when using a smaller area.*

Based on historical data of residential electricity demand the shape of the load profile, and the relative increase of the maximum peak demand, remains stable from 50 dwellings and more[39] [Veldman, Gibescu, Slootweg, & Kling, 2013]. Due to the higher individual peak demand of commercial buildings the number of buildings at which the stability is achieved is even higher. A smaller area for the model districts thus results in a more accurate peak demand for the distribution transformers. The distribution transformers serving less buildings of electricity are likely to have a larger difference between the calculated peak demand and the actual peak demand. The rural accessible and village districts are likely to have the most transformers that serve a limited number of buildings, causing the generally already overloaded transformers to be even more overloaded.

Does this mean that using PC4 areas as the size of the model districts is not usable for the analysis of the peak demand and the loading of the transformers? The aim of this research is to construct representative model districts for the Dutch build environment in order to determine the effect of the regional deployment of PV and heat pumps on the distribution transformers. Using the PC4 areas has shown the differences between the model districts, and the loading of the transformers. No previous research has provided this insight, which means that the PC4 area analysis does provide additional insight into the effects of the energy transition in different regions. However, the differences in deployment rates of PV and heat pumps, and the electricity demand between the model districts are more diversified when using smaller areas. Also the more correct type of district is attributed to the transformers, with a more accurate number of commercial and residential buildings, which is especially important for the transformers that serve a limited number of buildings.

[39] This is related to the simultaneousness factor of the consumers in the districts, see section 2.1.5.

It is therefore concluded that the PC4 area size can be used, although a smaller area size would improve the analysis of the peak demand and the loading of the transformers.

### 9.2.2 Model districts or individual district analysis

Another main choice in the approach is the use of model districts, rather than calculating the peak demand and transformer loading for each PC4 area individually. Current approach thus uses averages of multiple districts grouped together.

How does this affect the resulting peak demand per district? The main variables that change when deploying the individual district analysis compared to the grouped model district analysis are the number of buildings, and the distribution of reference buildings. Other variables are dependent on these two variables. Only changing the number of buildings does not influence the increase in peak demand between 2013 and 2040 since the model is linear, and also because the peak demand increase is defined as the percentual increase. However, the ratio between commercial and residential buildings does influence the peak demand. For example, the peak demand in the centrum-urban plus districts for the **Paces** scenario is 0,5 kW per residential building and 4,5 kW per commercial building (see Appendix D). This means each commercial building has a peak that is 9 times higher than a residential building. The time period in which this peak demand occurs determines the influence on the overall peak demand of the district, but this reasoning does show the importance of the ratio between commercial and residential buildings. Analysis of the individual PC4 areas requires a substantial amount of data, but also leads to a more detailed approach.

### 9.2.3 Considering districts in isolation

The load calculations of the distribution transformers are performed in isolation, meaning the supply and demand characteristics of surrounding transformers are not taken into account. This is due to the assumption that all excess supply, or net-demand of the district is compensated by the supply or demand from the MV and/or HV networks. In other words, the network balancing between supply and demand of the distribution grid is not included in the analysis. Since the demand (or supply) of the districts is not dependent on the demand (or supply) of other districts, this has no implications for the load demand of the transformers.

The net-demand of the individual districts is however dependent on the geographical location since the PV supply depends on the weather conditions. During a day in which the sunny and cloudy periods change frequently, the fluctuations in the net-demand of the districts are substantially increased. For the peak demand the geographical dependency is not an issue since the network capacity is based on the extreme weather situations that can occur. In this research this has been simulated by using an extreme PV supply profile in which clear skies are assumed throughout the year. Therefore the momentarily peak demand is dependent on the weather conditions, but the highest peak demand is not.

### 9.2.4 Verification of approach

The approach as proposed in this research is verified in Appendix F. The most important check is if the number of buildings of all model districts combined results in the same number of buildings as registered in the entire operating area. Difference are observed because the number of buildings differs due to using the mode instead of the average for the number of buildings in the model districts. This choice was made to create more identifiable districts, rather than average districts. The distribution between the number of dwellings and the number of households is nearly the same. Most of the other variables such as the electricity demand, PV deployment, and others are dependent on the number of buildings. The differences (when using the constant number of buildings) between the sum of the model districts, and the operating area, are smaller than 4% for the dependent variables. Therefore, the approach is considered to be performed correct even though differences do occur.

## 9.3 Positioning in scientific research

The extensions and alternative approaches are best described by discussing the position of this research in the scientific literature. This research is positioned as an intermediate up to a high hierarchical level of interest, and consists of elements from both top-down and bottom-up load profile construction (see Figure 66).

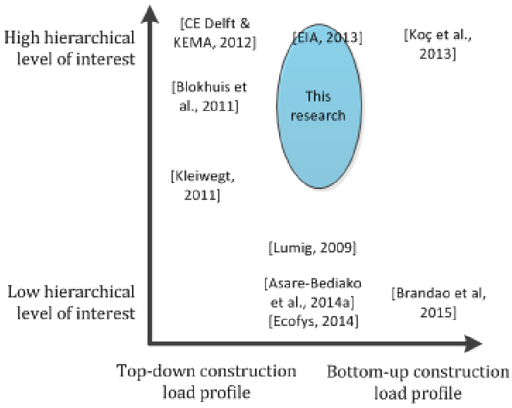



*Figure 66: Positioning of this research in relation to the existing load calculation methods. The methods are plotted on the hierarchical level of interest, and the approach to construct the load profiles.*

There are several observations to be made on our approach in relation to other approaches:

- Our approach uses model districts while maintaining the overview of the entire operating area. Using PC5 or PC6 areas for the construction of model districts creates a lower hierarchical level of interest, and focussing on reference buildings is the lowest hierarchical level of interest. The advantage of our approach is the relatively small data requirement, but a disadvantage is the use of the same load profile for each of the reference buildings which results in more average load characteristics in the model districts.
- Top-down load profiles do not provide insights into the types of demands within the load profile. Deploying PV and heat pump profiles in combination with the basic electricity demand profile (as done in this research), allows for a better future exploration since the deployment rates can be individually adapted in the model district load profiles.

Bottom-up construction of the load profile while focussing on a low hierarchical level of interest provides the most detailed approach, while the high hierarchical level of interest with top-down construction of load profiles provides the least detailed approach.

Extension of the approach is possible by:

- including load profiles of references buildings (see e.g. Brandão de Vasconcelos et al., 2015), positioning the research towards the more bottom-up load profile construction side.
- Including commercial reference buildings, possibly with different load profiles. This details the current approach.
- Including a model district for business parks. This is not possible with the PC4 areas since business parks are smaller than the PC4 areas, but is possible when using PC5 or PC6 areas.

- Including soft critaria to describe the perception of people as performed by Randsdorp & Schoemaker [2014]. This research resulted in a segmentation into 'unconscious energy users', 'pragmatic comfort seekers', 'environment improving consumers', and 'duty driven environment consumers', which is used to determine the willingness to adopt renewable energies and perform renovations or other activities. Coupling these results with the model districts might indicate the districts that are most likely to adopt PV and heat pumps.
- Including building year as an indicator for the heating demand. Older buildings are less energy efficient, while new buildings have a high energy efficiency (see e.g. Agentschap NL, 2011). The heating demand affects the electricity demand of the heat pumps.
- Include other technologies, such as electric vehicles and cooling by heat pumps. Both technologies can reduce the summer peak as occurs due to the large PV penetration. During the winter electric vehicles increase the (already high) demand.

This research is located in the field of load calculation, but the results can be used in the field of reducing the fluctuations and peak demands. This involves Demand Side Management (DSM), storage (in e.g. batteries or electric vehicles), or grid capacity extension. Each model district might have different solutions that are most effective. Extending the approach by using different load profiles for each of the reference buildings, increasing the knowledge on the drivers of deployment of PV/heat pumps, and using smaller areas that better align with the service areas of transformers is expected to result in sharper peaks and fluctuations in certain districts. This creates a better insight into the effectiveness of different fluctuation and peak reduction solutions, although current approach is also likely to create insights into these differences in effectiveness due to the observed differentiation in the model districts.

## 9.4 Discussion of main lessons learned

After the discussion of the possible extensions and limitations in the previous sections one might wonder if the current approach is of any use. This section discussed the main lessons learned, in combination with the main limitations, to which is returned on in the conclusions and recommendations chapter.

### 9.4.1 Observations in the differentiation

Due to the large size of the model districts the differentiation between the different districts is not as large as expected beforehand. This also results in a less diversified load profiles of the model districts. This is also partly due to the deployed scenarios, since the **Paces** and **Tides** scenarios are very similar in the sight year 2040. In the other years some differentiation between these scenarios is observed, but still relatively minor compared to the **Circles** scenario.

Although not as diversified as expected, there are difference observed in the different model districts. Therefore the results show that the speed of the sustainable developments depends on the geographical location. This would not have been clear in the uniform approach for the entire operating area. As discussed, additional differentiation is expected when applying a smaller area size for the model districts.

### 9.4.2 Representation of reality

The peak demand of the PC4 areas are compared with the results of other research (see validation in Appendix F). The difference between the calculated peak demand and the peak demand in Ecofys [2014] for the residential buildings is comparable when corrected for the electric vehicles. Only the temperature dependent COP is causing differences between the residential peak demand. When applying a temperature dependent COP in all of the heat pumps the peak demand of the households (on average 1,9 kW) increases with 0,5 kW. However, this assumes all heat pumps to be air-source heat pumps. As discussed, this is not expected to occur in the future. Therefore, the peak demand of this research is assumed to be correct. Additional research on actually measured data of certain highly measured districts is recommended to further increase the certainty.

Also during an expert meeting the peak demands are confirmed to be in the right range. Therefore the peak demand as calculated is considered to be in accordance with reality. The peak demand of the entire district can thus be considered to be calculated correctly. However, differences within different sections of the PC4 area can exist.

The scenarios as used in this research represent a possible future exploration. Especially the developments of the most influential actors, which are the national policy makers, and the consumers and rental organisations, can significantly influence a different future deployment rate of (sustainable) energy technologies.

### 9.4.3 Influence on state of electricity network

The validity of the distribution transformers loading rate is less certain than the load profile and peak demand calculations. The PC4 areas are relatively large, resulting in a large spread of the number of transformers in one PC4 area, ranging from 1 to 180 transformers. Also, as discussed the physical homogeneity, and therefore the correct type of model district application increases when using smaller areas of interest. The optimum size of the model districts to calculate the load demand of the transformers is when the number of buildings per transformer is equal to the number of buildings per model district. In other words, if the number of transformers per model district equals 1.

On average the number of transformers is 33 in the currently applied model districts, which means that the actual load demand of the transformers can differ from the calculated load demand. In the rural accessible districts the average number of transformers is the lowest of all districts, but still has on average 17 transformers in each PC4 area. Network design is therefore conducted on smaller areas of interest. The PC5 or PC6 better align with the network design requirements (see Table 24). Additionally, in order to perform network planning the scope needs to be expanded by (at least) including electric vehicles and cooling by heat pumps.

# 10. Conclusions and recommendations

The national policies to increase the penetration of renewable electricity generation and energy efficiency are causing the deployment rates of PV and heat pumps to increase. The deregulation of the electricity market causes large differences between the geographical deployment rates of PV and heat pumps.

Load forecasting helps decision makers in determining the optimum allocation of resources due to the changing demand characteristics of the consumers. It has been applied on high aggregation levels, resulting in load demand for an entire operating area, and on low aggregation levels resulting in the forecasting of specific regions. The purpose of this research is to provide an intermediate aggregation level that uses model districts as specific regions and incorporating these regions in the results for the entire operating area.

More specifically, the aim of this research is to construct representative model districts for the operating area of Stedin with which the effect of the different regional deployment rates of PV and heat pumps on the distribution transformers can be determined. The main research question is therefore:

> *Which model districts can be used to represent the Dutch distribution grids in a scalable manner, in order to analyse the future deployment rates of PV and heat pumps, and the effect on the load demand of the distribution transformers?*

The scalability refers to the ability to construct model districts that are a representation of a part of the operating area. Combining load demands, installed capacity of PV and heat pumps, and other variables for all of the model districts thus need to combine to the numbers as expected in the entire operating area.

## 10.1 Answering the sub-questions

### *What is the current status of PV and heat pump deployment?*

Since 2008 the worldwide installed PV capacity is growing substantially, with an annual increase of 40 GW in 2013 that is mainly driven by national deployment strategies. In the Netherlands PV supply accounted for only 0,5% of the total electricity supply in 2013, with an installed capacity of 739 MW. Around 80% is installed on residential rooftops, and 15% on commercial buildings on the LV network. Within the Netherlands there are large differences in deployment rates of PV, ranging from 1 $kW_p$ up until 6000 $kW_p$ per PC4 area.

Heat pumps are increasingly installed in the Netherlands since 2004. The total heat provision of 12.000 TJ in 2013 is mainly installed by commercial buildings (73%), compared to the residential deployment (27%). The main types of heat pumps are the air-source heat pumps (ASHP) and the ground-source heat pumps (GSHP), for which the former is sensitive to the external temperature in which low outside temperatures cause lower efficiencies. In commercial buildings both types are equally deployed, while in the residential sector the GSHP is slightly more used (60%).

The future deployment rates of PV and heat pumps, as well as the energy demand of the connected users, depend on the market and policy developments. The national policy is executed by the Ministry of Economic Affairs and the Ministry of Infrastructure and the Environment, in which the execution relies on the market parties. The market parties that are most influential are the rental organisations and the individual consumers. Especially the increase in energy efficiency that needs to result into an energy neutral build environment in 2050, can have a significant influence on the energy demand and deployment rates of PV and heat pumps.

***How can the consumers of the Dutch distribution grid be divided into representative model districts?***

The smallest building blocks in dividing the operating area are the reference buildings, for which the residential archetypes are the detached, semi-detached, terraced, common staircase and galleries, common staircase no galleries, maisonette, and other flats buildings. Each living environment contains a different distribution of reference buildings, which after specification result in model district types. There are roughly two approaches to specify the model districts; (1) by using the reference buildings in combination with the building year, (2) by using the reference buildings in combination with urban and rural density variables. The thought was that the connection between the density of the build environment would strongly relate to the characteristics of the electricity network. Therefore, combined with the data limitations, the second approach is used. This resulted in 13 living environments based on physical and geographical properties.

The main research choice in constructing the model districts is the size of the districts. Statistical data on the number of residential and commercial buildings is available on PC4, PC5, and PC6 levels, although the only freely available database is on the PC4 level. On this level the model districts are less accurate than the more detailed datasets due to the reduced physical homogeneity within the area. Within the boundaries of the resources in this research the PC4 area classification is deployed in combination with the 13 living environments to divide the operating area. After determining the number of residential and commercial buildings the operating area has been segmented into 18 model districts.

***How will the load profiles and peak demands develop in the future for the different model districts?***

Currently the winter peak is dominant in all districts. The winter peak remains dominant in most model districts in the **Tides** and **Paces** scenarios, except for the most urban districts; village and rural accessible. The largest proportion of the winter peak is due to the basic electricity demand, followed by the heat pump demand and PV supply.

Different to the current situation, the summer peak becomes dominant in the village and rural accessible districts, and in all districts in the **Circles** scenario. This is due to the large deployment of PV in these situations, and different to the current situation even causes a supply peak.

The first and highest impact of the energy transition is observed in the most urban districts. This substantiates the assumption that the energy transition manifests itself differently in different districts. In a uniform approach for the entire operating area this could not have been concluded.

***How can the model districts be coupled to the distribution transformers?***

Initially it was considered to use model transformers for each of the model districts that could represent the average stock of transformers within the areas classified with that specific district type. Analysis on these relations revealed a large spread between the transformer characteristics within a district type. First the number of transformers differs largely, ranging between 1 and 180 transformers per PC4 area. Additionally the spread in the number of buildings and the nominal capacity per building was too large for construction of model transformers.

There are however some rough relations found between the model districts the transformers located in it. The main findings are presented below, although it should be noted that these findings are not validated and need additional research due to the uncertainties in the dataset.

*Table 25: Overview of the districts with the largest and smallest number of transformers per PC4 area, number of building per PC4 area, and average nominal capacity per building.*

| | District with largest number | District with smallest number |
|---|---|---|
| Average number of transformers per PC4 area | Centrum-urban<br>Centrum-urban plus | Rural accessible<br>Village |
| Average number of buildings per transformer | Urban <1940<br>Urban >1940 compact | Rural accessible<br>Green-urban |
| Average nominal capacity per building | Green-urban<br>Centrum-urban plus | Urban <1940<br>Urban >1940 compact |

### *How does the future load demand of the distribution transformers in the operating area develop?*

On the distribution transformers that in reality have a registered loading rate of more than 120% of the nominal capacity an analysis is performed to determine duration and degree of overloading. In this research the transformers with a loading rate of 120% are assumed to be overloaded and might damage the equipment. The future load demand is determined for the transformers operated by Stedin for the provinces of South-Holland and North-Holland, but not for the province of Utrecht since the current load demands are not available for this area, resulting in an analysis on 67% of the entire stock of transformers.

The most substantial overloading in the **Paces** and **Tides** scenario for 2040 are registered in the village and rural accessible districts. Additionally the transformers in the urban >1940 groundbased peak 1 districts are relatively high overloaded for the **Tides** scenario. The **Circles** scenario causes a large part of the transformer stock to be overloaded, ranging between 80% and 96% of the transformers being overloaded in the model districts.

*Table 26: Percentage of transformers overloaded for each model district, with the current situation in 2013 and the future scenarios for 2040.*

| Model districts | Current | Paces | Tides | Circles |
|---|---|---|---|---|
| Centrum-urban Plus | 0% | 0% | 0% | 82% |
| Centrum-urban | 1% | 0% | 1% | 86% |
| Urban <1940 - Peak 1 | 0% | 0% | 0% | 91% |
| Urban <1940 - Peak 2 | 0% | 0% | 1% | 96% |
| Urban >1940 compact | 1% | 1% | 1% | 91% |
| Urban >1940 groundbased - Peak 1 | 1% | 1% | 9% | 92% |
| Urban >1940 groundbased - Peak 2 | 1% | 1% | 1% | 94% |
| Green urban - Peak 1 | 1% | 1% | 1% | 80% |
| Green urban - Peak 2 | 0% | 0% | 0% | 94% |
| Centrum-small urban - Peak 1 | 2% | 2% | 3% | 91% |
| Centrum-small urban - Peak 2 | 0% | 0% | 0% | 92% |
| Small urban - Peak 1 | 1% | 1% | 1% | 92% |
| Small urban - Peak 2 | 0% | 0% | 0% | 87% |
| Green-small urban - Peak 1 | 2% | 2% | 2% | 86% |
| Green-small urban - Peak 2 | 0% | 0% | 0% | 93% |
| Centrum-village | 1% | 1% | 3% | 91% |
| Village | 2% | 6% | 17% | 92% |
| Rural accessible | 1% | 5% | 16% | 92% |

## 10.2 Answer to the main research question

***Which model districts can be used to represent the Dutch distribution grids in a scalable manner, in order to analyse the future deployment rates of PV and heat pumps, and the effect on the load demand of the distribution transformers?***

In this research it is argued that the operating area of DNOs can be divided by using model districts that are based on the physical homogeneity of the individual areas. This resulted in 18 model districts, with a specification based on the living environment, the average number of commercial and residential buildings, and the types of residential buildings. The increasing deployment rates of PV and heat pumps are considered for each of the model districts.

When applying the approach as specified in this research, the earliest and largest impact of the energy transition is observed in the most rural districts (village and rural accessible). In the **Paces** scenario approximately 5% of the transformers are overloaded, increasing in the more sustainable **Tides** scenario to 16%. If the most sustainable scenario (**Circles**) applies nearly all transformers are overloaded (between 80 – 96%). However, perhaps more remarkable is that in the remaining districts in the **Paces** and **Tides** scenario the overloading is comparable to the current situation. If this applies, the current capacity of the transformers is sufficient, although flexibility solutions are desirable due to the large fluctuations in demand and supply. Additional research is required on the validity of these conclusions when electric vehicles and cooling of heat pumps is included.

Due to the relatively large size of the districts the diversity between the model districts is smaller than when using smaller areas of interest. Ideally the districts are of the same size as the service area of the transformers. The largest uncertainty is therefore at those districts with the smallest number of buildings per transformer, which are the rural accessible and village districts. In these districts the actual peak demand is likely to be higher than calculated, since the simultaneousness factor is lower due to the small number of buildings per distribution transformer. This causes the already (highly) overloaded transformers to be even more overloaded, and increases the ratio of overloaded transformers in these districts. The uncertainty due to the size of the area is smaller for the centrum-urban and centrum-urban plus districts since these have the highest urban density, resulting in a higher simultaneousness factor.

The sum of districts returns to the values for the entire operating area. Considering the entire operating thus results in the correct values as specified in the three scenarios, but the distribution between the districts is less certain. Overall it is concluded that the scalable model districts are an extension of the current methods to analyse the impact of PV and heat pumps on the electricity network. This research therefore contributed to the existing body of knowledge by introducing an intermediate aggregation level in which elements of the detailed capacity calculations are included, as well as elements from the high over aggregation level for strategic decision making.

The approach can be applied for all Dutch distribution network operators. The model districts are constructed by using data files on 668 PC4 areas of the total of 4000 PC4 areas in the Netherlands. Therefore the average number of buildings can shift when applied to a different region, but only limited changes are expected due to the large number of buildings within the areas. Performing this analysis on another operating area requires however the purchase of the living environment typology in order to determine the classification of each PC4 area. Also the current loading rate of the transformers is required.

## 10.3 Recommendations for DNO

This research is part of the future exploration performed by the client in order to determine the effects of the energy transition on the electricity network. This section describes the specific recommendations for the client, as well as for other DNOs, on how to use this research and which other improvements were met during this research.

***Possible applications of research***

At Stedin the social-cost benefit of intelligent network application and traditional grid extension are investigated by multiple studies. The (short term) approach is to adapt the current social cost benefit model (MKBINS) by including smaller areas, and flexibility solutions. This report contributes to the diversification into smaller areas. It is recommended to pay additional attention to the mort rural districts since the impact of the energy transition manifests itself at these districts first.

The model districts can (and will be) used in the report that Stedin provides to the Autoriteit Consument & Markt (ACM, supervisor of the Dutch DNOs) to report on the quality, capacity and safety of the gas- and electricity networks. To create (more) realistic results and observation it is recommended to include the electric vehicles, and the cooling of heat pumps into the future exploration. To include cooling only requires a cooling load profile for the heat pumps, and the (future) cooling demand per reference building. Electric vehicles can be included by using the number of cars in each model district, and multiply the number with the national percentage of cars that are electric. On the longer term it is recommended to perform a study on the regional difference in deployment rates of electric vehicles.

### *Exploring intelligent network applications*

This research provides insights into the future load demand of the distribution transformers within different model districts. The next step is to perform a comparative cost and benefit analysis for the different intelligent network solutions, such as Demand Side Management (DSM) and storage that can reduce the fluctuations and/or peak demand of the model districts. However, in the coming years only in the most rural districts the capacity of the distribution transformers might be insufficient. The project to determine the infrastructural footprint, as currently investigated at Stedin, can be coupled to the regional analysis from this research. This creates additional insight into the lowest social cost solution in different districts. Future research is recommended to identify suitable methods to reduce the peak demand, by means of Demand Side Management (DSM) (see e.g. [Luo et al., 2010]).

### *Improving future outlook*

Currently, the future energy scenarios are developed on the basis of the worldwide economic growth expectations. As observed in the actor analysis, regional actors can have a significant influence on the development of the build environment. It is therefore recommended to include the possible trends that actors can initiate into the future energy scenarios. A possible trend is the large scale improvement of the energy efficiency of the building stock, and another is the development of energy neutral buildings, in which for both strong regional differences can occur.

More detailed research is also recommended on the policy of municipalities and the activities of energy cooperatives. Current practice at the asset management divisions already include outlooks on the regional development plans for construction of the build environment. It is recommended that the PV and heat pump development policies are included in this analysis.

### *PV and heat pump registration*

As concluded from this research the heat pump demand is in some districts contributing to the annual net-peak demand. However, differences in regional deployment of heat pumps is barely registered or studied in the scientific literature even though it increases investment costs in network capacity significantly with high deployment rates. Registration is difficult to implement, as is currently the case with the Product Installation Register (PIR) for PV registration, but allows network operators to increase the understanding of the electricity demands. It is therefore recommended to increase the geographical registration of both heat pumps and PV installations.

### *Unused transformer capacity*

Companies are required to request the required capacity during the construction of the building. It is common practise to apply for a high capacity, while during operation the actual capacity is lower. This implies that districts with a high penetration rate of companies are likely to have a relatively high rate of unused transformer capacity. It is recommended to perform an analysis to investigate if this unused capacity can be deployed to elevate the networks that are restrained with high demands.

## 10.4 Research limitations

***Size of model districts***

Due to data limitations the PC5 and PC6 area sizes could not be used in this research. Using the relatively large PC4 areas results in multiple model district types within the area, of which the most applied specifies the overall model district classification. This results in more average model districts in terms of the distribution of reference buildings, which in turn results in less diversification of the PV and heat pump deployment. The current division in the PC4 areas provides enough detail to identify difference between the model districts, although these difference are likely to increase when applying a smaller area size.

***Commercial reference buildings***

The types of commercial buildings are not publicly available, and therefore no commercial reference buildings are applied, but instead only one average type of building. This results in less diversification of the electricity demand of the model districts, and creates an over/underestimation depending on the type of district.

***Distribution residential reference buildings***

Also the geographical location of the residential reference buildings is not publicly available. In this research an approximation is used to determine the distribution of reference buildings in each of the model districts. The approximation is expected to be relatively accurate (differences less than 17%), although difference do occur, resulting in a different basic electricity demand and deployment of PV and heat pumps.

***Regional deployment of PV and heat pumps***

As discussed, the geographical registration of installed PV capacity in the PIR is not complete, and registration of the heat pumps only occurs on the national level. Also regional deployment studies on the number of PV and heat pump installations are rare in literature. This implies that it is hard to distribute the renewable energy technologies over the different model districts, and in this study estimates are used. In the Netherlands the installed PV capacity is registered in the product information register (PIR) at the PC6 level. This allows to distribute the installed capacity in the operating area over the different model districts, but only for the current situation. Also the database is not complete due to the voluntary registration. However, it is much better organised than the registration of heat pumps, since this is only reported upon on the national scale.

***Focus on (isolated) LV networks***

The load demand of the distribution transformers is based on the load demand of the model districts, without including the electricity flows between distribution transformers over the MV or HV network. The distribution transformers are thus analysed in isolation. In reality a faulty (highly overloaded) transformer can result in a cascading effect throughout the electricity network. These kind of analysis cannot be performed with the current method of analysis.

***Electric vehicles***

The scope of this research includes PV and heat pumps, but electric vehicles are not taken into account. Including electric vehicle demands without smart charging options would increase the peak demands in the districts. Therefore the loading of the transformers is influenced by the loading patterns of the electric vehicles. The same argumentation holds for other demand or supply technologies that are not included in the analysis, although electric vehicles are the largest influencer.

### *Cooling by heat pumps*

Cooling by heat pumps is not included in the analysis. The electrical demand for cooling is smaller than the electrical demand for heating for the heat pumps. Therefore in reality the electrical demand, or the contribution to the peak demand, is smaller during the summer than the heating demand in the winter. Still, the large PV supply peak as observed in this research would be (slightly) reduced if cooling is included.

## 10.5 Future research

### *Size of model districts*

Compare the results with highly measured districts including detailed analysis for the types of buildings, the electricity demand, and (renewable) technology deployment. This can be used as an additional validation of this research, but also to investigate the difference when PC5 or PC6 area sizes are deployed for the model districts.

### *Commercial reference buildings*

Current research can be expanded by including reference buildings for commercial entities, and using the floor surface as an indicator for the electricity demand. This information is registered in the LISA database in the Netherlands, for which a paid data subscription is required.

### *Regional deployment of PV and heat pumps*

Deployment rates of PV and heat pumps need to be registered and analysed on geographical differences. Investigation of the drivers of commercial and residential consumers to deploy PV and/or heat pumps in order to predict the (future) geographical differences is desirable. Establishing a predictive model using socio-demographic variables greatly enhances the understanding of the deployment rates.

### *Application approach other scope*

Using the research approach on the gas network requires relatively minor changes. The model districts can still be used, as can the future energy scenarios, although the specification of the model districts requires some attention. Ideally the to be constructed gas network model is then coupled to the electricity network model to enhance the insights into the capacity requirements in multiple model districts. For example, the hybrid heat pumps can only be applied in districts with a natural gas network. Coupling both approaches provides additional insights.

Additionally research can be conducted on the application on other DNOs LV network in the Netherlands, or on the effect for the MV or HV network by expanding the model and including elements such as wind turbines, and industrial consumers. Other DNOs network analysis can use the model districts with the specification, although the distribution transformers loading capacity requires the currently observed demands.

### *Other possibilities*

Other future research possibilities are:

- Including detailed bottom-up load profiles for each of the reference buildings and thereby expanding the model.
- Determine the effect of the decentralised (renewable) energy technologies demand and supply on the large scale power plants operation.

# 11. Reflection on the research

In this reflection the research difficulties and learning moments are discussed from the personal point of view. This also includes the ability to generalise the approach and/or results of this research for other DNOs in the Netherlands.

### *Interdisciplinary research*

One of the main difficulties in performing the research was the coupling of the multiple disciplines. These were the build environment with its physical characteristics, but also the socio-demographic and social characteristics. Determining the correct approach, without making the scope too broad, was difficult to maintain when reading so many interesting papers and research reports. Also within the electricity network characteristics the scope was often difficult to maintain, especially since the Demand Side Management and storage options are extensively discussed in literature. It took me a while before it was clear that the research as found in the literature mainly assumed the load demand as a constant, and then tries to determine the effectiveness of the solutions based on this given fact. However, the effectiveness of the solutions can only be determined after the correct load profiles and demand characteristics are determined. Positioning this research on the 'preparation' phase helped me delineate the research much better.

### *Build environment VS network characteristics*

In retrospect, it would have been better to start investigating the network characteristics first instead of the physical characteristics of the build environment since the loading rate of the distribution transformers is better approximated when deploying PC5 or PC6 areas. During the period in which the literature research was conducted many discussions were held with the client and at the university on which approach to take. During this phase the speed of work was starting to decline, and therefore the decision was made to take the physical characteristics as a starting point after which the connection with the distribution transformers would be made. Looking back, this might be the wrong decision, but at the time it was necessary to choose an approach and try to create meaningful results.

Also, if the network characteristics were chosen as initial starting point other problems would have emerged. The data on the PC4 areas is the only publicly available database, which means that if the network approach was considered initially the model districts would still be of the PC4 area size. Overall, it was difficult to maintain the balance between an aggregated level of interest in order to maintain the overview for the entire operating area, while also maintaining enough detail to create valuable results and insights into the geographical differences of the energy transition on the electricity network.

### *Number of model districts*

The detail is definitely maintained by the large number of model districts, of which there were 13 at the beginning and eventually resulted in 18 model districts. This resulted in a lot of time consuming data analysis since the same procedure often had to be done multiple times. Other researchers therefore often use one or two example model districts to show how the approach can be applied and which results can be obtained. From a scientific point of view this is a logical approach, but from the point of view of the client this is an incomplete approach. One of the main contributions of this research is the ability to represent the entire operating area, rather than just a few example districts. However, there are some model districts that have an overlap and that are comparable to each other. This was only visible at the end of the research, which is the reason why no additional attention is paid on this aspect. Also the client has the desire to perform this approach on smaller areas sizes, which could manifest additional differences in the model districts. Therefore no grouping is applied.

### *Data acquisition*

Throughout the research one of the most difficult, or at least time consuming activity, was the data acquisition. Data is required on the number of buildings, the types of buildings, and the loading rate of the transformers. Especially the last was hard to obtain since multiple datasets needed to be connected in order to create a database in which the registered loading rate was coupled to the geographical location of the distribution transformer. Much appreciated is the help of the data specialists at the client, without which the data would not have been obtained. During the data acquisition phase it was a good learning moment that it is of high importance to maintain contact with the relevant people in order to decrease the waiting time.

### *Generalisation of the research*

Approximately a quarter of the buildings in the Netherlands are operated by the client, and the operating area consists of a multitude of different area types ranging from urban to rural. The model district specifications are based on these buildings. Applying the same approach on the operating area of other DNOs might create small changes, but since the large proportion of the Netherlands is operated by the client the differences are expected to be negligible. To apply this approach on operating area of another DNO in the Netherlands the dataset of ABF Research on the categorisation of the PC4 areas into model districts needs to be obtained, as well as the current load demand of the distribution transformers combined with the geographical location. Alternatively, the results of the load profiles and the peak demands can be used directly by the DNOs. However, applying the research approach and/or results abroad is likely to result in a mismatch due to the different physical properties of the build environment.

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# Appendix A Construction of model districts

The 13 types of living environments are used to construct the model districts. The first section describes the distribution of the living environments in the operating area together with the total number of buildings. Section 2 includes an overview of possible databases on which the number of reference buildings for commercial entities can be determined, followed by section 3 with a discussion on the future number of buildings. In section 4 the number of buildings per model districts are determined, after which the distribution of reference buildings within the model districts are specified in the last section.

## A.1 Living environments in entire operating area

### *Accuracy living environment classification*

For each postal code (4 digit) in the operating area the living environment typology has been set (see Figure 67). The rural accessible (17%), urban >1940 compact (14%), small urban (13%) and centrum-village (13%) are most present in the operating area and combined represent 57% of the classification of the area. The operating area of Stedin is mainly located in the provinces of North-Holland, South-Holland and Utrecht which are predominantly urban regions. Therefore, before the analysis it was expected that a large part of the operating area would be classified as urban and centrum-urban.

Only 5 % of the postal code areas are classified as centrum-urban (plus), 35% as urban, and 22% as small urban, resulting in a total of 62% of the operating area classified as urban. A high percentage, although not as high as expected. This can either be a good insight, a misleading result caused by the definitions of the living environment classification, or mean that the 4 digit postal code regions are too broad for representing the (centrum-) urban category.

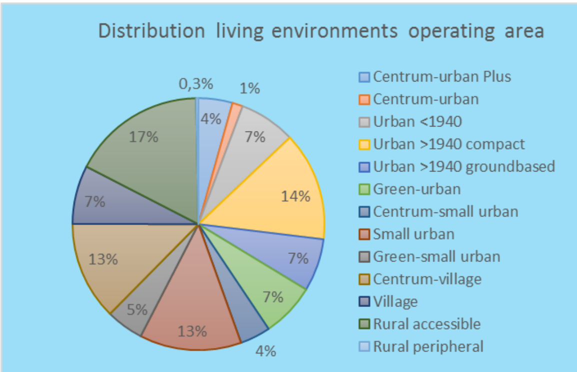



*Figure 67: Distribution of living environments and residential buildings in the operating area.*

Additional research into the urban density factor of neighbourhoods can indicate the most valid reason. The CBS classifies neighbourhoods, which are smaller and therefore more detailed than 4 digit postal code areas, with the urban density factor of 1 – 5 (with 1 being the highest density). The distribution of the urban density factor for the detail level of neighbourhoods and PC4 areas are different, although for both distributions there is a large spread (see Figure 68). Density factors 1 and 2 are indicators for the urban regions. The urban density factor 1 (high density) represents between 31% and 21% of the operating area (PC4 area and neighbourhood level respectively), and factor 2 applies to between 16 and 25% of the area. Combined this results in 47% of the PC4 areas classified as factor 1 and 2, and 46% on the neighbourhood scale.

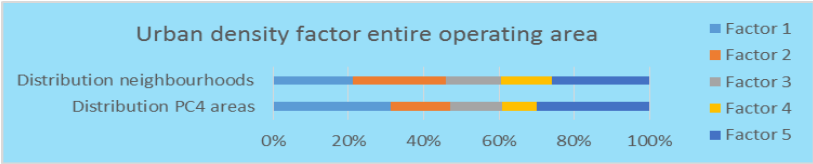



*Figure 68: Urban density factor distribution for the neighbourhoods and PC4 areas in the operating area*

So when looking at the distribution of the density factor per residential living environment, between 46 and 47% of the living environment should contain the density factors 1 and 2. The distribution of the urban density factor per living environment is presented in Figure 69. Multiplying the urban density factor 1 and 2 in each of the living environments (see Figure 69), with the availability of living environments in the operating area (see Figure 67), should sum up to the urban density distribution in the operating area for factors 1 and 2 combined (see Figure 68). Doing that shows that 46% of the operating area consists of urban density factor 1 and 2, which is similar to the distribution with PC4 areas (47%) or when using the neighbourhood scale (46%). Therefore, it can be concluded that use of the data of ABF Research with the living environment categorisation on PC4 level, or use of the data of CBS with urban density factor 1 and 2 on PC4 level, or on neighbourhood level, all result in the same distribution of urban classified regions. Based on this conclusion it is assumed that the level of detail of the living environment typology is valid for representing the distribution of urban regions in the operating area.

However, in the first section a total of 62% of the operating area was classified as urban by summing up the first 9 living environments (centrum-urban plus up until green-small urban). This is substantially higher than the 46% of urban regions in the second part. This difference is explained when considering that each living environment consists of both high urban and lower urban density factor areas (see Figure 69). When this difference is considered, which has been done in this analysis, there is no longer a difference between the numbers. Therefore it is important to remember that the postal codes classified by the same living environment are not necessarily homogeneous in terms of urban density. The same analysis has been performed for the urban density factors 3, 4 and 5, which resulted in the same conclusions.

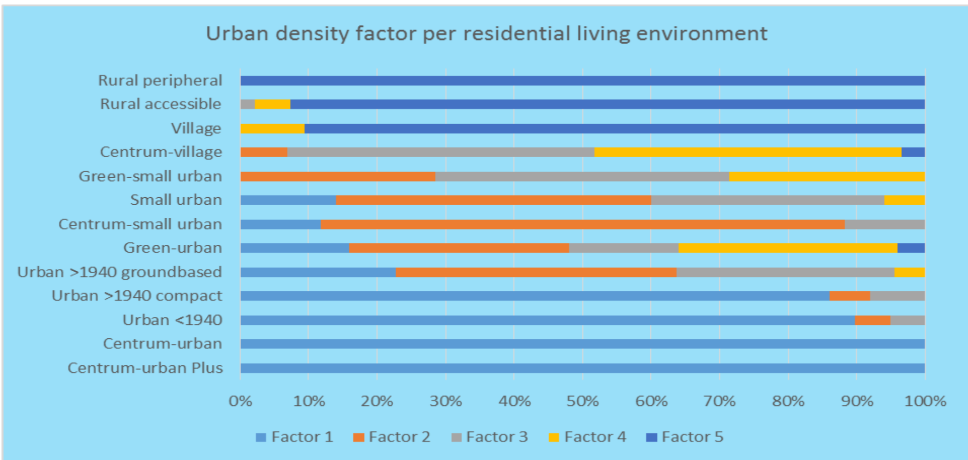



*Figure 69: Urban density factor distribution per residential living environment.*

Therefore, the expectation that a large part of the operating area should be classified as urban is valid, based on the information sources of ABF Research and CBS. Especially the data provided by CBS is considered reliable. However, an urban living environment is not necessarily homogeneous in terms of urban density factors. Additionally the living environment classification on PC4 areas is equally accurate as the classification on neighbourhood scale for the division of the entire operating area.  The same argumentation holds for the other factors and living environments. Overall, around half of the geographical area of the operating region is classified as urban.

### *Residential and commercial buildings*

Previous section discussed relationship between the urban density factor and the living environments. In Figure 70 the distribution of the total number of residential and commercial buildings in the operating area over the different living environments is included for additional insight.

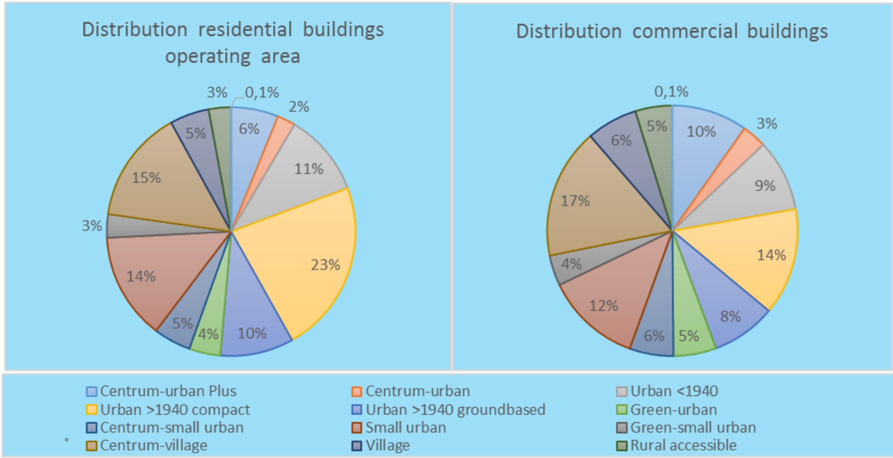



*Figure 70: Distribution of residential and commercial buildings over the different living environments.*

An overview of the living environments, residential buildings and commercial buildings in the operating area is provided in Table 27. The operating region consists of 668 PC4 areas, while the Netherlands has a total of 3.865 PC4 areas [CBS, 2013b], meaning that 17% of all the PC4 areas are operated by Stedin. When looking at the buildings, the operating area consists of 2.039.098 buildings, while there are a total of 8.539.005 buildings in the Netherlands [CBS, 2013b][40], meaning that 24% of the buildings in the Netherlands are operated by Stedin. The total number of small consumer connections in the operating area of Stedin was 1.992.033 in 2013 [Stedin Netbeheer B.V., 2014]. This is slightly lower than the total number of buildings provided by the CBS, which can be explained by the fact that certain buildings do not have an electricity connection.

*Table 27: Overview of living environment distributions in the operating area*

| Living environment | Number in operating area | Distribution in operating area | Residential buildings | Distribution residential buildings | Commercial buildings | Distribution commercial buildings |
|---|---|---|---|---|---|---|
| Centrum-urban Plus | 29 | 4% | 115.743 | 6% | 15.215 | 10% |
| Centrum-urban | 9 | 1% | 44.523 | 2% | 4.903 | 3% |
| Urban <1940 | 48 | 7% | 203.358 | 11% | 14.453 | 9% |
| Urban >1940 compact | 93 | 14% | 423.699 | 23% | 21.463 | 14% |
| Urban >1940 groundbased | 45 | 7% | 179.858 | 10% | 12.940 | 8% |
| Green-urban | 46 | 7% | 76.393 | 4% | 8.605 | 5% |
| Centrum-small urban | 26 | 4% | 91.488 | 5% | 8.828 | 6% |
| Small urban | 87 | 13% | 261.361 | 14% | 19.223 | 12% |
| Green-small urban | 32 | 5% | 57.194 | 3% | 6.113 | 4% |
| Centrum-village | 84 | 13% | 277.286 | 15% | 26.150 | 17% |
| Village | 50 | 7% | 95.947 | 5% | 10.238 | 6% |
| Rural accessible | 114 | 17% | 53.724 | 3% | 7.330 | 5% |
| Rural peripheral | 2 | 0,3% | 1.004 | 0,1% | 98 | 0,1% |
| *No data available* | *3* | *0,4%* | *#N/A* | *#N/A* | *1.965* | *1%* |
| **Total sum** | **668** | **100,0%** | **1.881.578** | **100,0%** | **157.520** | **100,0%** |

[40] The number in of buildings provided by the CBS exclude the buildings in the sectors of government, education and healthcare due to uncertainty in the numbers, which means the actual numbers are slightly higher, but the distribution is likely to remain the same.

Overall, it can be concluded that the current division of the operating area by means of the living environments on the PC4 area is accurate when considered for the entire operating area. Also the number of buildings is similar to the number of small consumer connections.

## A.2 Databases for company buildings

Two databases are leading in research on geographical locations of commercial buildings; the LISA database and the CBS database.

The micro data of the LISA database includes all registered offices in which paid jobs are performed in the Netherlands [Stichting LISA, 2013]. A registered offices is defined as 'a location of a company, institution or self-employed undertaking (meaning each factory, working place, office, store or other business accommodation) in which or from which an economic activity of an independent (free) occupation is performed by at least 1 employed person' [Stichting LISA, 2013]. The database includes the type of company, the location (PC6 or PC4 level), the total parcel size, and more.

The CBS database uses the same definitions for the categories of companies as the LISA database, namely the 'Standaard Bedrijfsindeling SBI 2008'. The methods for obtaining the number of registered offices are roughly the same, and the definition for a registered offices is: 'each separately located space, terrain or complex of s**Paces**, used by a company for performing activities; each company consists of at least one registered office' [CBS, n.d.].

The database of the CBS is free of charge for PC4 area level, while the more detailed data of the LISA database requires payments. The LISA database is significantly more accurate, and includes parcel sizes which can be converted into roof areas. However, since this data is not freely available the database of the CBS has been used.

## A.3 Future number of buildings

The expectancy is that in 2050 at least 90% of the current housing stock is still operational [DHPA, 2013]. Each year around 20.000 buildings are decommissioned, while in the last decade between 50.000 and 90.000 buildings have been constructed [PBL, 2014b]. With a building stock of around 7,6 million, this means between 14 – 30% of the building stock is renewed in 2050, and between 10 – 23 % in 2040. The assumption of the DHPA therefore appears to be on the low side based on current decommissioning rates.

It is assumed that most newly build houses are constructed in either renovation areas in which current stock is decommissioned and rebuild, or at an area in which no previous dwellings have been build. The first option means that current MV/LV-transformer capacity needs to be revised, and for the second option a new transformer needs to be placed. Either way, new calculations need to be made since significant changes in load characteristics can be expected.

In this analysis it is assumed that current dwelling stock contains the same building types in 2040. It should be noted that this is a simplification of reality, but is acceptable for this analysis for peak demand analysis of existing transformers.

## A.4 Number of buildings per model district

The goal of this section is to determine the number of residential and commercial buildings per living environment in order to set the number of building to be used per model district. Therefore the characteristics of the postal codes classified as a certain living environment will be analysed. This requires a large enough sample size which is preferably greater than 30, which is the minimum size required for normal distribution. Two living environments are clearly below this number, namely the centrum-urban (9 values) and the rural peripheral (2 values). The rural peripheral living environment will no longer be taken into account in the analysis. The centrum-urban remains within the scope although it should be kept in mind that the sample size is very small for conducting data analysis.

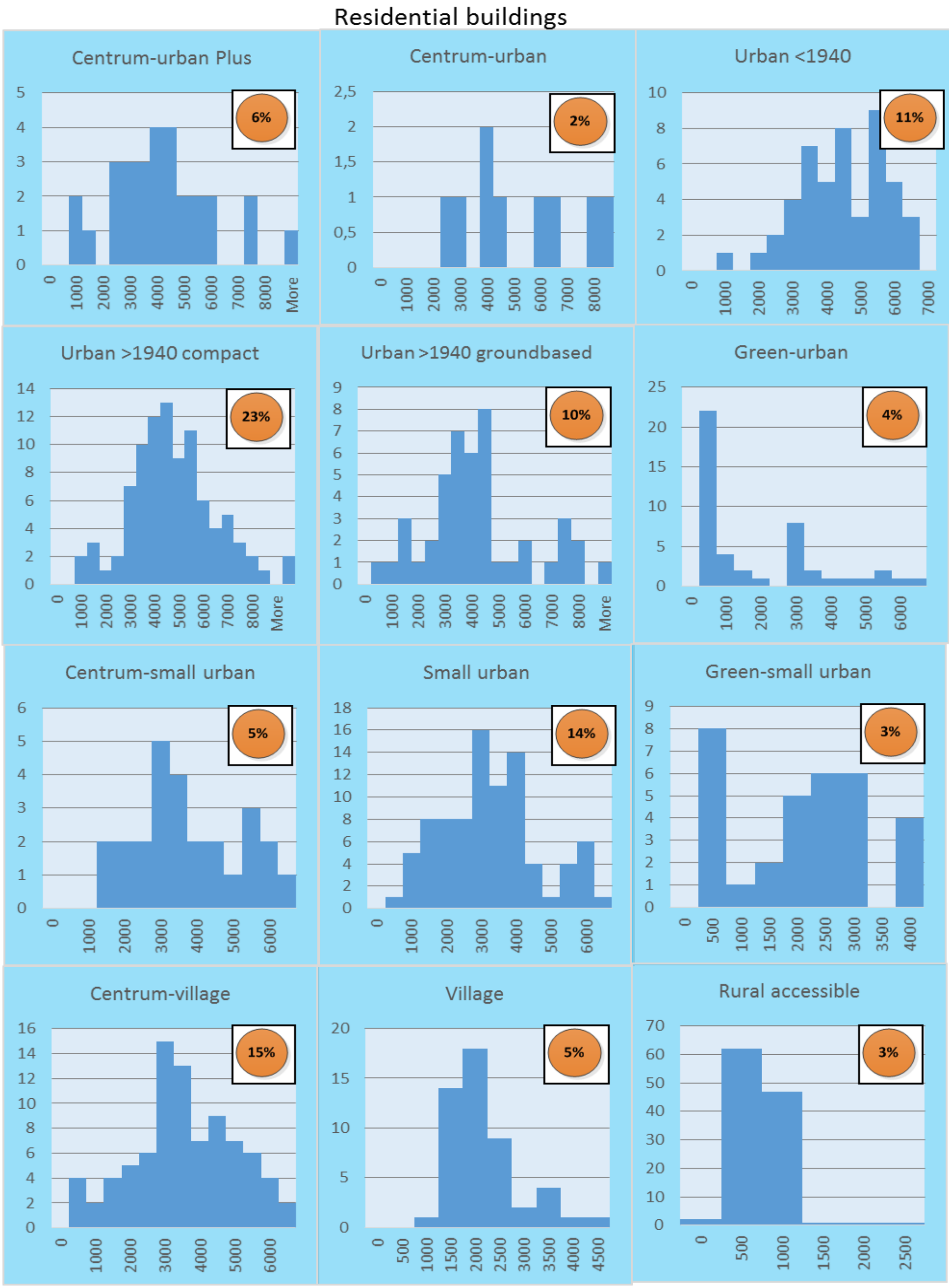



*Figure 71: Histograms of number of residential buildings per postal code area classified with a particular living environment. Constructed with fixed bin size of 500, ranging from 0 until 9000. In case there are more than 9000 buildings the area falls into the 'more' category. Only the bins with at least 1 value are included. The top right **Circles** show which part of the operating area is covered by the model district.*

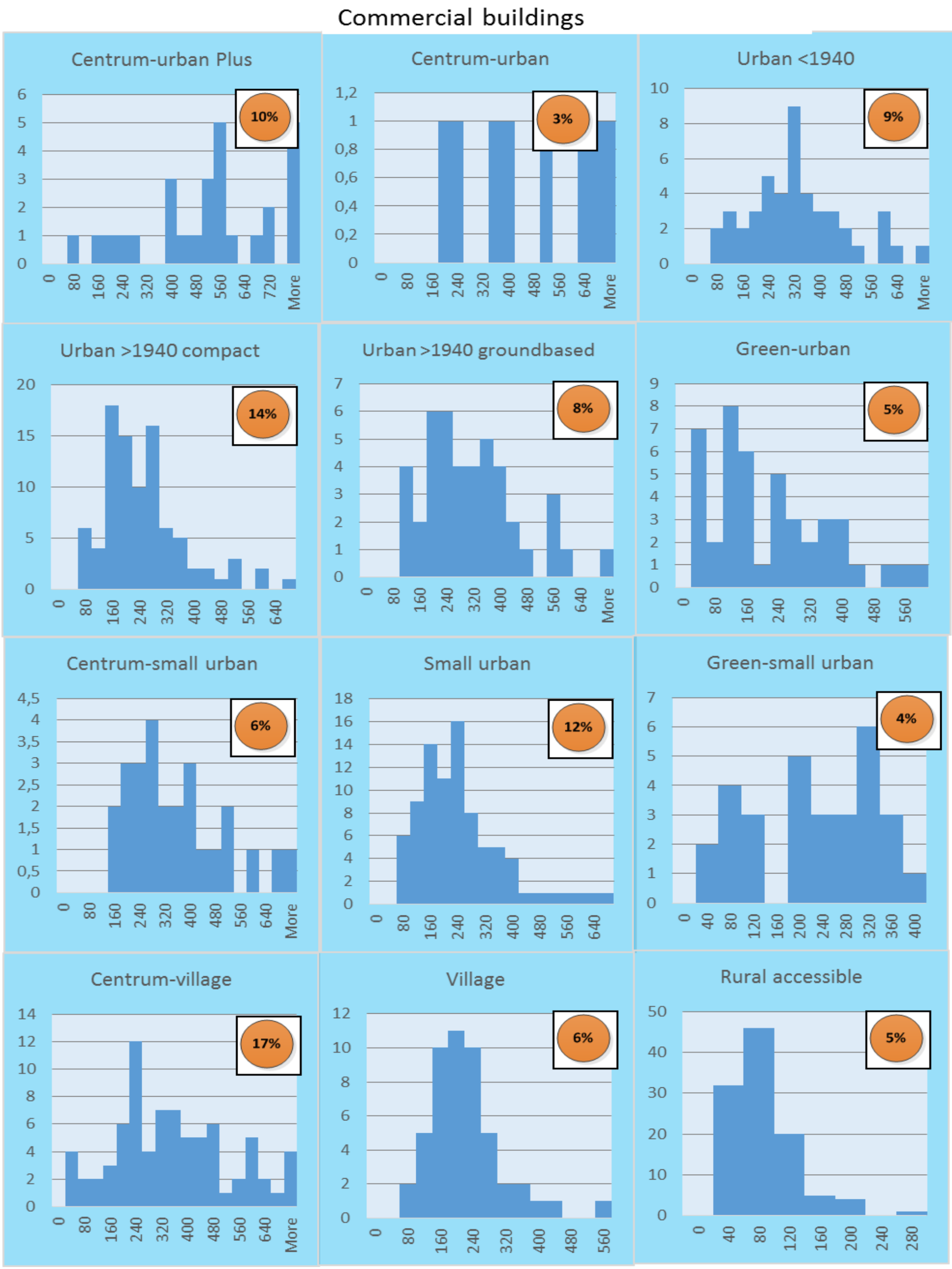



*Figure 72: Histograms of number of commercial buildings per postal code area classified with a particular living environment. Constructed with fixed bin size of 40, ranging from 0 until 680. In case there are more than 680 buildings the area falls into the 'more' category. Only the bins with at least 1 value are included. The top right* ***Circles*** *show which part of the operating area is covered by the model district.*

Figure 72 shows the same for the number of commercial buildings. Most of the living environments show a dispersed distribution of the number of residential buildings. It can be noticed that most of the histograms are not normally distributed and have one or multiple peaks. The general patterns of the residential building distributions are either a single peak, or a double peak distribution. The 6 model districts categorised as double peak are urban <1940, urban >1940 groundbased, green urban, centrum-small urban, small urban, and green small urban. The other model districts have a single peak distribution.

The peaks can be used to construct the mean average around the peak, or use the mode of the peak area. By taking the average, the most average model district will be constructed. The goal is to create model districts that are representative for the Dutch build environment. Using the average allows for easy reconstruction of the entire operating area, but reduces the ability to clearly distinguish the differences between the district classifications. Clearly different model districts are deemed most important by the client since this is likely to enhance the insights. Additionally this allows other DNOs to use the same model districts. Therefore it has been chosen to use the mode to represent the number of buildings for each of the peak of the model district. The mode is the number most frequently available in the sample. The number of residential buildings within a PC4 area can be as low as 0 or as high as 11.000, which makes it unlikely that there are a lot of similar number of buildings in the sample. Therefore the number of buildings have been categorizes into bins of 500, meaning a postal code area with 49 buildings will fall in bin 1 (0 – 499), and a PC4 area with 594 buildings will fall in bin 2 (500 – 999). The number of commercial buildings ranges from 0 until 1.500, for which a bin size of 40 is used. This results in the following number of residential buildings and frequency of occurrence for the model districts:

*Table 28: Overview of number of residential and commercial buildings per model district.*

| Model district | # residential buildings – Peak 1 | # commercial buildings – Peak 1 | # PC4 areas | # residential buildings – Peak 2 | # commercial buildings – Peak 2 | # PC4 areas |
|---|---|---|---|---|---|---|
| Centrum-urban Plus | 4250 | 580 | 29 | - | - | - |
| Centrum-urban | 4250 | 497 | 9 | - | - | - |
| Urban <1940 | 4250 | 340 | 29 | 5750 | 340 | 19 |
| Urban >1940 compact | 4750 | 340 | 93 | - | - | - |
| Urban >1940 groundbased | 4750 | 260 | 38 | 7750 | 501 | 7 |
| Green urban | 750 | 140 | 29 | 3250 | 378 | 17 |
| Centrum-small urban | 3250 | 300 | 19 | 5750 | 555 | 7 |
| Small urban | 3250 | 260 | 75 | 6250 | 413 | 12 |
| Green-small urban | 750 | 100 | 9 | 3000 | 231 | 23 |
| Centrum-village | 3250 | 260 | 87 | - | - | - |
| Village | 2250 | 220 | 50 | - | - | - |
| Rural accessible | 750 | 100 | 114 | - | - | - |

The residential building peaks are taken as the basis, after which the number of commercial buildings accompanying it is determined. For the single peak model districts the mode of the commercial buildings is used. The exception is the centrum-urban district which has a multiple number of buildings with 2 occurrences, therefore the sample mean is used in this case. The model districts with two residential building peaks require additional analysis of the commercial buildings since it is unknown whether a large number of residential buildings is accompanied by a large number of commercial buildings, or rather a small number of commercial buildings.

### Urban <1940

Five peaks can be identified in the commercial building histogram; at 100, 240, 340, 440, and 600. When analysing the number of commercial buildings associated with the residential building peak 1 and peak 2 numbers, there is no clear trend that can be distinguished. For example the PC4 areas with less than 5000 residential buildings are assigned to peak 1, which has 4250 residential buildings. The results for mapping the PC4 areas associated with peak 1 and their corresponding number of commercial buildings are provided in Figure 73 on the left side, as well as the results for peak 2 on the right. There are no clear peaks identifiable within the two figures, meaning that a large number of commercial buildings does not automatically have a large number of commercial buildings, but rather either a small number or large number of commercial buildings. Also due to the large spread it would be unwise to use the mode to represent the number of commercial buildings. Therefore the average of the entire sample of commercial buildings is used for both the first and second residential peak.

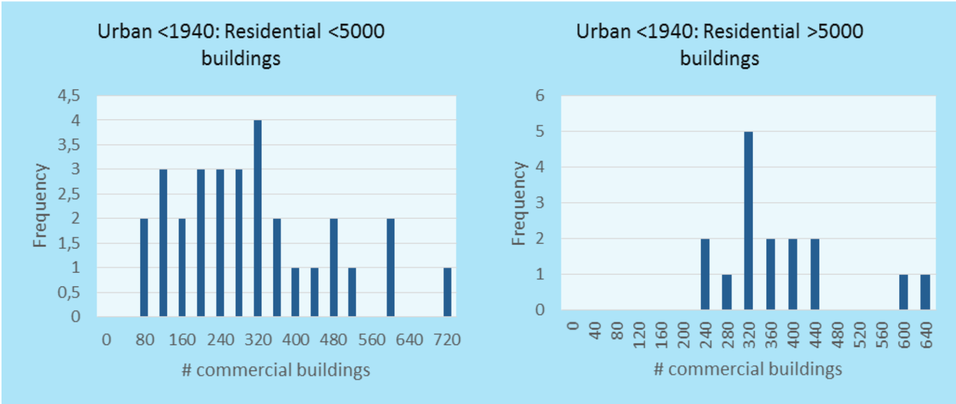



*Figure 73: Number of commercial buildings for PC4 areas classified with peak 1 (left) or peak 2 (right) for the model district Urban <1940.*

### *Urban >1940 groundbased*

The same approach is taken for this model district in which a distinction is made between the PC4 areas having less or more than 6500 residential buildings. The number of commercial buildings accompanying less than 6500 residential buildings show a dense spread between 40 and 160 commercial buildings. Therefore the average of this spread is used for peak 1, resulting in 100 commercial buildings. For the second peak the average of the right hand side figure is used, resulting in 197 commercial buildings.

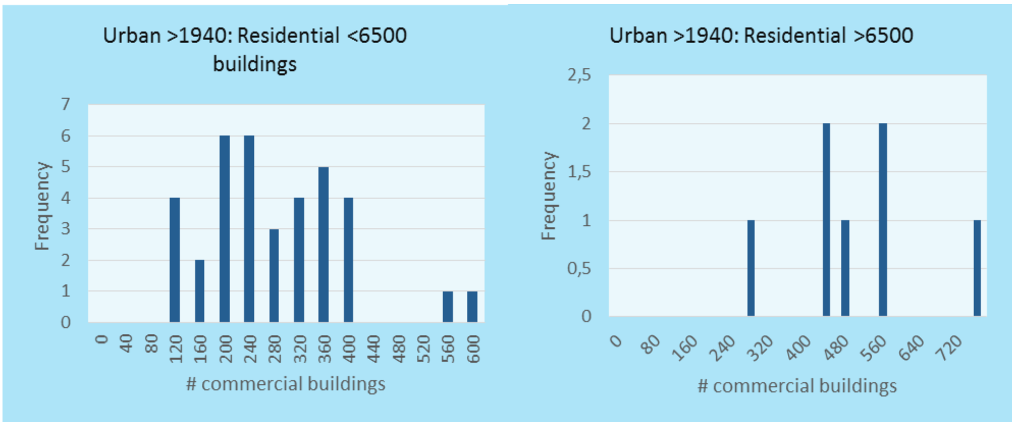



*Figure 74: Number of commercial buildings for PC4 areas classified with peak 1 (left) or peak 2 (right) for the model district Urban >1940 groundbased.*

Similar lines of reasoning are applicable to the remaining model districts. The figures of the spread of commercial buildings per peak area are provided below, and the results for the number of commercial buildings per peak are provided in Table 28.

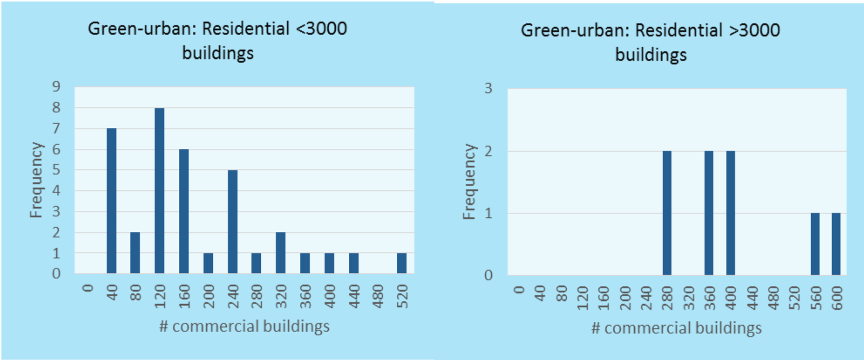



*Figure 75: Number of commercial buildings for PC4 areas classified with peak 1 (left) or peak 2 (right) for the model district green-urban.*

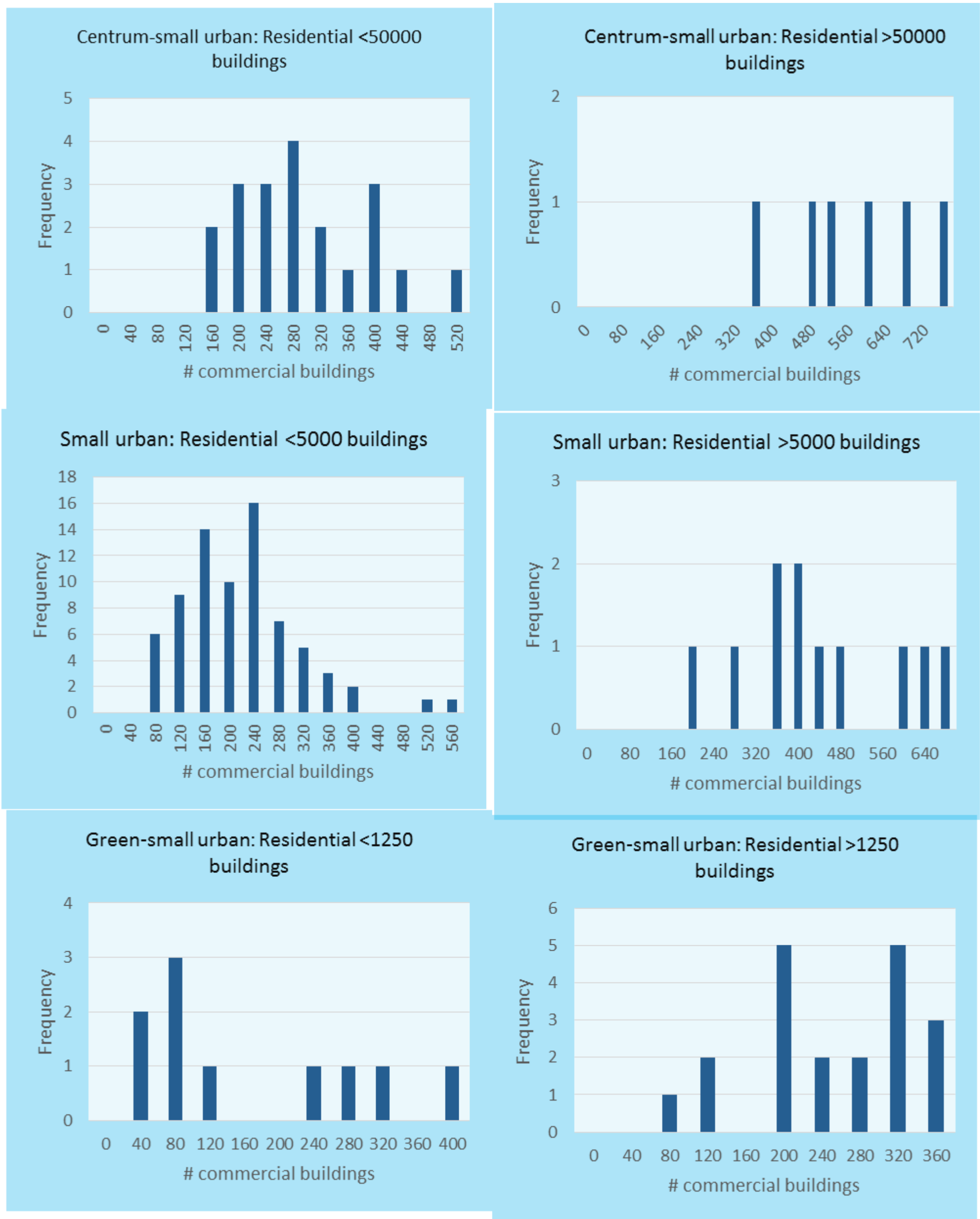



*Figure 76: Number of commercial buildings for PC4 areas classified with peak 1 (left) or peak 2 (right) for the model districts centrum-small urban, small urban, and green-small urban.*

| | Centrum-urban Plus | Centrum-urban | Urban <1940 | Urban >1940 compact | Urban >1940 groundbased | Green-urban | Centrum-small urban | Small urban | Green-small urban | Centrum-village | Village | Rural accessible |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Residential buildings** | | | | | | | | | | | | |
| **Mode** | **4250** | **4250** | **5750** | **4750** | **4750** | **750** | **3250** | **3250** | **750** | **3250** | **2250** | **750** |
| Mean | 3991 | 4947 | 4237 | 4556 | 3997 | 1661 | 3519 | 3004 | 1787 | 3301 | 1919 | 471 |
| Std. deviation | 1881 | 2175 | 1282 | 1792 | 2007 | 2109 | 1500 | 1402 | 1274 | 1481 | 751 | 361 |
| Sample size | 29 | 9 | 48 | 93 | 45 | 46 | 26 | 87 | 32 | 84 | 50 | 114 |
| Minimum | 610 | 2340 | 735 | 607 | 490 | 2 | 1142 | 287 | 3 | 118 | 965 | 0 |
| Maximum | 8900 | 8462 | 6460 | 10924 | 10364 | 9688 | 7087 | 6597 | 3989 | 7145 | 4050 | 2470 |
| **Commercial buildings** | | | | | | | | | | | | |
| **Mode** | **580** | **420** | **340** | **180** | **260** | **140** | **300** | **260** | **340** | **260** | **220** | **100** |
| Mean | 564 | 545 | 314 | 236 | 301 | 196 | 340 | 226 | 204 | 335 | 205 | 68 |
| Std. deviation | 313 | 298 | 148 | 122 | 152 | 146 | 163 | 125 | 108 | 182 | 91 | 44 |
| Sample size | 27 | 9 | 46 | 91 | 43 | 44 | 26 | 85 | 30 | 78 | 50 | 108 |
| Minimum | 78 | 195 | 60 | 53 | 100 | 13 | 133 | 50 | 20 | 15 | 73 | 8 |
| Maximum | 1530 | 1033 | 698 | 670 | 855 | 563 | 760 | 663 | 393 | 785 | 560 | 253 |

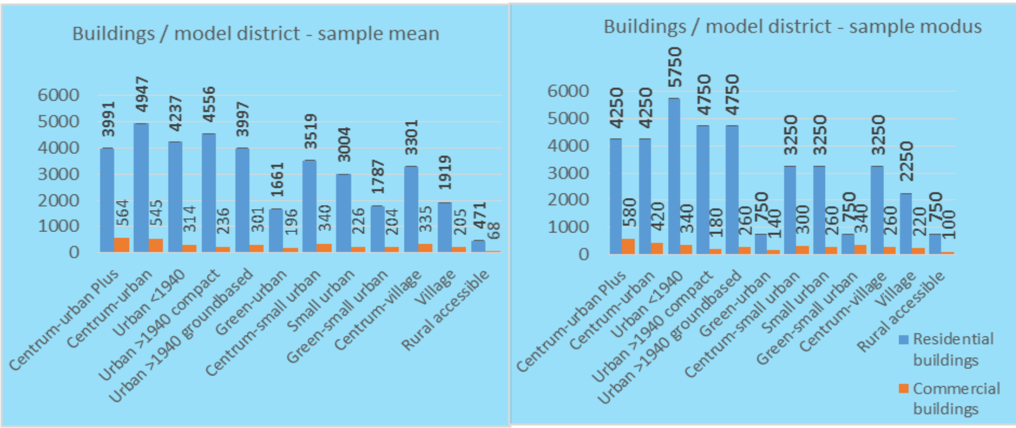



*Figure 77: Sample mean and mode of residential and commercial buildings.*

## Conclusion

Overall there are now 12 model districts, with 6 model districts that have two values for the number of buildings, resulting in 18 input values for the model districts with number of buildings (see Table 29).

*Table 29: Number of buildings per model district, resulting in 18 model districts in which 6 living environments are divided into two model districts.*

| | Model district | #residential buildings – Peak 1 | #commercial buildings – Peak 1 | # PC4 areas | #residential buildings – Peak 2 | #commercial buildings – Peak 2 | # PC4 areas |
|---|---|---|---|---|---|---|---|
| 1 | Centrum-urban Plus | 4250 | 580 | 29 | - | - | - |
| 2 | Centrum-urban | 4250 | 497 | 9 | - | - | - |
| 3 | Urban <1940 | 4250 | 340 | 29 | 5750 | 340 | 19 |
| 4 | Urban >1940 compact | 4750 | 340 | 93 | - | - | - |
| 5 | Urban >1940 groundbased | 4750 | 260 | 38 | 7750 | 501 | 7 |
| 6 | Green urban | 750 | 140 | 29 | 3250 | 378 | 17 |
| 7 | Centrum-small urban | 3250 | 300 | 19 | 5750 | 555 | 7 |
| 8 | Small urban | 3250 | 260 | 75 | 6250 | 413 | 12 |
| 9 | Green-small urban | 750 | 100 | 9 | 3000 | 231 | 23 |
| 10 | Centrum-village | 3250 | 260 | 87 | - | - | - |
| 11 | Village | 2250 | 220 | 50 | - | - | - |
| 12 | Rural accessible | 750 | 100 | 114 | - | - | - |

## A.5 Distribution reference buildings per model district

The goal of this section is to determine the distribution of reference buildings per model district. This data is available on postal code level, but is the property of commercial businesses and only available after purchasing. Therefore another approach is taken to quantify the distribution of reference buildings per model districts. An approximation is constructed by using the reference buildings (constructed by RVO/Agentschap NL), the general distribution of reference buildings in the Netherlands [Agentschap NL, 2011, 2013], the number of single-, and multi-family houses[41][CBS, 2013b], and reports that have reported about the types of houses within a certain area which did purchase the data [Kromhout, Bakker, & Schulenberg, 2014; Poulus & Heida, 2005; Van Leeuwen, Heida, Van Galen, & Poulus, 2010]. This data is used to construct a qualitative table about the distribution of reference buildings for each of the model districts (see Table 28).

The data of ABF Research containing the living environment also includes the number of houses that have been built in a certain period. This data is used to construct the number of buildings for all of the postal codes classified as a certain living environment (see Table 31). These figures are used in combination with the quantitative table in order to estimate the distribution of reference buildings in each of the model districts as presented in Table 31. The percentages of reference building specified per building period are not further used, but only the total percentages of reference building per model district are used in the remainder of this analysis.

[41] Single-family houses include the reference buildings detached, semi-detached and terraced houses. Multi-family houses include the reference buildings common staircase and galleries, common staircase no galleries, maisonettes, and other apartments.

*Table 30: Distribution of reference buildings per living environment in a qualitative manner. The data about the number of buildings for the Netherlands are adapted from [Agentschap NL, 2011]*

| Type of reference building | | Detached | Semi-detached | Terraced hosue | Maisonette | Common staircase and galleries | Common staircase no galleries | Other apartments |
|---|---|---|---|---|---|---|---|---|
| Distribution in the Netherlands | <1964 | 441.000 | 285.000 | 1.001.000 | 226.000 | 69.000 | 523.000 | 99.000 |
| | 1965-1974 | 119.000 | 142.000 | 606.000 | 22.000 | 174.000 | 112.000 | 125.000 |
| | 1975-1991 | 221.000 | 224.000 | 879.000 | 94.000 | 109.000 | 142.000 | 125.000 |
| | 1992-2005 | 178.000 | 173.000 | 353.000 | 40.000 | 113.000 | 70.000 | 136.000 |
| | **Total** | 959.000 | 824.000 | 2.839.000 | 382.000 | 465.000 | 847.000 | 485.000 |
| | **% of total** | 14% | 12% | 42% | 6% | 7% | 12% | 7% |
| **Centrum-urban Plus** | <1945 | -2 | -2 | -2 | 1 | 1 | 1 | 1 |
| | 1945 - 1970 | -2 | -2 | -2 | -1 | 0 | 0 | 0 |
| | 1971 - 1990 | -2 | -2 | -2 | -2 | 0 | 0 | 0 |
| | 1990 - 2010 | -2 | -2 | -2 | -2 | 0 | 0 | 0 |
| | >2010 | -2 | -2 | -2 | -2 | 0 | 0 | 0 |
| **Centrum-urban** | <1945 | -2 | -1 | -1 | -1 | 0 | 0 | 0 |
| | 1945 - 1970 | -2 | 0 | 0 | -1 | 0 | 0 | 0 |
| | 1971 - 1990 | -2 | 0 | 0 | -1 | 0 | 0 | 0 |
| | 1990 - 2010 | -2 | 0 | 0 | -1 | 0 | 0 | 0 |
| | >2010 | -2 | 0 | 0 | -1 | 0 | 0 | 0 |
| **Urban <1940** | <1945 | -2 | 1 | 1 | 1 | -1 | -1 | -1 |
| | 1945 - 1970 | -2 | 1 | 1 | 1 | -1 | -1 | -1 |
| | 1971 - 1990 | -2 | 0 | 0 | 0 | -1 | -1 | -1 |
| | 1990 - 2010 | -2 | 0 | 0 | 0 | -1 | -1 | -1 |
| | >2010 | -2 | 0 | 0 | 0 | -1 | -1 | -1 |
| **Urban >1940 compact** | <1945 | -2 | -1 | -1 | -2 | -1 | -1 | -1 |
| | 1945 - 1970 | -2 | 0 | 0 | 0 | -1 | -1 | -1 |
| | 1971 - 1990 | -2 | 0 | 0 | 0 | -1 | -1 | -1 |
| | 1990 - 2010 | -2 | 0 | 0 | 0 | -1 | -1 | -1 |
| | >2010 | -2 | 0 | 0 | 0 | -1 | -1 | -1 |
| **Urban >1940 groundbased** | <1945 | -1 | -1 | -1 | -1 | -1 | -1 | -1 |
| | 1945 - 1970 | -1 | 1 | 1 | -1 | -1 | -1 | -1 |
| | 1971 - 1990 | -1 | 1 | 1 | -1 | -1 | -1 | -1 |
| | 1990 - 2010 | -1 | 1 | 1 | -1 | -1 | -1 | -1 |
| | >2010 | -1 | 1 | 1 | -1 | -1 | -1 | -1 |
| **Green-urban** | <1945 | -1 | -1 | -1 | -1 | -1 | -2 | -2 |
| | 1945 - 1970 | 0 | 1 | 1 | -1 | -2 | -2 | -2 |
| | 1971 - 1990 | 0 | 1 | 1 | -1 | -2 | -2 | -2 |
| | 1990 - 2010 | 0 | 1 | 1 | -1 | -2 | -2 | -2 |
| | >2010 | 0 | 1 | 1 | -1 | -2 | -2 | -2 |
| **Centrum-small urban** | <1945 | -2 | -1 | -1 | -1 | -1 | -1 | -1 |
| | 1945 - 1970 | -2 | 1 | 1 | -1 | -1 | -1 | -1 |
| | 1971 - 1990 | -2 | 1 | 1 | -1 | -1 | -1 | -1 |
| | 1990 - 2010 | -2 | 0 | 0 | 0 | -1 | -1 | -1 |
| | >2010 | -2 | 0 | 0 | 0 | -1 | -1 | -1 |
| **Small urban** | <1945 | -1 | -1 | -1 | -1 | -1 | -1 | -1 |
| | 1945 - 1970 | -1 | 1 | 1 | -1 | -1 | -1 | -1 |
| | 1971 - 1990 | -1 | 1 | 1 | -1 | -1 | -1 | -1 |
| | 1990 - 2010 | -1 | 1 | 1 | -1 | -1 | -1 | -1 |
| | >2010 | -1 | 1 | 1 | -1 | -1 | -1 | -1 |
| **Green-small urban** | <1945 | -1 | -1 | -1 | -1 | -2 | -2 | -2 |
| | 1945 - 1970 | 0 | 1 | 1 | -1 | -2 | -2 | -2 |
| | 1971 - 1990 | 0 | 1 | 1 | -1 | -2 | -2 | -2 |
| | 1990 - 2010 | 0 | 1 | 1 | -1 | -2 | -2 | -2 |
| | >2010 | 0 | 1 | 1 | -1 | -2 | -2 | -2 |
| **Centrum-village** | <1945 | -1 | -1 | -1 | -1 | -2 | -2 | -2 |
| | 1945 - 1970 | 0 | 2 | 2 | -1 | -2 | -2 | -2 |
| | 1971 - 1990 | 0 | 2 | 2 | -1 | -2 | -2 | -2 |
| | 1990 - 2010 | 0 | 2 | 2 | -1 | -2 | -2 | -2 |
| | >2010 | 0 | 2 | 2 | -1 | -2 | -2 | -2 |
| **Village** | <1945 | -1 | -1 | -1 | -2 | -2 | -2 | -2 |
| | 1945 - 1970 | 0 | 1 | 1 | -2 | -2 | -2 | -2 |
| | 1971 - 1990 | 0 | 1 | 1 | -2 | -2 | -2 | -2 |
| | 1990 - 2010 | 0 | 1 | 1 | -2 | -2 | -2 | -2 |
| | >2010 | 0 | 1 | 1 | -2 | -2 | -2 | -2 |
| **Rural accessible** | <1945 | 1 | 1 | 1 | -2 | -2 | -2 | -2 |
| | 1945 - 1970 | 1 | 1 | 1 | -2 | -2 | -2 | -2 |
| | 1971 - 1990 | 1 | 1 | 1 | -2 | -2 | -2 | -2 |
| | 1990 - 2010 | 1 | 1 | 1 | -2 | -2 | -2 | -2 |
| | >2010 | 1 | 1 | 1 | -2 | -2 | -2 | -2 |

| Legend: This type of building in this building period is... | |
|---|---|
| -2 | ... nearly non-existent in the living environment, exceptions not included. |
| -1 | ... available in the living environment, but is relatively small compared to other buildings. |
| 0 | ... approximately the same distributed as other buildings with '0'. |
| 1 | ... relatively abundant in numbers compared to other building types. |
| 2 | ... most present in this living environment, other building types are nearly non-existing. |

*Table 31: Distribution of reference buildings per living environment quantified. Only the total percentages per model district are representative, the yearly percentages are only to provide insight into the construction of the total percentages.*

| Type of reference building | | Sum all dwellings | | Detached | Semi-detached | Terraced hosue | Maisonette | Common staircase and galleries | Common staircase no galleries | Other apartments |
|---|---|---|---|---|---|---|---|---|---|---|
| Distribution operating area Stedin | <1945 | 409.451 | 22% | | | | | | | |
| | 1945 - 1970 | 473.807 | 25% | | | | | | | |
| | 1971 - 1990 | 559.067 | 30% | | | | | | | |
| | 1990 - 2010 | 413.441 | 22% | | | | | | | |
| | >2010 | 25.714 | 1% | | | | | | | |
| | Total | 1.881.480 | 100% | | | | | | | |
| Centrum-urban Plus | <1945 | 62.614 | 54% | 0% | 0% | 0% | 14% | 14% | 14% | 14% |
| | 1945 - 1970 | 8.002 | 6,9% | 0% | 0% | 0% | 1% | 2% | 2% | 2% |
| | 1971 - 1990 | 24.562 | 21% | 0% | 0% | 0% | 0% | 7% | 7% | 7% |
| | 1990 - 2010 | 19.506 | 17% | 0% | 0% | 0% | 0% | 6% | 6% | 6% |
| | >2010 | 1.057 | 1% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| | Total | 115.741 | 100% | 0% | 0% | 0% | 15% | 28% | 28% | 28% |
| Centrum-urban | <1945 | 15.498 | 35% | 0% | 4% | 4% | 4% | 8% | 8% | 8% |
| | 1945 - 1970 | 7.423 | 17% | 0% | 3% | 3% | 2% | 3% | 3% | 3% |
| | 1971 - 1990 | 13.841 | 31% | 0% | 6% | 6% | 3% | 6% | 6% | 6% |
| | 1990 - 2010 | 7.134 | 16% | 0% | 3% | 3% | 1% | 3% | 3% | 3% |
| | >2010 | 609 | 1% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| | Total | 44.505 | 100% | 0% | 16% | 16% | 10% | 20% | 20% | 20% |
| Urban <1945 | <1945 | 146.459 | 72% | 0% | 18% | 18% | 18% | 6% | 6% | 6% |
| | 1945 - 1970 | 19.268 | 9% | 0% | 2% | 2% | 2% | 1% | 1% | 1% |
| | 1971 - 1990 | 14.281 | 7% | 0% | 2% | 2% | 2% | 1% | 1% | 1% |
| | 1990 - 2010 | 22.281 | 11% | 0% | 2% | 2% | 2% | 1% | 1% | 1% |
| | >2010 | 1.068 | 1% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| | Total | 203.357 | 100% | 0% | 24% | 24% | 24% | 9% | 9% | 9% |
| Urban >1945 compact | <1945 | 49.883 | 12% | 0% | 2% | 2% | 0% | 2% | 2% | 2% |
| | 1945 - 1970 | 164.726 | 39% | 0% | 9% | 9% | 9% | 4% | 4% | 4% |
| | 1971 - 1990 | 136.488 | 32% | 0% | 7% | 7% | 7% | 4% | 4% | 4% |
| | 1990 - 2010 | 67.107 | 16% | 0% | 4% | 4% | 4% | 2% | 2% | 2% |
| | >2010 | 5.492 | 1% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| | Total | 423.696 | 100% | 0% | 22% | 22% | 20% | 12% | 12% | 12% |
| Urban >1945 groundbased | <1945 | 12.266 | 7% | 1% | 1% | 1% | 1% | 1% | 1% | 1% |
| | 1945 - 1970 | 22.076 | 12% | 1% | 3% | 3% | 1% | 1% | 1% | 1% |
| | 1971 - 1990 | 56.645 | 31% | 3% | 9% | 9% | 3% | 3% | 3% | 3% |
| | 1990 - 2010 | 85.231 | 47% | 4% | 13% | 13% | 4% | 4% | 4% | 4% |
| | >2010 | 3.635 | 2% | 0% | 1% | 1% | 0% | 0% | 0% | 0% |
| | Total | 179.853 | 100% | 9% | 26% | 26% | 9% | 9% | 9% | 9% |
| Green-urban | <1945 | 14.281 | 19% | 4% | 4% | 4% | 4% | 4% | 0% | 0% |
| | 1945 - 1970 | 23.199 | 30% | 7% | 10% | 10% | 3% | 0% | 0% | 0% |
| | 1971 - 1990 | 25.476 | 33% | 7% | 11% | 11% | 4% | 0% | 0% | 0% |
| | 1990 - 2010 | 11.521 | 15% | 3% | 5% | 5% | 2% | 0% | 0% | 0% |
| | >2010 | 1.915 | 3% | 1% | 1% | 1% | 0% | 0% | 0% | 0% |
| | Total | 76.392 | 100% | 22% | 31% | 31% | 13% | 4% | 0% | 0% |
| Centrum-small urban | <1945 | 13.359 | 15% | 0% | 2% | 2% | 2% | 2% | 2% | 2% |
| | 1945 - 1970 | 29.966 | 33% | 0% | 10% | 10% | 3% | 3% | 3% | 3% |
| | 1971 - 1990 | 28.604 | 31% | 0% | 9% | 9% | 3% | 3% | 3% | 3% |
| | 1990 - 2010 | 17.622 | 19% | 0% | 4% | 4% | 4% | 2% | 2% | 2% |
| | >2010 | 1.937 | 2% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| | Total | 91.488 | 100% | 0% | 26% | 26% | 14% | 11% | 11% | 11% |
| Small urban | <1945 | 23.886 | 9% | 1% | 1% | 1% | 1% | 1% | 1% | 1% |
| | 1945 - 1970 | 63.210 | 24% | 2% | 7% | 7% | 2% | 2% | 2% | 2% |
| | 1971 - 1990 | 102.369 | 39% | 4% | 11% | 11% | 4% | 4% | 4% | 4% |
| | 1990 - 2010 | 69.121 | 26% | 2% | 7% | 7% | 2% | 2% | 2% | 2% |
| | >2010 | 2.755 | 1% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| | Total | 261.341 | 100% | 10% | 26% | 26% | 10% | 10% | 10% | 10% |
| Green-small urban | <1945 | 11.165 | 20% | 5% | 5% | 5% | 5% | 0% | 0% | 0% |
| | 1945 - 1970 | 18.636 | 33% | 7% | 11% | 11% | 4% | 0% | 0% | 0% |
| | 1971 - 1990 | 18.519 | 32% | 7% | 11% | 11% | 4% | 0% | 0% | 0% |
| | 1990 - 2010 | 8.626 | 15% | 3% | 5% | 5% | 2% | 0% | 0% | 0% |
| | >2010 | 248 | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| | Total | 57.194 | 100% | 23% | 32% | 32% | 14% | 0% | 0% | 0% |
| Centrum-village | <1945 | 31.790 | 11% | 3% | 3% | 3% | 3% | 0% | 0% | 0% |
| | 1945 - 1970 | 74.318 | 27% | 5% | 10% | 10% | 2% | 0% | 0% | 0% |
| | 1971 - 1990 | 93.543 | 34% | 6% | 12% | 12% | 3% | 0% | 0% | 0% |
| | 1990 - 2010 | 73.116 | 26% | 5% | 10% | 10% | 2% | 0% | 0% | 0% |
| | >2010 | 4.472 | 2% | 0% | 1% | 1% | 0% | 0% | 0% | 0% |
| | Total | 277.239 | 100% | 19% | 35% | 35% | 11% | 0% | 0% | 0% |
| Village | <1945 | 15.154 | 16% | 5% | 5% | 5% | 0% | 0% | 0% | 0% |
| | 1945 - 1970 | 27.906 | 29% | 7% | 11% | 11% | 0% | 0% | 0% | 0% |
| | 1971 - 1990 | 29.491 | 31% | 8% | 12% | 12% | 0% | 0% | 0% | 0% |
| | 1990 - 2010 | 22.352 | 23% | 6% | 9% | 9% | 0% | 0% | 0% | 0% |
| | >2010 | 1.044 | 1% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| | Total | 95.947 | 100% | 26% | 37% | 37% | 0% | 0% | 0% | 0% |
| Rural accessible | <1945 | 12.813 | 24% | 8% | 8% | 8% | 0% | 0% | 0% | 0% |
| | 1945 - 1970 | 14.780 | 28% | 9% | 9% | 9% | 0% | 0% | 0% | 0% |
| | 1971 - 1990 | 15.019 | 28% | 9% | 9% | 9% | 0% | 0% | 0% | 0% |
| | 1990 - 2010 | 9.649 | 18% | 6% | 6% | 6% | 0% | 0% | 0% | 0% |
| | >2010 | 1.462 | 3% | 1% | 1% | 1% | 0% | 0% | 0% | 0% |
| | Total | 53.723 | 100% | 33% | 33% | 33% | 0% | 0% | 0% | 0% |

The accuracy of this distribution of reference buildings per model district should be investigated. This is tested by determining the difference between the percentage of multi-family buildings and single-family buildings of the ABF Research data, and of the calculated number based on the distribution of reference buildings and the number of houses for each of the postal codes classified as this model district type.

This is explained by using the centrum-urban plus model district as an example. It has been determined that in this model district; 0% of the dwellings are detached, semi-detached or terraced; 15% of the dwellings are maisonette; and the common staircase and galleries, common staircase no galleries, and other apartments each represent 28% of the dwellings (see Table 31). The detached, semi-detached and terraced types represent the single-family buildings, while the rest represent the multi-family building category. The calculated percentage of single-family buildings is therefore 0% of the buildings within a postal code area classified as centrum-urban plus, and the percentage of multi-family buildings is 100%. By multiplying these percentages with the total number of buildings per postal code area classified as centrum-urban plus, the number of single and multi-family buildings within these areas are calculated. Summing the calculated number of single-family buildings from all of the postal code areas classified as centrum-urban plus equals to 0 buildings, and the sum of the number of multi-family buildings equals to 115.743.

The data from ABF Research contains the number of single- and multi-family houses within a PC4 area. The sum is determined for the centrum-urban plus districts, resulting in 18.386 single-family buildings and 97.357 multi-family houses.  This means that there is a large difference between the calculated number of single- and multi-family buildings and the actual number of single- and multi-family buildings.

*Table 32: Single- and multi-family buildings per model district.*

| Model district | Sum single-fam. ABF | Sum multi-fam. ABF | Percentage single-fam. ABF | Sum single-fam. Calculated | Sum multi-fam. Calculated | Percentage single-fam. Calculated | Difference calculated and ABF single-fam. | Difference calculated and ABF multi-fam. |
|---|---|---|---|---|---|---|---|---|
| Centrum-urban Plus | 18.386 | 97.357 | 16% | - | 115.743 | 0% | -16% | 16% |
| Centrum-urban | 14.531 | 29.992 | 33% | 13.998 | 30.525 | 31% | -1% | 1% |
| Urban <1940 | 48.167 | 155.191 | 24% | 99.588 | 103.770 | 49% | 25% | -25% |
| Urban >1940 compact | 125.109 | 298.590 | 30% | 186.094 | 237.605 | 44% | 14% | -14% |
| Urban >1940 groundbased | 121.785 | 58.073 | 68% | 111.906 | 67.952 | 62% | -5% | 5% |
| Green-urban | 31.527 | 44.866 | 41% | 63.779 | 12.614 | 83% | 42% | -42% |
| Centrum-small urban | 52.029 | 39.459 | 57% | 48.288 | 43.200 | 53% | -4% | 4% |
| Small urban | 166.861 | 94.500 | 64% | 161.357 | 100.004 | 62% | -2% | 2% |
| Green-small urban | 34.272 | 22.922 | 60% | 49.288 | 7.906 | 86% | 26% | -26% |
| Centrum-village | 212.877 | 64.409 | 77% | 247.020 | 30.266 | 89% | 12% | -12% |
| Village | 83.071 | 12.876 | 87% | 95.947 | - | 100% | 13% | -13% |
| Rural accessible | 48.749 | 4.975 | 91% | 53.724 | - | 100% | 9% | -9% |

The differences between the calculated number of buildings and the actual number of buildings from the ABF data ranges from small (2%) to large (100%). These results are used to improve the distribution of reference buildings in the model districts. Therefore the quantitative distribution of reference buildings per model district are analysed in order to determine the correct mean single- and multi-family houses from the data of ABF.

### *Centrum-urban Plus*

The difference within this model district is caused by the lack of single-family houses. The distribution of reference buildings reveals that 0% of the reference buildings are classified as single-family. This percentage is determined on the basis of Table 30, in which the single-family houses are qualitatively assigned a -2 value. The definition used for a -2 value is: 'nearly non-existent in the living environment, exceptions not included'. It therefore seems that a -2 value does not equal to a value of 0% availability, but rather a higher percentage. However, is it justified to change the 0% value into a higher percentage?

Two other model districts also have a 0% value (for multi-family buildings), namely village and rural accessible. The 3 model districts with 0% values are analysed together since it is not justifiable to only increase the 0% value of one model district while not changing the other.

What should the percentage be to obtain the actual number of buildings as obtained with the ABF data? For the centrum-urban plus this equals to 16%, for village to 13%, and for rural accessible to 9% of the total number of buildings. This indicates that indeed the -2 value should not be equal to 0%. Therefore the percentage accompanying the qualitative -2 value has been set to 3% of the total number of buildings within a building period of a model district. This is justifiable since it is indeed likely that all reference building types are present in a district, even though for some types this is only a very small part.

This reduces the difference between the calculated and actual number of buildings from 16% to 8%. Also the other model districts are slightly changed with this change in weight factor (see Table 33).

*Table 33: Single- and multi-family buildings per model district after first adaptation.*

| Model district | Sum single-fam. ABF | Sum multi-fam. ABF | Percentage single-fam. ABF | Sum single-fam. Calculated | Sum multi-fam. Calculated | Percentage single-fam. calculated | Difference calculated and ABF single-fam. | Difference calculated and ABF multi-fam. |
|---|---|---|---|---|---|---|---|---|
| Centrum-urban Plus | 18.386 | 97.357 | 16% | 9.887 | 105.856 | 9% | -7% | 7% |
| Centrum-urban | 14.531 | 29.992 | 33% | 14.877 | 29.646 | 33% | 1% | -1% |
| Urban <1940 | 48.167 | 155.191 | 24% | 107.304 | 96.054 | 53% | 29% | -29% |
| Urban >1940 compact | 125.109 | 298.590 | 30% | 193.327 | 230.372 | 46% | 16% | -16% |
| Urban >1940 groundbased | 121.785 | 58.073 | 68% | 121.282 | 58.576 | 67% | 0% | 0% |
| Green-urban | 31.527 | 44.866 | 41% | 59.845 | 16.548 | 78% | 37% | -37% |
| Centrum-small urban | 52.029 | 39.459 | 57% | 53.443 | 38.045 | 58% | 2% | -2% |
| Small urban | 166.861 | 94.500 | 64% | 174.642 | 86.719 | 67% | 3% | -3% |
| Green-small urban | 34.272 | 22.922 | 60% | 45.516 | 11.678 | 80% | 20% | -20% |
| Centrum-village | 212.877 | 64.409 | 77% | 238.900 | 38.386 | 86% | 9% | -9% |
| Village | 83.071 | 12.876 | 87% | 85.981 | 9.966 | 90% | 3% | -3% |
| Rural accessible | 48.749 | 4.975 | 91% | 48.840 | 4.884 | 91% | 0% | 0% |

The 4 largest differences between calculated and actual number of single-, or multi-family buildings occur in the Green-urban, Urban <1940, Green-small urban, and Urban >1940 compact districts. All of these districts have an excess of single-family households compared to the actual data. Looking at the characteristics of these districts at the qualitative analysis (see Table 30), all districts have a large contribution of single-family households compared to the multi-family households. Additional data is required to determine which type of residential building is over abundantly available.

Researchers at the institution of Ecofys have conducted a research for the type of households in the province of Utrecht [Franken, 2010]. These numbers have been analysed and it can be concluded that the model district distribution of the province of Utrecht is similar to the distribution of the operating area of Stedin. Therefore the distribution of types of houses can be used as a comparison.

*Table 34: Comparison of types of houses in the Netherlands, operating area of Stedin and the province of Utrecht*

| Type of reference building | | Detached | Semi-detached | Terraced hosue | Maisonette | Common staircase and galleries | Common staircase no galleries | Other apartments | Single-family | multi-family |
|---|---|---|---|---|---|---|---|---|---|---|
| Distribution in the Netherlands | Total | 959.000 | 824.000 | 2.839.000 | 382.000 | 465.000 | 847.000 | 485.000 | 4.622.000 | 2.179.000 |
| | % of total | 14% | 12% | 42% | 6% | 7% | 12% | 7% | 68% | 32% |
| Stedin area (ABF data) | Total | | | | | | | | 957.364 | 923.210 |
| | % of total | | | | | | | | 51% | 49% |
| Stedin area calculated | Total | 147.123 | 505.087 | 505.087 | 238.980 | 162.590 | 160.805 | 160.805 | 1.157.297 | 723.179 |
| | % of total | 8% | 27% | 27% | 13% | 9% | 9% | 9% | 62% | 38% |
| Province Utrecht (ABF data) | Total | | | | | | | | 272.280 | 262.720 |
| | % of total | | | | | | | | 51% | 49% |
| Province Utrecht (Ecofys) | Total | 33.500 | 126.300 | 88.000 | 87.000 | 50.700 | 50.700 | 50.700 | 247.800 | 239.100 |
| | % of total | 7% | 26% | 18% | 18% | 10% | 10% | 10% | 51% | 49% |

The results of the comparison (see Table 34) show that the percentage of single- and multi-family households in the ABF data of the operating area and the data for the province of Utrecht are similar.

Also the total number of single-family households of the ABF data and the Ecofys data are similar when taking into account that the analysis of Ecofys was conducted in 2009, while the ABF data stems from 2013, meaning that the total building stock has grown by 3% per year which is a reasonable growth rate. The data therefore (again) seem reasonable to be used for comparison.

This means that we can look at the difference between the distribution of types of reference buildings within the operating area (Stedin area calculated) and the province of Utrecht (Province Utrecht Ecofys). The percentage of terraced houses is 9% lower in the province of Utrecht, the percentage of maisonettes is 5% higher in the province of Utrecht, and the other multi-family households are each 2% higher in the Utrecht data. This indicates that the calculated number of terraced houses is too high in the calculations, and the calculated number of maisonettes, and to some degree the other multi-family buildings are too low in the calculations.

Now the knowledge of the 4 largest differences between the actual and calculated number of single- and multi-family buildings with the over abundancy of the type of reference buildings is coupled. This shows that the Green-urban, Urban <1940, Green-small urban, and Urban >1940 compact districts have too many terraced houses, too little maisonettes, and only a fraction too little common staircase with or without galleries, or other apartments. Therefore the qualitative analysis is adapted by subtracting 0,5 points from the terraced houses in these model districts, while adding 0,2 to the maisonettes and 0,1 to the other multi-family houses. The results after these changes are included in Table 35. These differences are considered acceptable.

*Table 35: Single- and multi-family buildings per model district after second adaptation.*

| Model district | Sum single-fam. ABF | Sum multi-fam. ABF | Percentage single-fam. ABF | Sum single-fam. Calculated | Sum multi-fam. Calculated | Percentage single-fam. calculated | Difference calculated and ABF single-fam. | Difference calculated and ABF multi-fam. |
|---|---|---|---|---|---|---|---|---|
| Centrum-urban Plus | 18.386 | 97.357 | 16% | 9.887 | 105.856 | 9% | -7% | 7% |
| Centrum-urban | 14.531 | 29.992 | 33% | 14.877 | 29.646 | 33% | 1% | -1% |
| Urban <1940 | 48.167 | 155.191 | 24% | 82.993 | 120.365 | 41% | 17% | -17% |
| Urban >1940 compact | 125.109 | 298.590 | 30% | 171.003 | 252.696 | 40% | 11% | -11% |
| Urban >1940 groundbased | 121.785 | 58.073 | 68% | 121.282 | 58.576 | 67% | 0% | 0% |
| Green-urban | 31.527 | 44.866 | 41% | 42.176 | 34.217 | 55% | 14% | -14% |
| Centrum-small urban | 52.029 | 39.459 | 57% | 53.443 | 38.045 | 58% | 2% | -2% |
| Small urban | 166.861 | 94.500 | 64% | 174.642 | 86.719 | 67% | 3% | -3% |
| Green-small urban | 34.272 | 22.922 | 60% | 31.455 | 25.739 | 55% | -5% | 5% |
| Centrum-village | 212.877 | 64.409 | 77% | 238.900 | 38.386 | 86% | 9% | -9% |
| Village | 83.071 | 12.876 | 87% | 85.981 | 9.966 | 90% | 3% | -3% |
| Rural accessible | 48.749 | 4.975 | 91% | 48.840 | 4.884 | 91% | 0% | 0% |

Overall, there is enough confidence in the distribution of reference buildings within the model districts. The resulting distribution of reference buildings, as will be used in the remainder of the research, is presented in Figure 78.

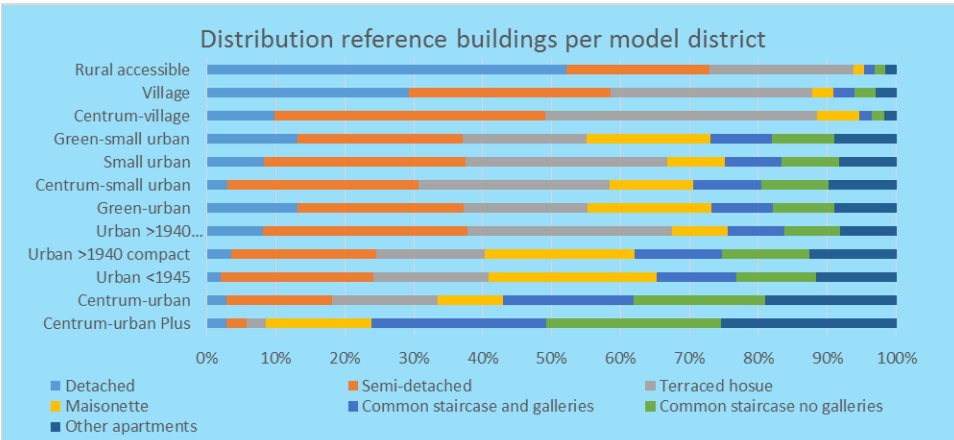


*Figure 78: Overview of distribution of reference buildings within the model districts*

# Appendix B Quantified future energy scenarios

The following pages include the quantification of the future energy scenarios as constructed by Eneco in April 2015. It includes the three scenarios (**Paces**, **Tides**, and **Circles**) for the years 2020, 2030, 2040 and 2050, and are constructed for the situation in the Netherlands.

The quantification of the national future energy scenario are included in B.1, these are converted into the scenarios for the operating area of Stedin in B.2, which in turn are converted into the quantification of the model districts in B.3.

## B.1 National scenarios

*The national scenarios are confidential due to the high amount of details.*

## B.2 National scenarios converted into scenarios operating area

The national scenarios are converted into the number for the operating area of Stedin, mainly by using the number of residential or commercial buildings. Only the relevant variables for this research are included in this section. These are the Stedin scenarios of May 2015.

| STEDIN.NET | | | Reference | Paces | | | | Tides | | | | Circles | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 2012 | 2020 | 2030 | 2040 | 2050 | 2020 | 2030 | 2040 | 2050 | 2020 | 2030 | 2040 | 2050 |
| **Residential** | | | | | | | | | | | | | | | |
| **Demographics** | Residential connections | # mln | 1,85 | 1,96 | 2,06 | 2,09 | 2,09 | 1,96 | 2,06 | 2,09 | 2,09 | 1,96 | 2,06 | 2,09 | 2,09 |
| **Electricity demand** | Total electricity demand appliances | TWh | 5,9 | 6,14 | 5,26 | 5,31 | 5,73 | 6,52 | 6,27 | 6,57 | 6,62 | 5,73 | 5,80 | 6,22 | 6,81 |
| **Gas demand** | Total gas demand (heating) | mln m3 | 2710 | 2.619 | 2.501 | 2.296 | 1.969 | 2.725 | 2.800 | 2.756 | 2.526 | 2.836 | 2.893 | 2.478 | 982 |
| | Total gas demand (heating) | TWh | 26,47 | 25,58 | 24,43 | 22,43 | 19,24 | 26,62 | 27,35 | 26,92 | 24,68 | 27,71 | 28,26 | 24,21 | 9,60 |
| | Gas connections | # mln | 1,84 | 1,95 | 2,02 | 2,00 | 1,85 | 1,93 | 1,92 | 1,95 | 1,72 | 1,93 | 1,90 | 1,43 | 1,02 |
| **Heat pumps** | Heat pumps | #x1000 | 20 | 49 | 128 | 185 | 274 | 71 | 286 | 286 | 420 | 62 | 254 | 806 | 1.121 |
| | of which hybric | #x1000 | 10 | 35 | 92 | 92 | 32 | 35 | 143 | 143 | 50 | 35 | 92 | 149 | 52 |
| | of which full electric | #x1000 | 10 | 14 | 36 | 93 | 242 | 35 | 143 | 143 | 370 | 26 | 162 | 657 | 1.069 |
| | Total electricity demand heat pumps | TWh | 0,04 | 0,07 | 0,18 | 0,36 | 0,77 | 0,16 | 0,64 | 0,64 | 1,42 | 0,13 | 0,76 | 3,04 | 4,96 |
| **PV** | Connections with PV | #x1000 | 74 | 111 | 166 | 412 | 610 | 177 | 240 | 507 | 554 | 222 | 915 | 1.755 | 1.848 |
| | Total installed PV capacity | GWp | 0,22 | 0,55 | 1,00 | 2,88 | 4,88 | 0,89 | 1,44 | 3,55 | 4,43 | 1,11 | 6,40 | 14,04 | 18,48 |
| | Total generated electricity PV | TWh | 0,19 | 0,47 | 0,85 | 2,45 | 4,15 | 0,75 | 1,22 | 3,02 | 3,77 | 0,94 | 5,44 | 11,94 | 15,70 |
| **Commercial** | | | | | | | | | | | | | | | |
| **Demographics** | Small commercial connections | #x1000 | 158 | 159 | 150 | 176 | 227 | 192 | 211 | 265 | 275 | 177 | 218 | 277 | 338 |
| **Electricity demand** | Average electricity demand | Mwh | 20 | 20,00 | 19,42 | 17,39 | 15,55 | 18,27 | 14,02 | 13,52 | 10,14 | 17,68 | 14,51 | 12,77 | 11,44 |
| | Total electricity demand | TWh | 3,2 | 3,18 | 2,92 | 3,05 | 3,53 | 3,51 | 2,95 | 3,59 | 2,78 | 3,13 | 3,17 | 3,53 | 3,87 |
| **Gas demand** | Total gas demand (heating) | TWh | 13 | 11,42 | 7,90 | 7,44 | 7,94 | 14,35 | 11,43 | 11,47 | 10,78 | 10,67 | 9,09 | 8,49 | 7,09 |
| | Average gas demand per connection | MWh | 80,6 | 71,88 | 52,52 | 42,37 | 34,94 | 74,68 | 54,31 | 43,26 | 39,24 | 60,29 | 41,64 | 30,67 | 20,96 |
| | Average gas demand per connection | M3 | 8251 | 7358 | 5376 | 4337 | 3576 | 7644 | 5560 | 4428 | 4017 | 6171 | 4262 | 3140 | 2145 |
| **Heat pumps** | Heat pumps | #x1000 | 18 | 30 | 41 | 69 | 108 | 18 | 69 | 91 | 163 | 35 | 122 | 257 | 454 |
| | Total electricity demand heat pumps | TWh | 0,3 | 0,49 | 0,80 | 1,26 | 1,86 | 0,32 | 1,12 | 1,50 | 2,53 | 0,60 | 1,97 | 3,91 | 6,59 |
| **PV** | Connections with PV | #x1000 | 0,89 | 1,33 | 2,00 | 4,95 | 7,32 | 2,13 | 2,89 | 6,09 | 6,66 | 2,66 | 15,22 | 43,28 | 66,58 |
| | Installed capacity PV | GWp | 0,02 | 0,04 | 0,08 | 0,23 | 0,39 | 0,07 | 0,12 | 0,28 | 0,36 | 0,09 | 0,71 | 2,31 | 4,44 |
| | Total generated electricity PV | TWh | 0,02 | 0,04 | 0,07 | 0,20 | 0,33 | 0,06 | 0,10 | 0,24 | 0,30 | 0,08 | 0,60 | 1,96 | 3,77 |

*Figure 79: Scenarios for the operating area of Stedin, constructed in May 2015.*

## B.3 Operating area scenarios converted into model district scenarios

The macro-scenarios have been described for the Netherlands and the operating area of Stedin. Next step is to translate the effects for the model districts. This section describes the applied methods and assumptions.

### B.3.1 Roof surface PV in the Netherlands

Multiple studies have tried to make an indication of the roof surface available for PV in the Netherlands with each study using its own method. The Planbureau voor de Leefomgeving has constructed a spatial energy model for the build environment (Vesta model) [PBL, 2012]. The model assumes an average roof area of 10 m2 per household, resulting in a total of 71 km2 in the Netherlands. This residential roof surface available for PV is lower compared to other studies, while the utility roof surface (356 km2) is much higher compared to other studies. They assume that 80% of the utility roof surface is suitable for PV [PBL, 2011].

*Table 36: Differences in estimations on the technical potential of PV in the build environment.*

| Research | Technical potential (km2) | | | Capacity potential estimation (GWp) |
|---|---|---|---|---|
| | Roof surface | Residential | Utility | |
| [ECN, 2004][1] | 897 km2 | - | - | 110 GWp (175 Wp/m2) |
| [IEA, 2001] | 357 km2 | - | - | 107 GWp |
| [ECN, 2011] | 343 km2 | - | - | 54 GWp |
| [PBL, 2011] | 427 km2 | 71 km2 | 356 km2 | 88 GWp |
| [PBL & DNV GL, 2014] | 412 km2 | 256 km2 | 156 km2 | 66 GWp (160 Wp/m2) |

[1] The area suitable for BIPV, without taking into account limitations due to orientation. Based on an inventory of roof and façade area in the year 2001.

The residential roof surface of the [PBL, 2011] is significantly lower due to the assumption that each household has 10 m2 of roof space available for PV. In [PBL & DNV GL, 2014] the roof surface has been calculated using average roof surfaces of houses over different buildings year, resulting in an average of 33 m2 per household and causing the total roof surface to increase significantly. The difference in utility surface is caused by the data use in the two studies; [PBL & DNV GL, 2014] uses estimations based on the number of utilities and ground-surface, while [PBL, 2011] uses actual data from building registered characteristics. Therefore the residential roof surface of [PBL & DNV GL, 2014] and the utility roof surface of [PBL, 2011] are deemed most reliable. However, this results in a significantly higher total roof surface of 612 km2 for the Netherlands, which would lead to an overestimation of the total technical potential for PV. Therefore the study of [PBL & DNV GL, 2014] is used as the standard for this research. To conclude, in the remainder the data for residential and utility roof surfaces of  [PBL & DNV GL, 2014] are used.

This study uses 7 types of residential buildings, for which the average roof surface is depicted in Table 37. Since there is no data available about the different types of commercial buildings in the different postal areas, only the total number of utility buildings are used from the CBS [2012]. These numbers exclude healthcare and education buildings. In this study the weighted average roof surface of the remaining categories of utility buildings (offices, stores, retail, hotel and catering industry, and others) is used, which is 137 m2 per location.

### B.3.2 Residential and commercial PV

*The focus of this section is on describing the residential PV, but the same argumentation holds for the utility PV.*

PV deployment on households has a technical potential that equals the surface on which PV can be installed and has a sufficient ability for electricity generation. The available roof surface of dwellings for building type and building year is analysed in PBL & DNV GL [2014]. The study is based on the height of objects and horizontal surface for the province of Utrecht, taking into account the horizontal and vertical tilt of roofs, and solar irradiance. Roof surface located on the north is excluded, but south, west and east are all included. Also the edges on the roof are excluded for the first 20cm due to whirlwinds and the resulting safety hazard, as well as other obstacles like chimneys, dormers, or lift shafts. The study includes 13 types of dwellings including types like student housing or retirement homes, making it more detailed than our use of 7 dwelling types. The results of the study for the 7 reference buildings used in our study are presented in Table 37. These surfaces are presented in surface per household, meaning that multiple layers in buildings are taken into account. The available roof surface for PV per household lies between 13 and 61 m2.

*Table 37: Roof surface on which PV can be applied, for the 7 reference buildings. Adapted from* [PBL & DNV GL, 2014].

| Average roof surface per dwelling type (m2) | Building year | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1600 | 1800 | 1900 | 1920 | 1940 | 1960 | 1970 | 1980 | 1990 | 1995 | 2000 | 2010 | Average |
| Detached | 79 | 80 | 54 | 56 | 58 | 47 | 85 | 50 | 71 | 64 | 60 | 60 | 61 |
| Semi-detached | 45 | 66 | 32 | 45 | 39 | 41 | 50 | 44 | 45 | 58 | 46 | 58 | 45 |
| Terraced hosue | 36 | 27 | 29 | 30 | 32 | 32 | 38 | 33 | 33 | 35 | 36 | 21 | 32 |
| Maisonette | 22 | 27 | 23 | 22 | 45 | 20 | 19 | 16 | 19 | 29 | 26 | 9 | 24 |
| Common staircase and galleries | 29 | 18 | 24 | 20 | 17 | 15 | 22 | 16 | 18 | 19 | 20 | 17 | 18 |
| Common staircase no galleries | 25 | 27 | 24 | 22 | 23 | 26 | 22 | 19 | 12 | 17 | 21 | 12 | 23 |
| Other apartments | | 24 | 24 | 13 | 13 | 10 | 6 | 15 | 12 | 16 | 22 | 26 | 13 |

The roof surface area can be validated by the ground floor surface of the reference buildings as reported by Agentschap NL [2011]. Using these data in combination with the average number of floors for each of the reference buildings should result in a slightly higher surface available for PV since the obstacles are not included. Performing this analysis indeed results in a higher surface area, with differences between 10 and 25%. This rough estimation increases the confidence in the available roof surface numbers for PV.

The study of PBL & DNV GL [2014] did not include shadows of trees, surrounding buildings, windows in the roof, or other applications for the roof like green roofs, solar collectors for hot water, fans for cooling or for heat pumps. Therefore this technical potential should be considered an absolute maximum, which in reality is likely to be lower.

For each of the model districts the installed capacity of PV on residential buildings is calculated with the following formula:

*Installed capacity residential PV model district (Wp) = Available roof surface PV (m2) x PV covered roof surface (%) x PV efficiency per m2 (Wp/m2) x Chance PV per district (%)*

The available roof surface for PV is determined for each model district by multiplying the total number of residential buildings with the distribution of reference buildings within that district. This results in the number of reference buildings for each of the 7 types, after which these numbers are multiplied with the available roof surface for PV applicable for each of the dwelling types. The resulting surface is multiplied by the deployment factor for PV as provided by the national future energy scenarios from section Appendix A, and the same holds for the PV efficiency of the panels. The chance of PV per district is explained in the following section.

Analysing the formula reveals that the relationship is linear. Differentiation between the model districts is only achieved by the different number of residential buildings and the resulting roof surface applicable for PV. The output is largely dependent on the percentage of roof surface covered with PV, which is provided by the national scenarios and therefore lack differentiation between model districts. By including the chance that PV will be installed in a district additional differentiation can be achieved. However, this variable depends on socio-demographic parameters. This leads to the following question: are there socio-demographic parameters that can (significantly) explain the regional deployment rates of PV?

### *Chance PV deployment per model district*

A literature review has not resulted in clear parameters that can be used for 'prediction' of the residential PV deployment. A former graduate at Stedin has performed an analysis to determine if certain demographic parameters can predict the deployment of PV in residential areas [Bleumink, 2013]. The research used the data of CBS and CPB in combination with the Product Installation Register (C-PIR) which contains all registered PV installations known to network operators in the Netherlands. The statistical analysis on socio-economic status and purchase price of buildings did not lead to any predicting parameters. Research on the number of non-western foreigners resulted in a slight predicting power, as well as the building year of the dwellings. However, both parameters were not deemed significant enough to explain the large differences in regional deployment rates.

Additionally in this research a trend has been observed between current installed PV capacity in urban areas and in rural areas in the Netherlands from the C-PIR database. Data is available from the provinces of Utrecht and South-Holland of the year 2013. This data has been plotted against the density factor of (residential and commercial) buildings, with 1 being a high density and 5 being a low density. The results indicate that more electricity is generated by PV in low density areas compared to high density areas. Also the size of the PV installations is larger in low density areas. These data are only available for all buildings, not separately for commercial and residential buildings. Analysing the percentage of private buildings in relation to commercial buildings shows that in lower dense areas relatively more commercial buildings are located. However, it is unsure what this means for the average size of a PV installation for residential and commercial buildings with the different density factors.

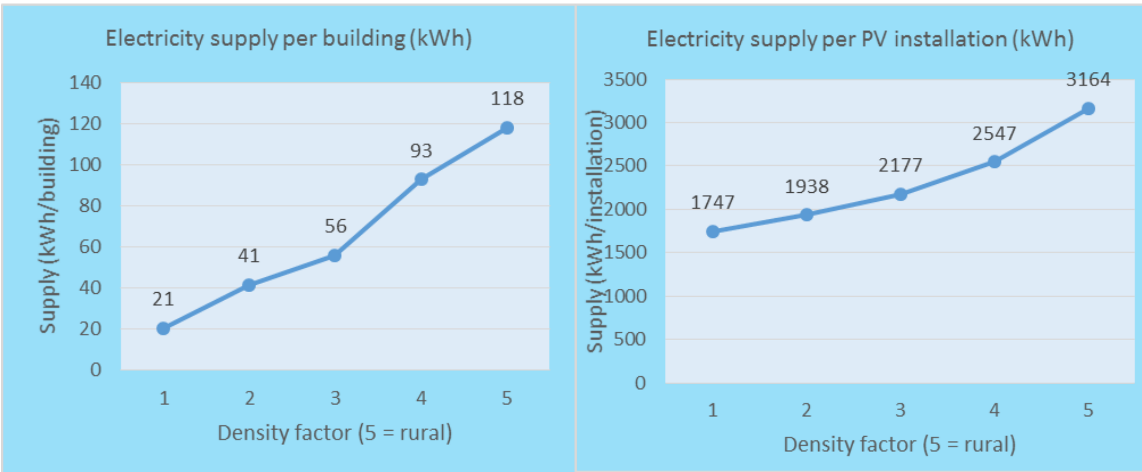



*Figure 80: Electricity supply PV per building and per PV installation, plotted against the density factor. Density factor 1 is high density and factor 5 is low density.*

It could also be the case that buildings have a larger roof surface in rural areas, which means that more PV can be installed per building. The electricity supply from PV is visualised for each of the model districts, as well as the roof surface for residential buildings (see Figure 80). There seems to be a similar trend, but the difference cannot be explained by the roof surface of residential buildings alone. Perhaps there is a large differentiation between roof surfaces of commercial buildings, or perhaps there are other parameters to be included.

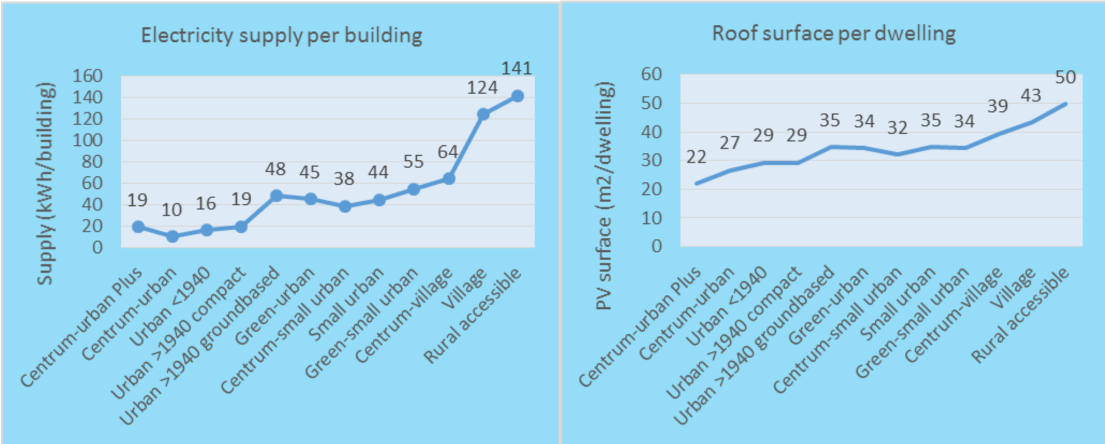



*Figure 81: Electricity supply per building plotted for each model district (left), and the roof surface per dwelling (right).*

One last check is performed to indicate the current differences in PV deployment rates between model districts. The PV supply per building is calculated from the C-PIR database for the provinces of Utrecht and South-Holland in 2013, as well as the percentage of private buildings, which when multiplied approximates the PV supply per private building. This is divided by 0,75 kWh/Wp which is an accepted number in the sector to estimate the yearly supply of PV installations, which in this case is used the other way around. Using the average of 150 Wp/m2 results in the average PV surface per buildings. Comparing these areas with the previously described roof surface per model districts results in the percentage of roof surface available for PV that is covered by current deployment of PV.

*Table 38: Part of the technical potential for PV per dwelling that is covered by the current deployment of PV (in 2013) for the provinces of Utrecht and South-Holland*

| | PV supply per building (kWh) | Percentage of private buildings | PV supply per private building (kWh) | PV capacity per private building (Wp) | PV surface per private building (m2) | Roof surface available for PV per private building | Percentage of PV applicable roof space covered |
|---|---|---|---|---|---|---|---|
| Centrum-urban Plus | 19 | 79% | 15 | 19,8 | 0,13 | 22 | 0,6% |
| Centrum-urban | 10 | 83% | 8 | 10,8 | 0,07 | 27 | 0,3% |
| Urban <1940 | 16 | 89% | 14 | 18,8 | 0,13 | 29 | 0,4% |
| Urban >1940 compact | 19 | 93% | 18 | 24,1 | 0,16 | 29 | 0,5% |
| Urban >1940 groundbased | 48 | 90% | 43 | 57,8 | 0,39 | 35 | 1,1% |
| Green-urban | 45 | 86% | 39 | 51,8 | 0,35 | 34 | 1,0% |
| Centrum-small urban | 38 | 84% | 32 | 43,2 | 0,29 | 32 | 0,9% |
| Small urban | 44 | 86% | 38 | 51,0 | 0,34 | 35 | 1,0% |
| Green-small urban | 55 | 52% | 29 | 38,2 | 0,25 | 34 | 0,7% |
| Centrum-village | 64 | 86% | 55 | 73,7 | 0,49 | 39 | 1,2% |
| Village | 124 | 84% | 104 | 138,3 | 0,92 | 43 | 2,1% |
| Rural accessible | 141 | 79% | 112 | 148,9 | 0,99 | 50 | 2,0% |

Are these percentages realistic? For the Netherlands as a whole the covered roof surface of dwellings is 2% of the total roof surface available for PV deployment. The percentages presented above are significantly lower. Could this be explained by the relative less PV deployment in the analysed provinces of Utrecht and South-Holland compared to the other provinces? Looking at the number of buildings, 21% of all buildings in the Netherlands are located in the analysed provinces, while only 13% of the national PV electricity generation is generated in the provinces of Utrecht and South-Holland. This means that the percentages as presented in Figure 81 should be multiplied by a factor 1,6 to be compared to the national numbers. The same analysis has been performed for the companies, for which the results are presented in Table 39. Multiplying the PV capacity per building with the number of residential buildings and commercial buildings in the Netherlands should result in the total installed PV capacity. The calculated installed capacity in the Netherlands adds up to 515 MWp, while the CBS [2013] registered 740 MWp, a difference of 30%. However, the PIR data do not contain all PV installed capacity, with estimates ranging between 20 - 40% less registered than actually installed. Therefore this distribution can be used as an indication for the diversification of PV deployment over the different model districts. It should however be kept in mind that the aim of this research is not to replicate the current situation, but to make future expectations about the deployment of PV.

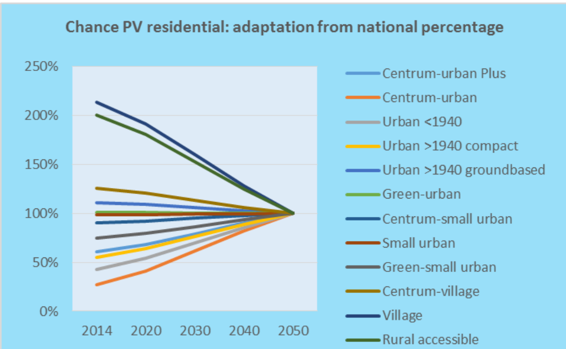
*Table 39: Part of the technical potential for PV per utility building that is covered by the current deployment of PV (in 2013) for the provinces of Utrecht and South-Holland*

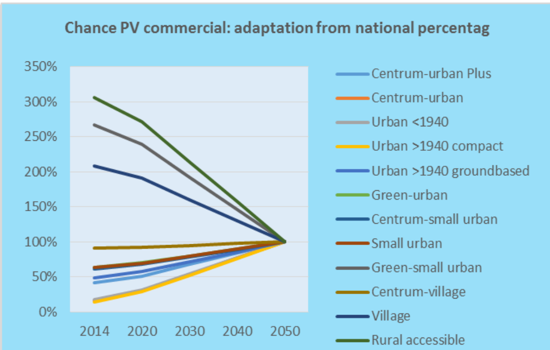
| | PV supply per building (kWh) | Percentage of commercial buildings | PV supply commercial building (kWh) | PV capacity commercial building (Wp) | PV surface commercial building (m2) | Roof surface available for PV per commercial building | Percentage of roof applicable for PV covered |
|---|---|---|---|---|---|---|---|
| Centrum-urban Plus | 19 | 21% | 4,0 | 5,4 | 0,04 | 207 | 0,017% |
| Centrum-urban | 10 | 17% | 1,6 | 2,1 | 0,01 | 207 | 0,007% |
| Urban <1940 | 16 | 11% | 1,7 | 2,2 | 0,01 | 207 | 0,007% |
| Urban >1940 compact | 19 | 7% | 1,4 | 1,8 | 0,01 | 207 | 0,006% |
| Urban >1940 groundbased | 48 | 10% | 4,7 | 6,3 | 0,04 | 207 | 0,020% |
| Green-urban | 45 | 14% | 6,2 | 8,3 | 0,06 | 207 | 0,027% |
| Centrum-small urban | 38 | 16% | 6,0 | 8,0 | 0,05 | 207 | 0,026% |
| Small urban | 44 | 14% | 6,1 | 8,2 | 0,05 | 207 | 0,026% |
| Green-small urban | 55 | 48% | 26,0 | 34,6 | 0,23 | 207 | 0,111% |
| Centrum-village | 64 | 14% | 8,8 | 11,8 | 0,08 | 207 | 0,038% |
| Village | 124 | 16% | 20,3 | 27,1 | 0,18 | 207 | 0,087% |
| Rural accessible | 141 | 21% | 29,8 | 39,7 | 0,26 | 207 | 0,128% |

To conclude, the roof surface can be used as a first indicator for PV deployment. However, the technical potential alone does not result in a large enough differentiation between the model districts or in reality. Including a variable which increases the differentiation between the districts cannot be substantiated with statistical analysis of socio-demographic variables. Only the current deployment of PV can indicate rough estimates for differentiation between model districts. Since the numbers are calculated on the basis of quite some steps with some assumptions, the reliability of the numbers can be questioned. However, in the authors and the clients opinion including an additional factor for diversification of the deployment rates of PV between the model districts is desirable. Therefore, however surrounded with uncertainty, the factors will be included.

The percentages of Table 39 and Table 41 are used to determine the difference for each model district from the national percentage of roof surface on which PV is installed. These percentages represent the chance that PV is installed in a model district. Since future changes are unsure, the percentages are assumed to convert to 100%, meaning that each model district installs exactly the amount of PV as specified on the national scale. The final numbers are visualised in

*Figure 82: Difference from national percentage of roof surface being used for PV for each model district. These percentages represent the 'chance PV per district'.*



***Supply profile PV panels***

The orientation and angle of installing PV panels influences the electricity yield as well as the moment of peak supply. Real life testing of PV panels shows that south orientation has the highest yield, followed by east and west orientations which provide approximately 10% less peak supply (see Figure 83). The optimum angle of installation is $30^0$ [Bogerd, 2015]. At high penetration rates the electricity supply from PV is quickly able to cause capacity problems on the LV network. To provide insights into the extreme situations the profile for PV assumes each day of the year as sunny.

[CE Delft, 2014] has constructed the PV profile by using the highest solar irradiation that has been measured during each hour of the month, for all 12 months, for the last 14 years at the KNMI measuring station of Rotterdam. Using the NEN7120:2011 the solar irradiance (measured as J/cm2/hour) is converted to the kW supply of the installation, resulting in the extreme day profile for each month with hourly intervals. A mix of orientations and angles has been used, for which the supply in kWh per $kW_p$ is provided in Table 40 for a 1 $kW_p$ installation for an ideal situation without losses (e.g. shadows). Using the average kWh/$kW_p$ electricity supply for this system would result in a yearly yield of 853 kWh/$kW_p$, but since the interest is on the extreme supply profile the actual electricity supply of 1640 kWh/$kW_p$ is much higher.

Future research could be performed on the relationship between the return on investments for non-optimal orientation for PV owners, and the costs for dealing with the peak supply.

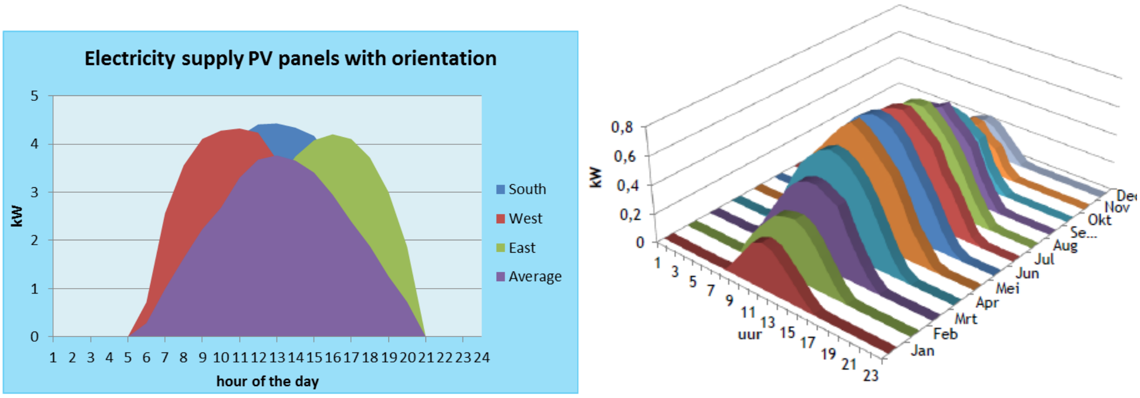



*Figure 83: (left) Electricity supply PV panels for different orientations; data provided by [Bogerd, 2015], capacity system unknown. (right) Day profiles PV for a 1 $kW_p$ installation as used in the MKBINS; source [CE Delft, 2014].*

*Table 40: kWh/$kW_p$ values for the assumed contribution of orientations and angles. Adapted from [CE Delft, 2014].*

| Angle (degrees) | Orientation N | NE | E | SE | S | SW | W | NW | Contribution |
|---|---|---|---|---|---|---|---|---|---|
| 0 | 811 | 811 | 811 | 811 | 811 | 811 | 811 | 811 | 5% |
| 30 | 569 | 630 | 773 | 901 | 951 | 898 | 768 | 682 | 70% |
| 45 | 450 | 540 | 729 | 891 | 952 | 886 | 723 | 539 | 25% |
| Contribution | 2% | 4% | 10% | 20% | 30% | 20% | 10% | 4% | 100% |

## B.3.3 Residential heat pumps

The DHPA [2013] has calculated the technical potential of heat pumps for different residential building types and expressed them as a percentage of buildings on which heat pumps can be applied (see Table 41 left). Similar to the method used in the calculation of the technical potential of PV, the number of reference buildings of residential buildings per model district are multiplied with the percentage of buildings on which heat pumps can be applied. This results in a differentiation of the percentage of dwellings that are suitable for heat pump application between model districts (see Table 41 right).

*Table 41: Percentage of the reference buildings on which heat pumps can be applied (left). Percentage of dwellings in a model district suitable for heat pumps (right)*

| Reference buildings | Technical potential heat pumps |
|---|---|
| Detached | 95% |
| Semi-detached | 85% |
| Terraced house | 75% |
| Maisonette | 50% |
| Common staircase and galleries | 50% |
| Common staircase no galleries | 50% |
| Other apartments | 50% |

| Model district | % of dwellings suitable for heat pumps |
|---|---|
| Centrum-urban Plus | 53% |
| Centrum-urban | 60% |
| Urban <1940 - Peak 1 | 63% |
| Urban <1940 - Peak 2 | 63% |
| Urban >1940 compact | 63% |
| Urban >1940 groundbased - Peak 1 | 71% |
| Urban >1940 groundbased - Peak 2 | 71% |
| Green urban - Peak 1 | 69% |
| Green urban - Peak 2 | 69% |
| Centrum-small urban - Peak 1 | 68% |
| Centrum-small urban - Peak 2 | 68% |
| Small urban - Peak 1 | 71% |
| Small urban - Peak 2 | 71% |
| Green-small urban - Peak 1 | 69% |
| Green-small urban - Peak 2 | 69% |
| Centrum-village | 78% |
| Village | 81% |
| Rural accessible | 86% |

There are no known studies that successfully reported about socio-demographic variables that can explain the deployment of heat pumps in residential areas in the Netherlands. One parameter that could be included is the percentage of dwellings that is owned by rental organisations. These numbers are available, but require assumptions about the future willingness of rental organisations to implement heat pumps in their building stock. After a meeting with experts on this subject within the organisations of Stedin and Eneco it has been decided that the uncertainty is too large and therefore the technical potential remains the only differentiation between model districts for the moment. The number of residential heat pumps per model district are calculated with the following formula:

*Number of residential heat pumps (#/district) = [ Number of dwellings suitable for heat pumps (#/district) / [Number of residential buildings (# NL) x Percentage of residential buildings suitable for heat pumps (% NL) ]] x Number of residential heat pumps (# NL)*

The number of residential heat pumps in the Netherlands are multiplied by the percentage of residential buildings suitable for application of heat pumps in the entire building stock of the Netherlands. This results in the number of residential buildings in the Netherlands that are suitable for heat pumps. By dividing the number of dwellings in the district that are suitable for the heat pumps by the national number of dwellings, and multiplying this with the total number of heat pumps specified by the scenarios, the number of residential heat pumps in the district are determined.

### *Demand profile heat pumps*

The profiles for the electricity demand of heat pumps in both residential and commercial buildings as used in the MKBINS model are based on the demand on a cold winter day.

Profiel voor het E-verbruik van warmtepompen voor woningen en kantoren gemaakt op basis van de elektrische warmtevraag voor een koude winter.
Als extreem koude winter zijn de KNMI-klimaatdata 1.963 gebruikt.
Het dagprofiel is opgebouwd d.m.v. een profiel uit een onderzoek van EnergyMatters (2014).

De methodiek van de warmtevraag volgt verder de RVO Uniforme Maatlat voor de gebouwde omgeving. In de bibliotheek zijn enkele keuzes te maken m.b.t. de kwantificering: o.a. de COP van de warmtepompen.

### B.3.4 Commercial heat pumps

Geographical and regional data about the number of companies which have installed a heat pump is not available. Therefore the chance that a company will install a heat pump is assumed equal for different regions, meaning that it is equally likely that a company in an urban area installs a heat pump compared to a company in a rural area. The formula for determining the number of commercial heat pumps in a district is:

*Number of commercial heat pumps (#/district) = Heating demand per commercial building (kWh/building) x Number of commercial buildings (#/district) x Part of commercial heating demand provided by heat pumps (% NL)*

This means that only the number of commercial buildings in a model district creates the differentiation between the number of commercial heat pumps in the model district.

### B.3.5 Other variables

#### *Growth rates electricity demand*

The electricity demand for residential and commercial buildings is based on the national scenarios, and visualised in Figure 84 for the different scenarios. No differentiation between districts is applied. Differentiation for electricity is applied at the average electricity demand.

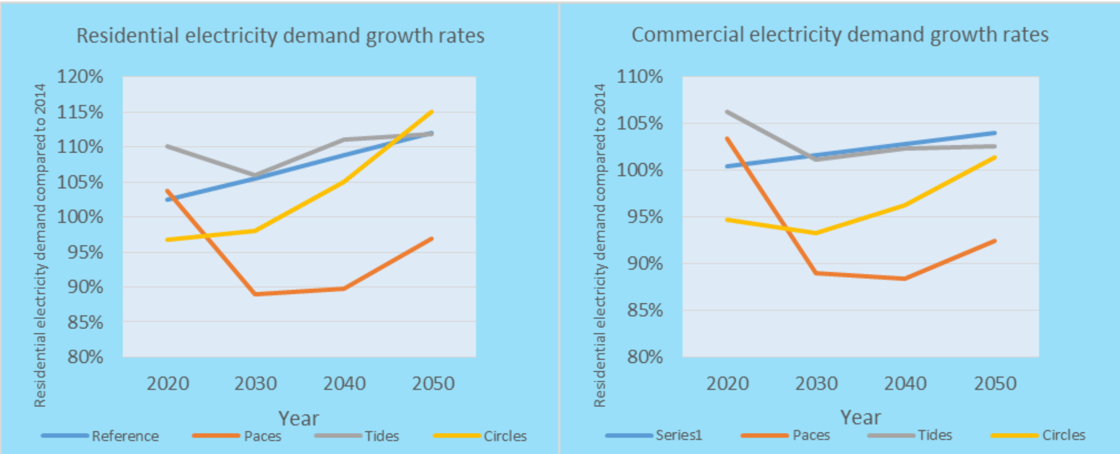



*Figure 84: Electricity demand growth rates compared to demand in 2014.*

#### *Average electricity demand per connection*

The electricity demand is determined by multiplying the average electricity demand per reference building with the number of reference buildings within each model district. The average electricity demand for a residential building in the Netherlands is assumed to be 3320 kWh in 2014, and for commercial buildings 20 MWh for each location in 2014.

#### *General assumptions/notions*

- Socio-demographic parameters are excluded in determining the deployment rates of PV and heat pumps due to the uncertainty related to it.
- Cooling by heat pumps is excluded from the analysis.
- Growth rates of the heating demand are included in the commercial and residential heating demand.

## B.4 Peak demand per model district

The load profiles are combined and result in the peak demand per model district. The highest demand or supply of the districts result in the highest peak demand for the model districts during the year (see Figure 85). The **Circles** scenario clearly results in the highest peak demand. The number of buildings per district depends on the district type (see chapter 8).

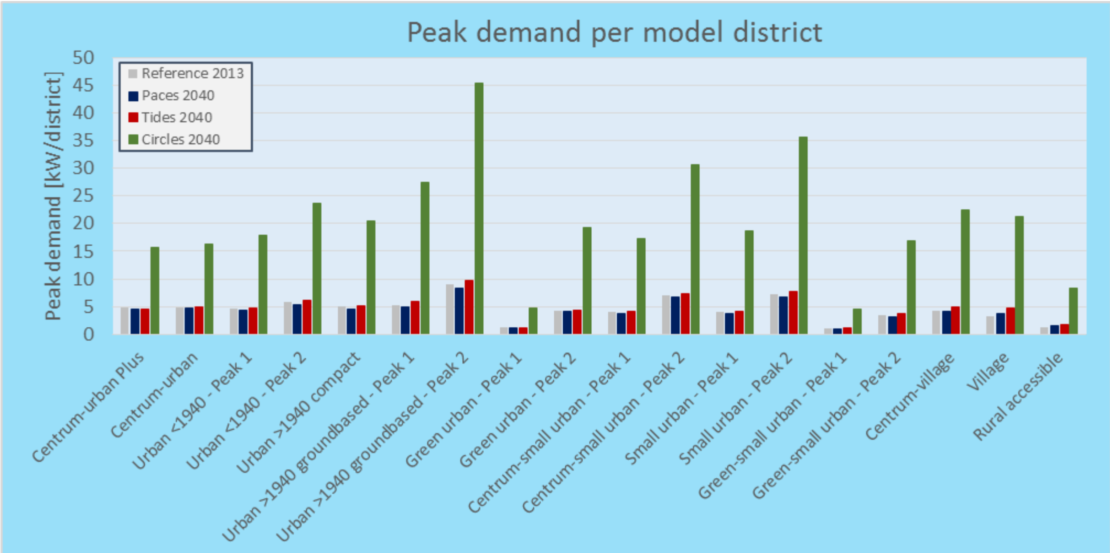



*Figure 85: Peak demand per model district*

# Appendix C Full list of assumptions

This appendix provides an overview of all the assumptions in the modelling approach. The assumptions are either a simplification of reality or substantiated with literature references. The influence of the most important assumptions are discussed in chapter 9.

## C.1 Model district classification

- Each **postal code area** (4 digit level) is classified as one model district, even though (when looking at a more detailed distribution) multiple model districts could be identified within one postal code area. Each postal code area is assigned one model district in terms of distribution of reference buildings, PV and heat pumps.
- The model districts are based on **residential environment characteristics**, and not on commercial buildings characteristics. This means that the representation of the dwellings is rather accurate, while the business representation is quite rough.

## C.2 Future energy scenarios

- Each value of the scenarios consists of assumptions, but the main assumption is the coupling of the scenarios to the **economic growth** developments. All other values are based on the narrative based on the worldwide economic developments.

## C.3 Number and types of residential and commercial buildings per model district

- Each **model district specification** is determined by means of the distribution of the 7 reference buildings. Data is not publicly available[42] about the distribution of reference buildings in each postal code area. Therefore information from multiple sources is combined to make a qualitative assessment about the distribution of reference buildings within a model district, after which this qualitative assessment is translated into a quantitative assessment. This quantitative assessment has been validated by using the data about single-family households (including detached, semi-detached and terraced houses) and multi-family households (including common staircase and galleries, common staircase no galleries, maisonettes and other apartments).
- The model district has the same distribution of dwelling types for each **geographical location** of the different postal codes that are classified by that particular model district type. This means a centrum-urban district in Utrecht has the same distribution of reference buildings as a centrum-urban district in Rotterdam.
- Only one parameter is changing when comparing two districts at different geographical locations that are both classified with the same model district, namely the **number of buildings**. For the calculations in this research the number of buildings is set to the sum of the average number of households in the postal code areas classified as the model district, and the average number of commercial buildings.
- The number of buildings within a model district remains constant until 2040.

[42] This data is available, but has to be purchased.

## C.4 Construction of load profiles

- The **load profile** of households, as well as the electricity demand profile of heat pumps, and supply profile of PV, are similar for each household connection. The commercial connection has a different demand, but also all commercial connections are similar. This means that there is no difference between model districts or within model district connections. (no load profile for each reference building, but only an average for all dwellings)
- The deployment of PV and heat pumps is based on the technical potential of the individual districts.

### C.4.1 PV deployment

**Main assumptions**

- Total available roof surface PV for residential buildings is 256 km2, and 152 km2 for utility buildings. Per residential building the average available roof surface equals 34 m2, and 137 m2 per utility building. For residential buildings the available roof surface for PV is calculated by using the roof surface available for each of the 7 reference buildings (ranging from 13 up until 62 m2), while the utility buildings are assumed to all have the same roof surface.
- The PV covered roof surface is expressed as the percentage of (commercial or residential) roof surface covered by PV based on the national installed PV capacity and the number of buildings, meaning that a linear relation is used from the national scenarios. The total installed capacity of PV in 2014 is set to 1 GWp, and rises to a capacity between 20 and 100 GWp in 2050.
- The PV efficiency is equal to the national scenarios, ranging from 160 Wp/m2 in 2014 up until 350 to 420 Wp/m2 in 2050. No differentiation between model districts.
- Differentiation of PV deployment between different model districts (named the 'Chance PV per district (%)') in 2014 is based on the weighted percentage deviation from the average installed capacity (per residential or commercial building) in the Netherlands in 2012. Since future changes are unsure, the percentages are assumed to convert linearly to 100% in 2050, meaning that each model district installs exactly the amount of PV as specified on the national scale in 2050.
- EDSN profile

**Additional assumptions**

- All of the PV capacity is installed on roofs of utility and residential buildings, meaning only BIPV are included and GBPV are excluded. Also novel technologies like PV cells integrated in windows or in clothes are excluded.
- The PV load profile is based the maximum irradiation measured over the last 14 years in the KNMI weather station of Rotterdam. Using the NEN7120:2011 the solar irradiance (measured as J/cm2/hour) is converted to the kW supply of the installation, resulting in the extreme day profile for each month with hourly intervals.
- The orientation of the PV panels are assumed to be mixed, as well as the angle of inclination. An installation oriented east or west has approximately a 10% lower peak supply compared to a fully south facing installation [Bogerd, 2015]. The average profile would result in a yearly supply of 853 kWh/kW$_p$, while the maximum profile as used in the MKBINS provides 1640 kWh/kW$_p$.
- All PV installations are assumed to be fully in the sun, without shadows of surrounding objects.
- Simultaneousness of supply of PV and demand of the consumer is set to 80%, meaning 20% is directly consumed while 80% is fed into the LV network. Again, this is based on the conditions that apply on an extremely sunny day.

### C.4.2 Heat pump deployment residential

**Main assumptions**

- Within each model district the number of reference buildings for each of the 7 types are multiplied with the technical potential each of these reference buildings has for application of (full electric or hybrid) heat pumps [see DHPA, 2013]. This results in the total number of dwellings suitable for heat pump deployment for each model district, which ranges between 53% and 86% of the dwellings.
- The percentage of residential buildings in the Netherlands that are suitable for heat pumps are determined by multiplying the number of dwellings in the Netherlands for each of the 7 reference buildings with the technical potential of these reference buildings. For 74% of the Dutch dwellings heat pump deployment is technically feasible.
- The number of residential heat pumps are determined in the national future energy scenarios and range from 80.000 in 2014 up until 1.1 to 4.5 million in 2050.
- EDSN profile

**Additional assumptions:**

- The average heating demand for residential buildings for each of the model districts is determined by multiplying the number of reference buildings with the heating demand for each of the 7 reference buildings as specified by [Agentschap NL, 2011].
- Residential heat pumps consists of full electric and hybrid heat pumps, of which the latter is assumed to provide 50% of the heat by means of natural gas. Therefore only the electric required heating demand is used as an input for the MKBINS model, since the load profile for heat pumps in that model is based on the electricity demand of the heat pump.
- The COP (Coefficient of Performance) of the residential heat pumps is calculated by the distribution of full electric and hybrid heat pumps. Full electric heat pumps have been assigned a COP of 3, and hybrid heat pumps a COP of 4. Using the number of full and hybrid heat pumps in a model district results in the average COP of the district.
- The load profile for the residential heat pump in the MKBINS model is based on the electric heating demand for a cold winter day, for which the KNMI data for January 1st, 1963 have been used [CE Delft, 2014]. During that year the heating demand was 58 GJ/year, which is 123% above the average residential heating demand. The same percentual increase is used for the commercial heating demand.
- The heat demand of each consumer that installs a heat pump is fully provided by the heat pump. In reality the heat pumps are often under-dimensioned to create a higher return on investment.

### C.4.3 Heat pump deployment commercial

**Main assumptions:**

- The total heating demand of a company is assumed to be provided by the full electric heat pump.
- Heating demand per location is on average 202 GJ. Since the aim is to provide extreme profiles the heating demand is increased with 123% which is the same percentage as used in the residential heating demand for the extremely cold year of 1963.
- The electricity demand of these full electric heat pumps is determined by using a COP of 3 and the average heating demand per commercial building. *Electricity demand = average heating demand / COP.*

## C.5 Specification transformer variables

- **Transformers** are specified in order to determine the impact of the future peak demand and load profile.
- A transformer is **overloaded** when reaching 120% of its rated capacity. It is assumed that the overloaded transformers need to be replaced.
- The transformers are assumed to have no redundancy, meaning that each consumer is connected to only one transformer. In reality redundancies exist. The exact influence of the meshed network on the outcomes of this research needs further investigation, although an initial estimation can be made. Stedin has approximately 2 million small consumers in its operating area, although when determining the number of connections when using the electricity grid as a starting point, the number adds up to 8 million connections. This shows that there are redundancies, although the exact influence is not further investigated.

# Appendix D Peak demand per model district

| Model district | Scenario | per dwelling (kW) | Peak demand per utility (kW) | model district (MW) |
|---|---|---|---|---|
| Centrum-urban Plus | Reference 2013 | 0,60 | 4,26 | 4,73 |
| | Pacer 2040 | 0,51 | 4,51 | 4,62 |
| | Tider 2040 | 0,66 | 3,25 | 4,55 |
| | Circler 2040 | 2,90 | 4,34 | 15,67 |
| Centrum-urban | Reference 2013 | 0,73 | 4,26 | 4,92 |
| | Pacer 2040 | 0,63 | 4,53 | 4,73 |
| | Tider 2040 | 0,82 | 3,25 | 4,93 |
| | Circler 2040 | 3,18 | 4,30 | 16,37 |
| Urban <1940 - Peak 1 | Reference 2013 | 0,79 | 4,26 | 4,62 |
| | Pacer 2040 | 0,69 | 4,53 | 4,30 |
| | Tider 2040 | 0,90 | 3,25 | 4,81 |
| | Circler 2040 | 3,68 | 4,30 | 17,88 |
| Urban <1940 - Peak 2 | Reference 2013 | 0,79 | 4,26 | 5,80 |
| | Pacer 2040 | 0,69 | 4,53 | 5,33 |
| | Tider 2040 | 0,90 | 3,25 | 6,15 |
| | Circler 2040 | 3,68 | 4,30 | 23,67 |
| Urban >1940 compact | Reference 2013 | 0,79 | 4,27 | 4,98 |
| | Pacer 2040 | 0,68 | 4,53 | 4,62 |
| | Tider 2040 | 0,89 | 3,25 | 5,22 |
| | Circler 2040 | 3,83 | 4,30 | 20,50 |
| Urban >1940 groundbased - Peak 1 | Reference 2013 | 0,92 | 4,26 | 5,32 |
| | Pacer 2040 | 0,85 | 4,50 | 4,89 |
| | Tider 2040 | 1,06 | 3,25 | 5,98 |
| | Circler 2040 | 5,32 | 4,47 | 27,56 |
| Urban >1940 groundbased - Peak 2 | Reference 2013 | 0,92 | 4,26 | 8,97 |
| | Pacer 2040 | 0,85 | 4,50 | 8,29 |
| | Tider 2040 | 1,06 | 3,25 | 9,75 |
| | Circler 2040 | 5,32 | 4,47 | 45,34 |
| Green urban - Peak 1 | Reference 2013 | 0,87 | 4,25 | 1,18 |
| | Pacer 2040 | 0,83 | 4,49 | 1,16 |
| | Tider 2040 | 1,02 | 3,25 | 1,17 |
| | Circler 2040 | 5,14 | 4,73 | 4,73 |
| Green urban - Peak 2 | Reference 2013 | 0,87 | 4,25 | 4,20 |
| | Pacer 2040 | 0,83 | 4,49 | 4,03 |
| | Tider 2040 | 1,02 | 3,25 | 4,36 |
| | Circler 2040 | 5,14 | 4,73 | 19,31 |
| Centrum-small urban - Peak 1 | Reference 2013 | 0,88 | 4,25 | 3,94 |
| | Pacer 2040 | 0,76 | 4,50 | 3,69 |
| | Tider 2040 | 1,00 | 3,25 | 4,12 |
| | Circler 2040 | 4,62 | 4,69 | 17,21 |
| Centrum-small urban - Peak 2 | Reference 2013 | 0,88 | 4,25 | 7,06 |
| | Pacer 2040 | 0,76 | 4,50 | 6,63 |
| | Tider 2040 | 1,00 | 3,25 | 7,35 |
| | Circler 2040 | 4,62 | 4,69 | 30,58 |
| Small urban - Peak 1 | Reference 2013 | 0,92 | 4,25 | 3,93 |
| | Pacer 2040 | 0,81 | 4,49 | 3,67 |
| | Tider 2040 | 1,06 | 3,25 | 4,19 |
| | Circler 2040 | 5,14 | 4,72 | 18,71 |
| Small urban - Peak 2 | Reference 2013 | 0,92 | 4,25 | 7,25 |
| | Pacer 2040 | 0,81 | 4,49 | 6,71 |
| | Tider 2040 | 1,06 | 3,25 | 7,81 |
| | Circler 2040 | 5,14 | 4,72 | 35,54 |
| Green-small urban - Peak 1 | Reference 2013 | 0,87 | 4,25 | 1,02 |
| | Pacer 2040 | 0,76 | 4,48 | 0,99 |
| | Tider 2040 | 1,00 | 3,25 | 1,04 |
| | Circler 2040 | 4,77 | 8,31 | 4,62 |
| Green-small urban - Peak 2 | Reference 2013 | 0,87 | 4,25 | 3,44 |
| | Pacer 2040 | 0,76 | 4,48 | 3,22 |
| | Tider 2040 | 1,00 | 3,25 | 3,67 |
| | Circler 2040 | 4,77 | 8,31 | 16,96 |
| Centrum-village | Reference 2013 | 1,04 | 4,25 | 4,32 |
| | Pacer 2040 | 1,01 | 4,48 | 4,04 |
| | Tider 2040 | 1,24 | 3,25 | 4,84 |
| | Circler 2040 | 6,25 | 5,21 | 22,56 |
| Village | Reference 2013 | 1,04 | 4,25 | 3,14 |
| | Pacer 2040 | 1,46 | 4,48 | 3,81 |
| | Tider 2040 | 1,80 | 3,25 | 4,67 |
| | Circler 2040 | 8,45 | 7,28 | 21,27 |
| Rural accessible | Reference 2013 | 1,09 | 4,25 | 1,18 |
| | Pacer 2040 | 1,66 | 4,48 | 1,46 |
| | Tider 2040 | 2,04 | 3,25 | 1,78 |
| | Circler 2040 | 9,47 | 9,01 | 8,25 |
| Operating area Stedin | Reference 2013 | 0,80 | 4,16 | 2052 |
| | Pacer 2040 | 0,95 | 4,71 | 2092 |
| | Tider 2040 | 1,17 | 4,06 | 2620 |
| | Circler 2040 | 5,65 | 10,29 | 12546 |

# Appendix E Load demand of transformers

This appendix provides an overview of the load demand of all distribution transformers for which the current loading rate is known, which is 67% of the entire stock of 22.285 transformers. The following pages contain the current loading rate, and the future loading rate for the three future energy scenarios, and are grouped per model district in which the transformer is located.

### *Range of loading*

In the year 2013 the average load demand of the transformers in the operating area is 60%, for which the average in the different model districts ranges between 53% and 69% (see Figure 86). Therefore, on average, there is a large reserve capacity available at the transformers.

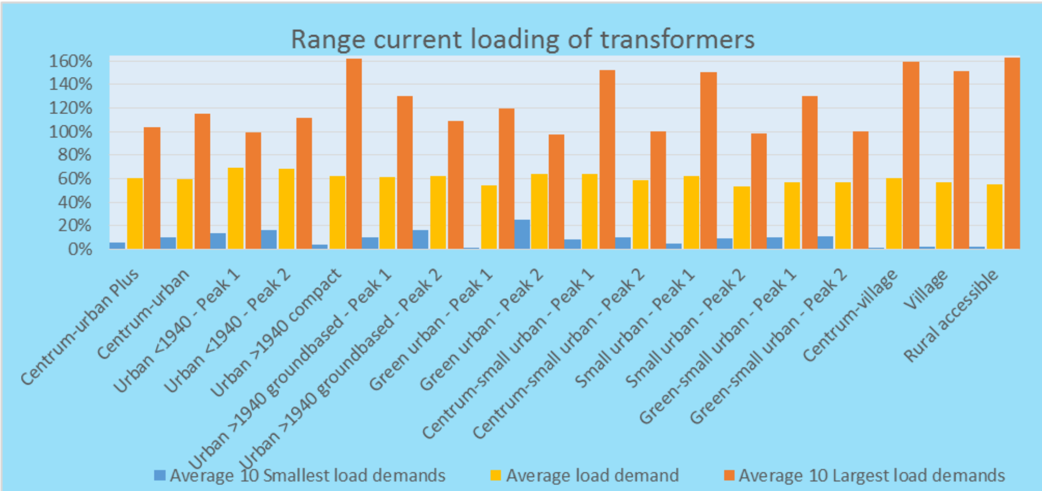



*Figure 86: The load demand of the transformers in the year 2013 for the different model districts. For the largest and smallest values the average is based on 10 transformers. The overall average is based on all transformers in the model districts.*

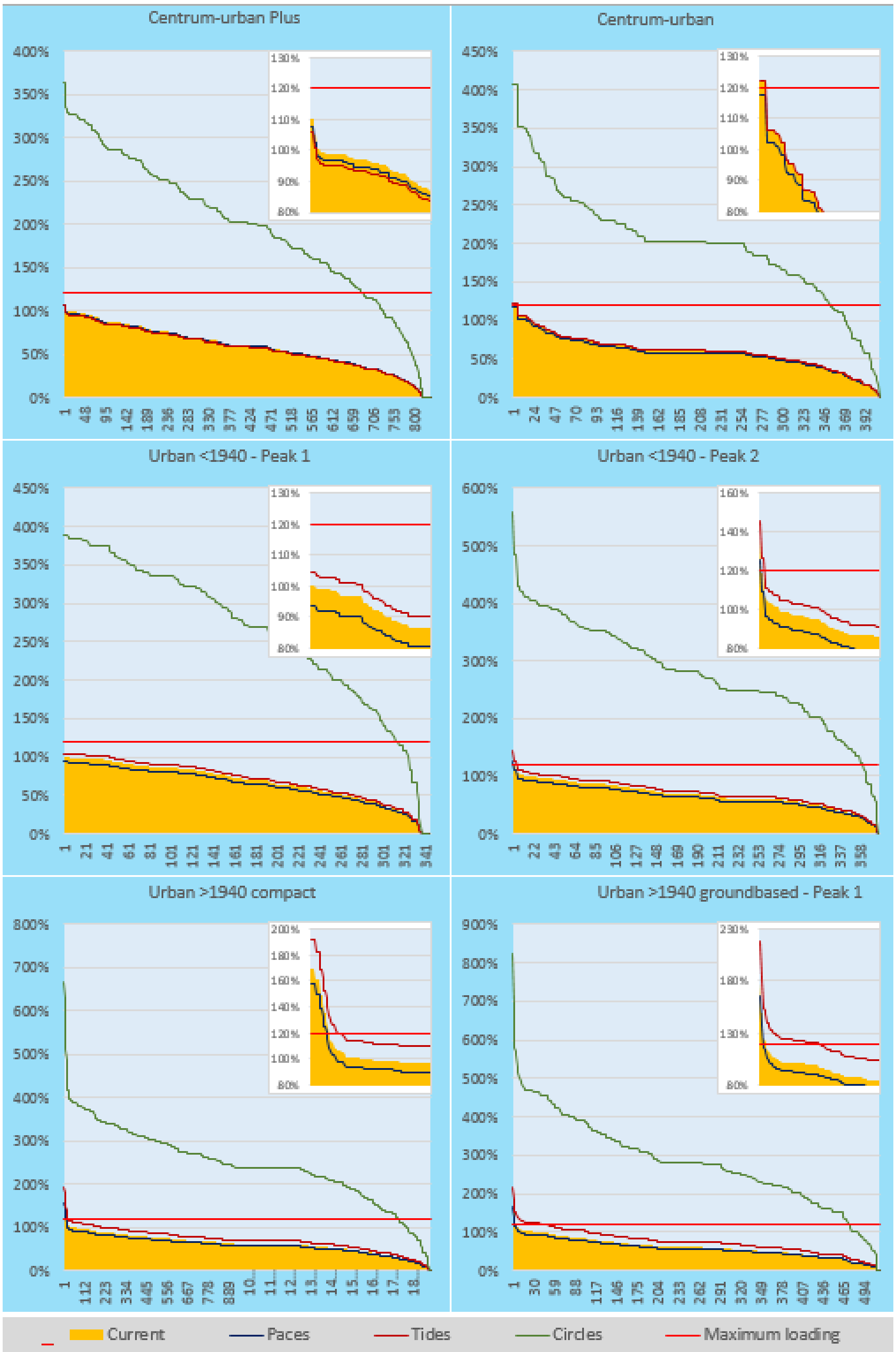



*Figure 87: Future load demand of MV/LV-transformers for the current situation (2013), and future situation (2040). The smaller graph in the top right corner zooms in on the load demand of the 100 transformers with the highest load demand for the scenarios* ***Paces*** *and* ***Tides****.*

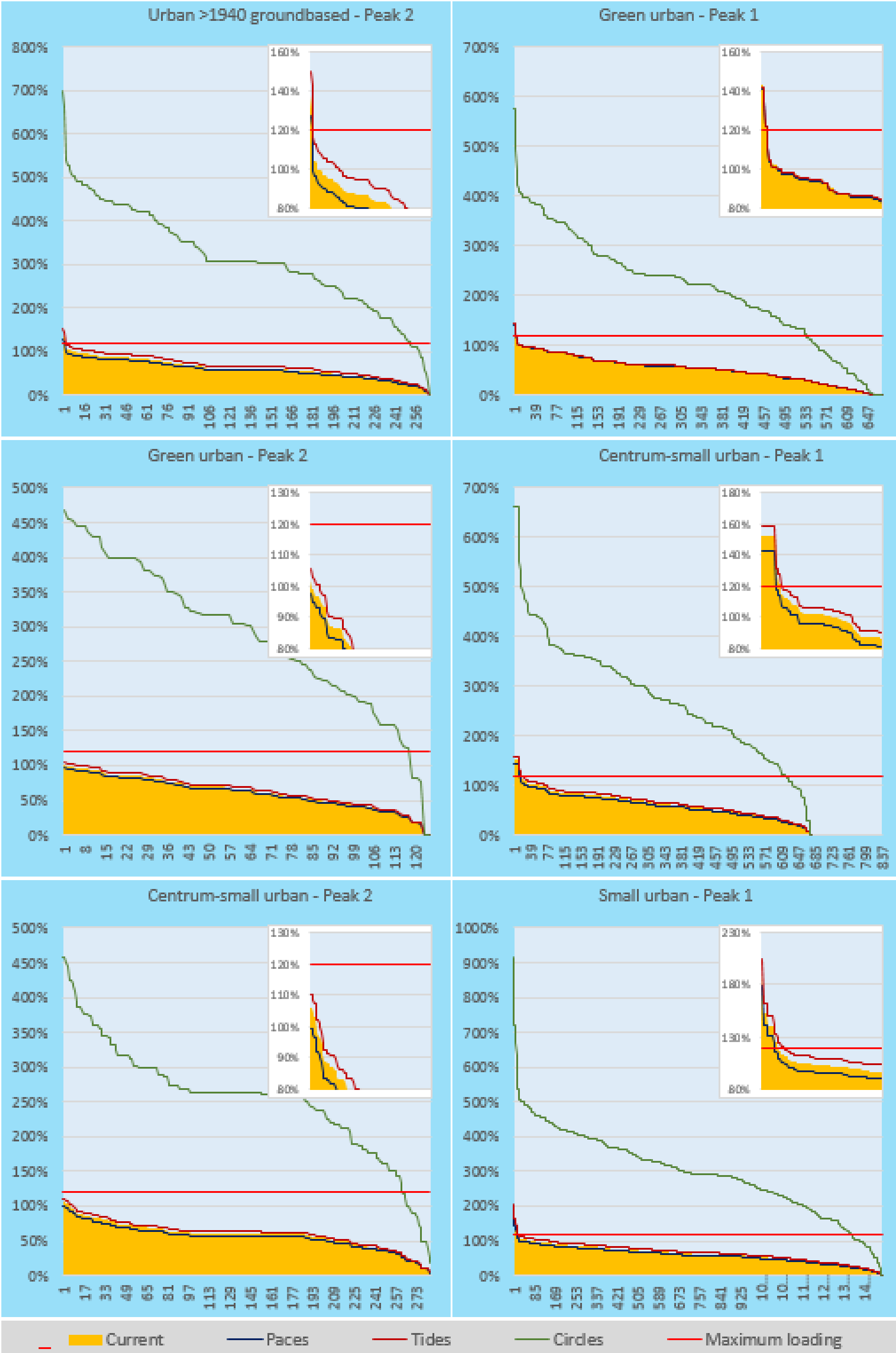



*Figure 88: Future load demand of MV/LV-transformers for the current situation (2013), and future situation (2040). The smaller graph in the top right corner zooms in on the load demand of the 100 transformers with the highest load demand for the scenarios **Paces** and **Tides**.*

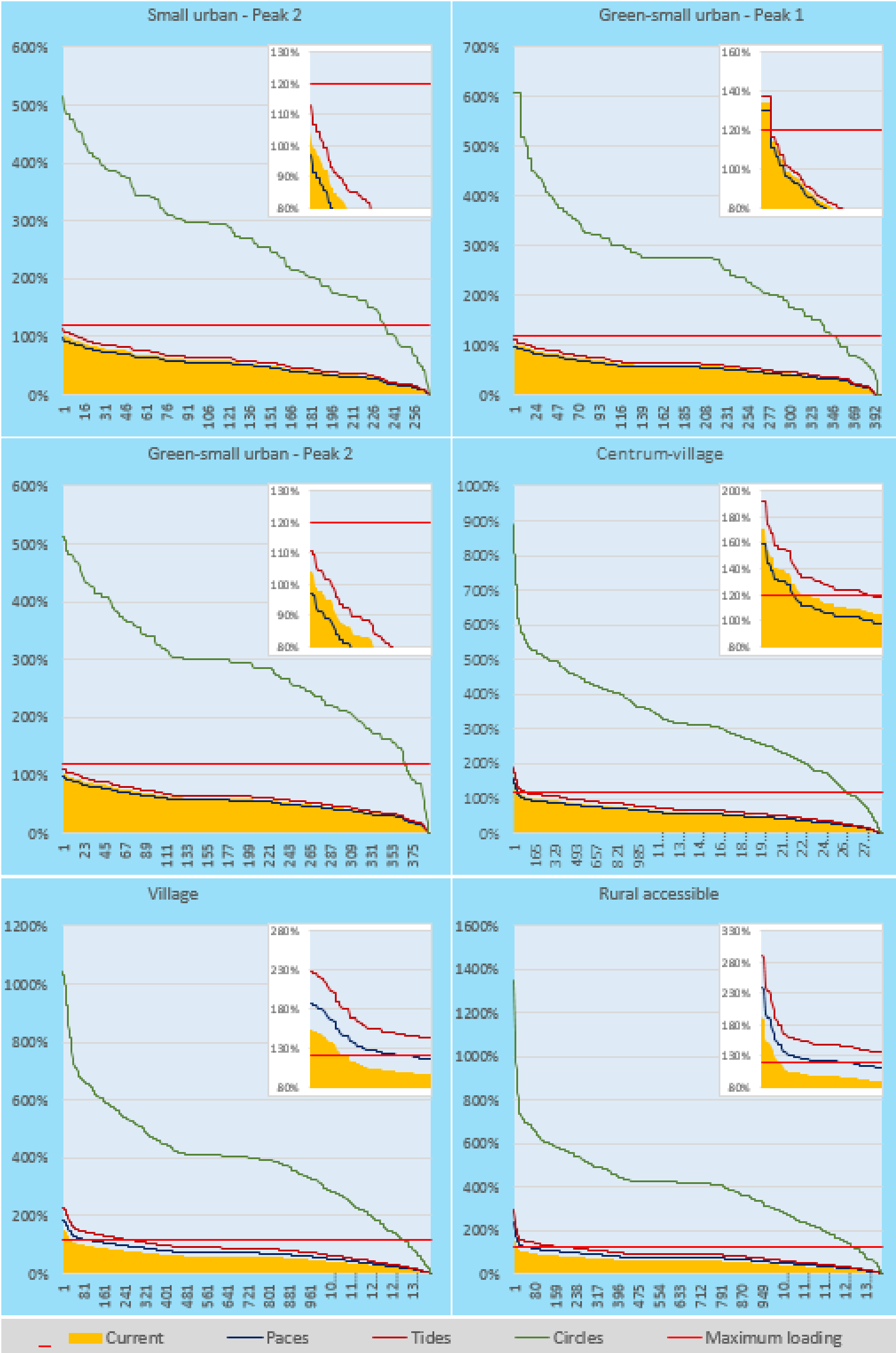



*Figure 89: Future load demand of MV/LV-transformers for the current situation (2013), and future situation (2040). The smaller graph in the top right corner zooms in on the load demand of the 100 transformers with the highest load demand for the scenarios **Paces** and **Tides**.*

# Appendix F Verification and validation

In this research an approach is proposed to determine the impact of the geographical differences in basic electricity demand and deployment of (renewable) technologies on the distribution transformers. This appendix reflects on the approach by determining if the approach as proposed is actually performed (verification). Additionally the certainty in the results needs to be increased by determining if the results are a good representation of reality (validation).

## F.1 Verification

The internal consistency of the model is checked during the verification. The results are obtained by creating an additional module to the existing model for grid-load calculations at the client. The existing model [CE Delft, 2014] is based on the ideas and methods of the national model for social-cost benefit analysis regarding smart grids in the Netherlands [CE Delft & KEMA, 2012]. This model has been used extensively for assessing the impact of the energy transition in the Netherlands, is verified in [CE Delft, 2014], and is therefore considered as a verified model. Validation of this approach is, however, questionable since it entails future exploration, which are inherently flawed.

The additional module creating the model districts with its relevant variables have been continuously checked during the model construction by the researcher. This includes the following tests:

- Correct coding of the input variables.
- Correct execution of the model-logic.
- Correct calculation of the output variables.

Several flaws were discovered and changed, such as wrong cell references in formulas. However, differences were found between the values in the operating area and the values from the sum of model districts in the operating area (see 0). Besides these differences the model has been verified and checked for the working as specified beforehand.

***Do the model districts add up to the numbers in the entire operating area?***

The number of buildings in the model districts are assumed to remain the same over the years in this research, meaning that no new buildings are constructed or old buildings demolished. In the scenarios for the entire operating area there are growth and decline rates for the number of buildings. Since some of the variables are calculated by using the number of buildings, the number of individual model districts when multiplied with the occurrence in the operating area, will not add up to the numbers of the entire operating area. Therefore, the number of buildings in the scenarios for the operating area are first set to the same number as used in the sum of the model districts. The number of buildings in 2013 in the model districts sum to:

- 2,12 million household;
- 0,178 million utility buildings.

Using these number for the operating areas of Stedin in the analysis creates the same results as obtained by the sum of model districts.

However, the sum of the number of buildings in the model districts is higher than the number of buildings used in the 2013 situation for the operating area. The number of buildings in the operating area are:

- 1,85 million households;
- 0,157 million utility buildings.

This means that the model districts have a 13% overestimation of the number of households, and a 13% overestimation of the number of utility buildings, compared to the entire operating area. What causes these numbers to differ? The model district numbers are constructed by using the [CBS, 2013b] database for districts in the Netherlands. The mode for the number of residential and commercial buildings from the real-life data obtained (after classifying the district with a certain type) was used to determine the number of buildings. Using the mode creates a difference compared to using the average. Looking at the original number of buildings (without manipulation of the numbers by using the mode or average) results in:

- 1,85 million households;
- 0,157 million utility buildings.

Therefore the number of buildings differs due to using the mode instead of the average for the number of buildings. This choice was made to create more identifiable districts, rather than average districts. The distribution between the number of dwellings and the number of households is nearly the same.

The differences (when using the constant number of buildings) between the sum of the model districts, and the operating area, are smaller than 4% for the following variables:

- Growth rate electricity demand
- Annual electricity demand
- Installed capacity PV
- Distribution PV over utility and residential buildings
- PV capacity per installation
- Number of heat pumps
- COP
- Annual heating demand

Therefore it is concluded that the number of buildings per model district as obtained with the model can be used in the analysis, even though there is an overestimation of 13% compared to the operating area. The number of buildings in the operating area scenarios are set to the same level as in 2012, meaning no new buildings or demolished buildings are included in the analysis. Since the distribution of residential and utility buildings is the same, the overestimation does not influence the patterns as obtained in the analysis, but only the height of the load profiles.

## F.2 Validation

For validation the replicative and structural validation can be applied. Replicative validation checks for differences in the measured values in reality versus the calculated values from the model. Structural validation investigates the structure (also called model logic) of the model from either a quantitative or qualitative approach. A quantitative approach uses extreme input values for variables, which should result in an extreme value as expected beforehand (also called sensitivity analysis). The qualitative approach uses the judgement of experts, which is especially useful when measuring data (or outcomes) are not available.

### F.2.1 Replicative validation (cross-validation)

Replicative validation thus uses actual data, or results from similar research. In this case a cross-validation is performed by comparing the results of this research with the outcomes of a research with similar scope and purpose.

Ecofys [2014] has performed a study on the impact of PV, heat pumps, and electric vehicles for residential buildings in order to determine the effectiveness of peak reduction solutions. Analysis were performed on the MV-networks of one green-urban district and one rural accessible district for the years 2020, 2030, and 2050, which have the same definition as used in this research.

There are however some difficulties in comparing the results of this research with the results of Ecofys [2014]. The year 2040 is not present in the study, but only the years 2030 and 2050. Therefore it is assumed that the peak demand in 2040 lies between the values of 2030 and 2050. Also in the results there is no mentioning anymore about the green-urban and rural accessible districts, but only about the highest peak demand, making it unsure which results are presented. Therefore, both the rural accessible and green-urban district results of this research will be compared to the results of the comparable research. Also it is not entirely sure if the commercial buildings are included in the analysis. In the beginning of the report the commercial buildings are mentioned, and seem to be included, but no later reference to it is reported. It is assumed that the commercial load demand is not included in the results.

Looking at the reported peak demand in comparison with the results in this research shows that the numbers differ. Therefore the underlying assumptions are compared, for which an overview is included in Table 42.

*Table 42: Input values for Ecofys [2014] study, and green-urban peak 1 and rural accessible districts as used in this research.*

| Variables | [Ecofys, 2014] | Green-urban peak 1 | | | Rural accessible | | |
|---|---|---|---|---|---|---|---|
| | | Paces | Tides | Circles | Paces | Tides | Circles |
| Peak demand 2030 | **2,1 kW** | 0,75 kW | 1,0 kW | 2,2 kW | 1,0 kW | **1,3 kW** | 5,2 kW |
| Peak demand 2040 | *(between 2,1 – 4,4 kW)* | 1,1 kW | 1,2 kW | 4,7 kW | 1,5 kW | 1,8 kW | 8,3 kW |
| EV's penetration | 35% | - | - | - | - | - | - |
| PV capacity/ dwelling 2030 | **1,6 $kW_p$** | 0,5 $kW_p$ | 0,7 $kW_p$ | 3,2 $kW_p$ | 1,1 $kW_p$ | **1,6 $kW_p$** | 7,2 $kW_p$ |
| Heat pump deployment 2030 | **10%** | 5% | 10% | 8% | 6% | **12%** | 10% |

First of all, the Ecofys report also includes electric vehicles (EV) in the scope. 35% of all cars are assumed to be electric in 2030, with a capacity of 10 kW [Ecofys, 2014]. Due to the non-simultaneous charging the maximum demand of the EV's is lower, with a maximum of 0,9 kW per car. The number of cars in the districts are not mentioned, and therefore it is assumed that each household has one car, of which 35% is electric. Therefore the demand per average household is 0,31 kW in the district. Second main input variable is the PV capacity. In the Ecofys report the installed capacity in 2030 equals 1,6 $kW_p$ per household. Third input are the heat pumps, which is 10% of the heat provision in 2030 in the Ecofys report.

The rural accessible input values in this research for the year 2030 are roughly the same as the input variables of the Ecofys study. Only difference is the EV demand. As presented before it is reasonable to assume an average load demand of 0,31 kW per dwelling for EV. However, the time of the peak demand is required. The highest peak for the loading of EV's is during 18:00 hour. Since the highest peak demand of the rural accessible district as used in this research is also during this time, the load demand of EV's is simply subtracted from the total peak demand.

Doing so results in a peak demand of 1,8 kW per dwelling, while our research indicates a peak demand of 1,3 kW for a rural accessible district in 2030. Further investigation of the differences in the approach show that the Ecofys study uses a temperature dependent coefficient of performance (COP) for the heat pumps. This results in a COP of around 1, while this research uses a COP of 3 which is not temperature dependent. The COP has been manually adapted to 1, the rural accessible district peak demand recalculated for the year 2030, which resulted in a peak demand of 1,9 kW per dwelling.

The results thus become the same after adaptation of the COP in our model, so that it becomes temperature dependent. In our current approach the heat demand of the heat pumps is scaled according to the cold year of 1963. However, this does not include a temperature dependent factor for the efficiency with which the heat pump itself is operating during the cold days. Is there such an efficiency decrease of heat pumps during cold days?

The answer is that it depends on the type of heat pump that is applied. In the Ecofys study an air-liquid heat pump is applied which uses the outside air as the source (see 2.3 for background). The air temperature fluctuates much more than the ground temperature. In this research it has been assumed that most heat pumps are ground-source heat pumps. Therefore the temperature dependency is no longer included since the ground temperature is relatively stable throughout the year.

To conclude, the results of the rural accessible district in 2030 for the **Paces** scenario is similar to the results of the Ecofys [2014] study. Although the results seem similar, the assumptions in the Ecofys study are not explained in detail resulting in an uncertainty on the approach, and thus on the comparability of the studies. Additionally, the comparison shows the large dependency on the assumptions relating the temperature dependency of the COP. We will return to this point during the sensitivity analysis in the next section.

### F.2.2 Structural validation

Two types of structural validation are performed: a sensitivity analysis and an expert meeting.

#### *Sensitivity analysis*

A sensitivity analysis is performed in order to determine the confidence in the results, the change in results if the input variables are changed, and the degree to which this influences the outcomes [Chinneck, 2006]. The main question that is addressed is: are the results sensitive to changes in the input values of the model districts and the scenarios.

First step is determining the variables of interest, of which an overview of the most important variables is included in Table 43. The construction of the model district variables are best described in a qualitative manner due to the large number of variables and relations related to them. The remaining variables can be divided into two parts: determining the peak demand per model district, and determining the load demand of the transformers. The load demand of the transformers is determined by multiplying the current loading (in 2013) of the transformers with the increase in peak demand per model district (2013 – 2040). The current loading is fixed, and the increase in peak demand per model district is based on two calculations of the peak demand (in 2013 and 2040) with the same model. Therefore, if the model to calculate the peak demand per district is well understood in terms of sensitivity, the sensitivity of the entire approach including the overloading is understood as well. The focus of the sensitivity analysis is therefore on the model to calculate the peak demand in the model districts.

*Table 43: Main variables in research*

| Model district construction | Specification input variables | Load forecasting model at client | Transformers | Outputs |
|---|---|---|---|---|
| Size of area (PC4) | Number of buildings | EDSN profiles (basic, PV, heat pump) | Current loading transformers | Peak demand district (2040) |
| Number of district types | Basic electricity demand | COP heat pumps | Size of area (PC4) | Increase in peak demand district (2013 - 2040) |
| Types of buildings | Basic heat demand | Types of heat pumps | | (Over)loading of transformers |
| | Installed PV capacity | | | Load profile of districts |
| | Number of heat pumps | | | |

The function to determine the peak demand in each of the model districts as used in this research is a linear function, and is formulated in the following manner for one model district:

$$\text{Model district peak demand}_i(x_i) = \sum(x1\ \text{Number of dwellings} * x2\ \text{Yearly E-demand per dwelling}$$
$$* \ x3\ \text{EDSN fraction E1a}) + \sum(x4\ \text{Number of utility} * x5\ \text{Yearly E-demand per utility} *$$
$$x6\ \text{EDSN fraction E2b}) + \sum(\ (x7\ \text{Installed PV capacity dwellings} + x8\ \text{Installed PV}$$
$$\text{capacity utilities}) * x9\ \text{PV supply fraction}) + \sum(x10\ \text{Number of residential heat pumps} *$$
$$\left(\frac{x11\ \text{Yearly heat demand dwelling} * x12\ \text{'cold factor'}}{x13\ \text{COP dwelling} * 3{,}6}\right) * x14\ \text{EDSN fraction LS-HPd}) +$$
$$\sum(x15\ \text{Number of commercial heat pumps} * \left(\frac{x16\ \text{Yearly heat demand utility} * x12\ \text{'cold factor'}}{x17\ \text{COP utility} * 3{,}6}\right)$$
$$* \ x18\ \text{EDSN fraction LS-HPu})$$

Two model districts are used as an example to investigate the sensitivity of the model; the rural accessible and centrum-urban plus districts since these are the most extreme types. The scenarios **Paces** and **Tides** are similar in output results, and to reduce the number of calculations the **Tides** scenario is used, in combination with the more extreme **Circles** scenario. The main input and model variables are individually changed with a value of +10% and -10%, after which the change in peak demand is determined. The results are included in Table 44.

*Table 44: Results of the sensitivity analysis*

| Variable | Rural accessible Tides 10% | Rural accessible Tides -10% | Rural accessible Circles 10% | Rural accessible Circles -10% | Centrum-urban Plus Tides 10% | Centrum-urban Plus Tides -10% | Centrum-urban Plus Tides 10% | Centrum-urban Plus Tides -10% |
|---|---|---|---|---|---|---|---|---|
| Number of dwellings | -0,92% | 0,91% | -0,20% | 0,19% | 4,69% | -5,18% | -0,31% | 0,31% |
| Yearly E-demand per dwelling | -0,92% | 0,91% | -0,20% | 0,19% | 4,69% | -5,18% | -0,31% | 0,31% |
| Number of utility | -0,46% | 0,45% | -0,11% | 0,09% | 3,04% | -3,24% | -0,28% | 0,28% |
| Yearly E-demand per utility | -0,46% | 0,45% | -0,11% | 0,09% | 3,04% | -3,24% | -0,28% | 0,28% |
| Installed PV capacity | 10,11% | -12,67% | 9,25% | -11,37% | 0,00% | 0,00% | 9,49% | -11,72% |
| Number of residential heat pumps | 0,10% | -0,10% | 0,04% | -0,06% | 1,01% | -1,03% | 0,05% | -0,05% |
| Yearly heat demand dwelling | 0,10% | -0,10% | -0,04% | -0,06% | 1,01% | -1,03% | 0,05% | -0,05% |
| Cold factor | 0,10% | -0,10% | 0,01% | -0,07% | 1,01% | -1,03% | 0,05% | -0,05% |
| COP dwelling | -0,09% | 0,11% | -0,10% | 0,06% | -0,94% | 1,12% | -0,05% | 0,06% |
| Number of comemrcial heat pumps | 0,03% | -0,03% | 0,02% | -0,02% | 0,91% | -0,93% | 0,05% | -0,05% |
| Yearly heat demand utility | -0,06% | -0,03% | -0,02% | -0,02% | 0,91% | -0,93% | 0,05% | -0,05% |
| Cold factor | -0,06% | -0,03% | -0,04% | -0,03% | 0,91% | -0,93% | 0,05% | -0,05% |
| COP utility | -0,03% | 0,03% | -0,06% | 0,00% | -0,84% | 1,01% | -0,05% | 0,06% |

The resulting change in peak demand for most variables are small (less than 1%). The effect of the change in installed PV capacity on the peak demand is relatively large, meaning that PV is the main influencer. This can be explained by the moment on which the peak demand occurs. Both scenarios of the rural accessible districts, and the centrum-urban plus district for the **Tides** scenario, have a peak demand that is caused by the summer peak. The summer peak is largely caused by the PV supply, which is the reason for a substantial change in the peak demand. In the centrum-urban plus districts in the **Tides** scenario the peak is caused by the winter peak during the evening. Approximately 25% of this peak is caused by the heat pump demand, and 75% of the peak is caused by the basic electricity demand. Therefore it would be logical that the variables that influence the heat pump demand and the basic electricity demand cause a higher change in peak demand during the sensitivity analysis. As the results in Table 44 indicate, this is indeed the case.

Therefore, it can be concluded that the peak demand is sensitive for the variables that cause the peak demand. This is an unsurprising conclusion, but it does highlight the importance of improving the scenarios especially on the variables that influence the PV deployment, the basic electricity demand, and the heat pump deployment. More importantly this research has provided insights into the moment that the peak demand occurs during the year, and the variables that most influence this peak demand, for each of the model districts. Combining the two previous points can indicate the focus of future research on the peak demands of different model districts.

In the Ecofys [2014] study a temperature dependent COP is used in the construction of the load profile of heat pumps. In this sensitivity analysis the COP has a minor sensitivity to (minor) changes in the input values. It is therefore concluded that the influence is minor for the temperature dependent COP. However, major changes in the COP values might provide different outcomes since this could create a tipping point in the influence of heat pumps on the peak demand. Additional research is recommended in both the future deployment of air source heat pumps (not yet included in the future energy scenarios), and the influence of the temperature dependency of the COP.

### *Expert validation*

The most effective type of expert validation is by performing the meeting with experts that are not involved in any of the elements of the research. However, due to confidentially issues and time constraints the expert validation is performed by employees of Stedin and Eneco (on May 21$^{st}$, 2015). This internal expert validation is less powerful than the external expert validation.

Main conclusions as discussed during the meeting are:

- The approach is considered to be sufficiently correct for the approximation of the load demand and peak demand of the model districts.
- The peak demand per commercial or residential building is in the range as used by the asset management division, and can be assumed to be correct. The results align with internal investigations.
- Current approach is not sufficient to direct choices on the network design of actual (real life) transformers since this requires data on the PC5 or PC6 level. However, this approach does contribute to bridging the gap between the high level economic/policy models and the detailed capacity models at the asset management division.
- The PV deployment in the **Circles** scenario is considered to be extreme. This is confirmed during the meeting, although not all participants were convinced that these deployment rates are realistic.
- Impact of heat pumps on the future electricity demand seems smaller than at an earlier analysis. This is due to the lack of the temperature dependent COP in this research. However, the participants responded by the expectation that most heat pumps are expected to be ground based heat pumps in the future. These do not require a temperature dependent COP. Not all participants were convinced, resulting in the advice to perform additional research on the types of heat pumps to be expected in the future and the influence on the electricity demand.
- This research assumed a differentiation of the heat demand in different residential reference buildings. This is a good approach, but the scenarios are lacking detailed data about the energy efficiency due to isolation in different reference buildings (only an average increase in energy efficiency for all types of households). When the scenarios are adapted, the energy efficiency of different types of reference buildings needs to be specified since it is expected to have a relatively large differentiation in the future.
- During the discussion on the distribution transformer capacity a new way of thinking was established on the reserve capacity available at transformers. Perhaps there is a possibility to use the reserve capacity of transformers assigned to a single client to elevate the network demand at districts with high increasing peak demands. Future research is suggested.

To conclude, the expert meeting resulted in the believe that the current approach is sufficiently detailed to model the peak demand per building, or model district, and to construct the load profiles. However, the PC4 areas on which the geographical model districts are constructed are too large to make to make decisions about the (future) real life capacity requirements of the distribution transformers.

TUDelft Delft University of Technology

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**Master Thesis Jurgen Meerkerk**

Delft University of Technology
Faculty Technology, Policy & Management

In cooperation with Stedin Netbeheer B.V.