Scalable model districts for geographic load forecasting in the distribution grid

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Abstract

The electrical peak demand in the Netherlands is likely to increase due to renewable energy technologies and create a higher load demand for distribution transformers. Two technologies that increase the peak demand are solar-PV and heat pumps, for which the deployment on the distribution grid differs largely between geographical areas. In this research 18 model districts are constructed that are representative for the Dutch build environment connected to the low-voltage network, which are applied in a case study to determine the future load demand of the distribution transformers. The results indicate a larger overloading of distribution transformers in 2040 in the village and rural accessible districts, compared to the more urban district types. In two of the three scenarios, most transformers have sufficient capacity to cope with the energy transition. The outcomes can be used to construct regional approaches in maintaining the most cost effective operation of the distribution transformers.

Keywords: distribution grid, peak load, geographical dependency, model districts, energy transition

1. Introduction

In the Netherlands the objective is to generate 14% of the total energy demand by renewable sources in 2020, increasing to 16% in 2023, and aiming to achieve a completely renewable energy supply in 2050 [Rijksoverheid, 2014]. 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.

Load forecasting is used by decision makers of the distribution network operators (DNO) to determine the impact of the energy transition on the distribution grid equipment, with the aim to achieve the lowest costs for the distribution of electricity while maintaining sufficient capacity for a reliable distribution. Some authors expect that the increases in the peak load demand are expected to endanger the reliability of the electricity networks in the Netherlands [Blokhuis, Brouwers, van der Putten, & Schaefer, 2011]. Using load forecasting allows to determine the magnitude and the geographical location of the electricity demand during a specific time interval (e.g. an hourly time period) [Alfares & Nazeeruddin, 2002].

Introducing the sustainable energy system changes the demand and supply patterns in the distribution grid, causing two areas for concern: possible increases in peak loads, and increased intermittency of decentralised generation (DG) [Blokhuis et al., 2011]. The peak loads depend on the total electricity demand, increases in demand due to end-user appliances like electric vehicles, or heat pumps, and the reduction of demand due to decentralised electricity production by e.g. photovoltaic (PV) panels. The intermittency is related to the changes in demand and supply in districts, in which the current system depends on central balancing with a top-down delivery of centrally generated electricity. Small deployment rates of DG can be balanced, but this becomes increasingly difficult with increasing deployment rates, Current research focusses on the increased intermittency relating to network control [Lehtonen & Nye, 2009], the average peak load per dwelling or utility on the national scale [Blokhuis et al., 2011; Veldman, Gibescu, Slootweg, & Kling, 2013], or peak load development on a local scale performed by case studies of a specific region [Navarro-Espinosa & Mancarella, 2014]. Alternatively, investment decisions are made for the entire operating area, resulting in high over analysis [CE Delft, 2012]. There are however no studies that incorporate the geographical differences in deployment rates of PV and heat pumps, while maintaining the overview for the entire operating area.

This article therefore looks into the geographical differences in peak load demand in the build environment, in order to determine the future loading rate of the distribution transformers. This provides a new aggregation level that is located between the high aggregation level on analysis of large areas, and the low aggregation level on individual district or consumer analysis. The results can be used to provide insight into the geographical differences in the effect of the energy transition on the distribution transformers by increases in PV and heat pump deployment rates, and to identify feasible peak reduction or mitigation alternatives. The research question is therefore: w*hich model districts can be used to represent the Dutch distribution grids in a scalable manner, and what are the future load demands of the distribution transformers?*

A literature review is used to identify feasible categories to segment the operating area of distribution network operators (DNOs). The model districts that are constructed are used to perform a case study for the Dutch DNO Stedin. This DNO provides a quarter of the Dutch consumers of electricity, and is the third largest DNO in the Netherlands. The connections consists of 1,85 million residential connections and 0,16 million small commercial connections [Stedin Netbeheer B.V., 2014]. These are located in both rural and urban areas, and supplied of electricity by 22.285 distribution transformers.

The outline of the article is as follows. In chapter 2 current approaches in load forecasting are evaluated in order to position this research in the scientific literature. Current (regional) deployment rates of PV and heat pumps are included in chapter 3, followed by the approach description (chapter 4), and the results (chapter 5). Chapter 6 ends with the conclusions and a discussion on the limitations and possible applications of the results.

2. Literature review

Load forecasting methods can be assigned on two axis of the approach to construct the load profile (bottom-up or top-down), and the hierarchical level of interest (entire operating area, or individual consumer). Multiple studies are mapped on these studies to identify the current methods of analysis (see Figure 1).

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]. 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 [Hahn, Meyer-Nieberg, & Pickl, 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].

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 1). 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.

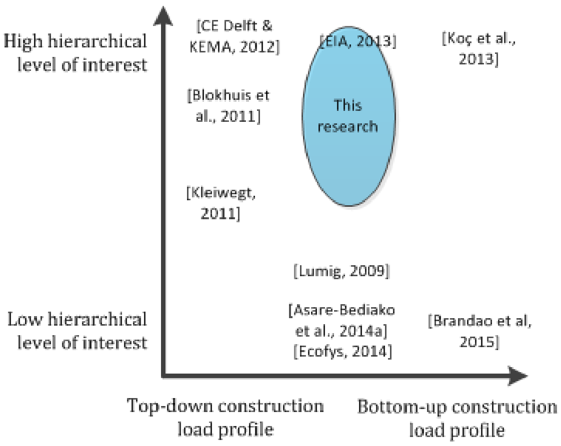

Figure 1: Positioning of this research in relation to the existing load calculation methods. The methods are plotted on the hierarchical level of interest, and the approach to construct the load profiles.

3. Current situation PV and heat pumps

DNOs need to maintain the reliability of supply, and therefore closely monitor the changing demand characteristics. Increases in electrification are especially expected in space heating and electric vehicles (e.g. Blokhuis et al., 2011; Eyre & Baruah, 2015). Additionally the increased penetration of decentralised electricity supply by PV causes the net-electricity demand to reduce.

Residential and commercial space heating can be provided by electric heat pumps, or hybrid heat pumps. A heat pump uses a source at low temperature, such as the air or groundwater, to upgrade the heat to a higher temperature. During high heat demands an additional heating element is applied, which is either an electrical driven element for full electric heat pumps, or a natural gas driven element. Due to the large gas infrastructure in the Netherlands both alternatives are possible. The installed capacity of heat pumps has substantially increased since 2003 in the Netherlands, with a combined capacity of 9000 TJ of heat provision of which ¼ is residential installed, and the remainder as commercial installed capacity [CBS, 2013].

The installed capacity of PV on the low-voltage (LV) grid is mainly located at rooftops of buildings. The supplied electricity is consumed by the consumer, and the excess electricity supply is fed into the distribution grid. A large increase in installed capacity is observed since 2011, with a cumulative installed capacity of 739 MW in 2013 [CBS Statline, 2014]. It is estimated that 80% of the installed capacity is residential PV, and 15% commercial deployed PV [EPIA, 2014]. Deployment rates between different four-digit postal code areas range between 1 kWp and 6000 kWp per area, resulting in a large geographical differences [Ministery of Infrastructure and the Environment, 2014].

Table 1: Living environment typologies ABF Research

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

4. Research approach

The aim 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 in the year 2040. This requires the number of residential and commercial connections, the electricity and heat demand per connection, the installed PV capacity, and the number of heat pumps per district. The Energy Data Services Nederland (EDSN) load profiles combined with the annual electricity demand and the number of connections, the installed PV capacity, and the number of heat pumps results in the basic electricity demand, the PV supply, and the heat pump demand for residential and commercial buildings respectively. These six load profiles combined form the load profile of the model district.

4.1 Construction model districts

The operating area is segmented into uniquely defined model districts that represent both rural areas, urban areas, and those in between. [ABF Research, 1998] has constructed identifiable living environments for the exploration of the needs and desires in the residential building sector. These are used extensively in the Netherlands for studies on the living environment policies that affect the residential build environment (e.g. [Van Leeuwen, Heida, Van Galen, & Poulus, 2010; VROM, 2001, 2006]). Each four digit postal code (PC4) area in the operating area is classified with one of the 13 corresponding living environments, and coupled to data on the number of residential and commercial buildings, resulting in 18 uniquely identifiable model districts. These are depicted in Table 1 and the description per type is included in the appendix.

The residential buildings are further specified by using reference buildings. The reference buildings provide a reflection of the main types of dwellings in the Dutch residential sector [Agentschap NL, 2011]. The residential stock is divided into 7 types of reference buildings, namely detached, semi-detached, terraced houses, maisonette, porch flat, gallery flats and other apartments. The commercial stock is not further specified.

4.2 Specifying model districts

For the future exploration 3 future energy scenarios are used that are constructed by Eneco[1]. These are based on the possible development of the economic growth rates, are named Paces, Tides and Circles, and provide outlooks for the years 2020, 2030, 2040 and 2050.

The national scenarios need to be converted into the specific numbers per model district. This is where the reference buildings are used to determine the technical potential, or maximum deployment rate, per model district. For the PV capacity the available roof surface on which PV can be applied is determined in [PBL & DNV GL, 2014] for each reference building, resulting in the available roof surface per model district. Similarly, the technical potential for residential heat pumps is determined by using [DHPA, 2013] that also reports the potential per reference building.

On the national scale the percentage of the technical potential that is used with the specified deployment rates of PV and heat pumps is determined per residential and commercial buildings. This percentage is applied to the technical potential of PV and heat pumps per model district to determine the installed PV and heat pump capacity. For example, in the Paces scenario the installed residential PV capacity is expected to be 12 GW in 2040, with a building stock of 8,5 million households that combined have a roof surface applicable for PV of 281 km^2. The PV capacity requires a roof surface of 43 km^2, resulting in the use of the technical potential of 15%. For the centrum-urban plus districts a total roof surface of 0,9 km^2 is available for PV installation based on the distribution of reference buildings, resulting in 15% x 0,9 km^2 = 0,13 km^2 of installed PV capacity in the district. This way the national numbers are converted into the deployment rates of PV and heat pumps in the 18 model districts.

The electricity and heat demand is different for different types of dwellings. The average

[1] The scenarios are explained in [Eneco, 2014].

electricity demand and heat demand per dwelling in each of the model districts is determined by using the average demand per reference building, multiplied by the number of reference buildings located within each model district. The deviations from the average electricity and heat demands are included in Table 2.

Table 2: Deviation from average electricity and heat demand per reference building. Source: [Agentschap NL, 2011]

Reference buildings	Deviation electricity demand	Deviation heat demand
Detached	142%	169%
Semi-detached	121%	131%
Terraced house	151%	108%
Maisonette	91%	91%
Porch flat	50%	66%
Gallery flat	70%	66%
Other apartments	75%	66%

4.3 Load profiles

Energy companies use the EDSN load profiles to perform load forecasting analysis. The profiles are constructed by measuring the load of 1000 connections for every 15 minutes for an entire year, and are divided into 9 categories on the basis of the physical connected capacity [Blokhuis et al., 2011]. For the basic electricity demand of the residential buildings the EDSN profiles E1a (<3 x 25 A, single tariff) and E1c (< 3 x 25 A, double tariff, evening active tariff) are used. It is assumed that half of the households is represented by the E1a profile, and the other half by the E1c profile. For the small commercial buildings the profile E2b (> 3 x 25 A, < 3 x 80 A, double tariff) is used for the basic electricity demand. The profiles provide the load fraction of the annual electricity demand as occurs during the hourly time frame (see Figure 2).

The PV profile is constructed in an extreme manner and assumes clear skies throughout the year. This allows to obtain the highest peak demands that the network needs to support. The heat pump profile is based on the heat demand during an extreme cold year, namely the year 1963. Both profiles are constructed in a previous study for the client Stedin [CE Delft, 2014].

4.4 Transformers specification

The distribution transformers are scattered throughout the operating area. For each distribution transformer the PC4 area in which it is located is determined. This way the transformers are coupled to the relevant model district.

Each (physical) transformer has an indicator that provides the highest load demand as occurred since the last registration moment. This is used as the current loading rate of the transformers in 2013. The future load demand is determined by: *Future load demand (%) = Current loading (%) x [1 + Increase in peak demand (%)].* The increase in peak demand (per model district that is associated with the transformer) is determined by calculating the peak demand in 2013 for the model district, followed by the peak demand in 2040, after which the percentual increase in peak demand is determined for each of the model districts.

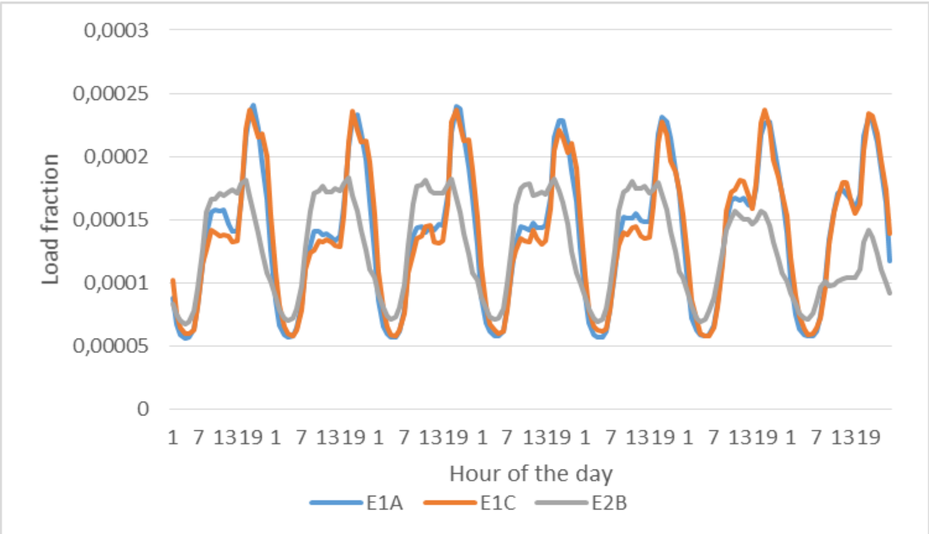

Figure 2: Load profiles for basic electricity demand for a winter week

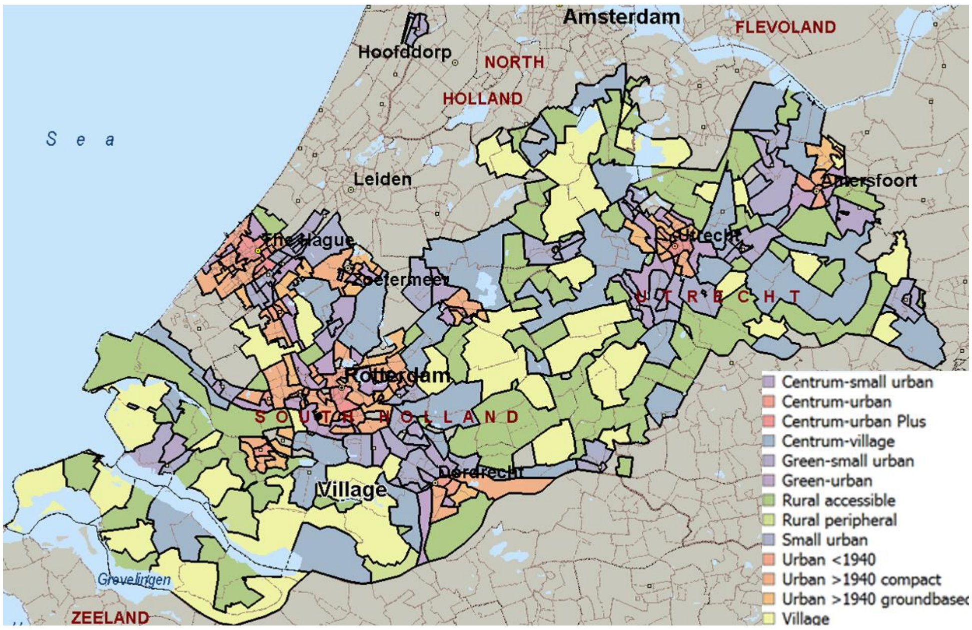

Figure 3: Segmentation of the operating area of Stedin into the model districts. The grey lines demarcate the four digit postal code areas, and the coloured parts are operated by the client.

5. Results of the case study

The method is applied on the operating area of the Dutch DNO Stedin. This section describes the distribution of the model districts, and the scenario results related to the future load demand of the distribution transformers in 2040.

5.1 Distribution model districts

For each PC4 area in the operating area the model district type is determined. The distribution of the number of connections per model district for the operating area are included in Table 4. The model districts in which the largest part of the connections are present are the rural accessible (17%), the urban >1940 compact (14%), and the small urban, and centrum-village (13% each).

5.2 Scenario results

The peak demand per dwelling is different for each of the model districts. It ranges between 0,6 kW per dwelling and 9,5 kW per dwelling (see Table 3). The residential peak demand is lowest in the most urban districts (first 5), highest in the most rural districts (last 3), 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 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 consumers. In the Circles scenario the maximum peak demand of the residential buildings is smaller than the maximum peak demand of commercial users in the Circles scenario due to 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 in scenarios

	Peak demand residential		Peak demand commercial	
	Min	Max	Min	Max
2013	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

The main output variable for the analysis is the future load demand of the distribution transformers. Damages in distribution transformers are a function of the degree of overloading and the duration. A distribution transformer is overloaded if the demand exceeds 120% of the nominal capacity. In 2013 less than 2% of the transformers is overloaded. Application of the scenarios provides the load demand for 2040. In the Paces and Tides scenario most transformers remain similar to the overloading of 2013, and the winter peak demand remains dominant. However, the most rural districts (village and rural accessible) show a substantial increase in overloaded transformers. In both districts the annual peak demand occurs during the summer, and is caused by the PV supply peak (at 12:00 hours). Also the transformers located in the 'urban >1940 groundbased –peak 1' districts show a large increase in overloaded transformers (9% of total stock) for the Tides scenario. In this case the highest peak demand is during the winter (at 18:00 hours), and caused by the basic electricity demand and heat pump demand. The Circles scenario shows a substantial increase of the overloaded transformers for all model districts. In this scenario the high deployment rates of PV cause the summer peak to be the largest demand moment.

Table 4: Percentage of transformers overloaded for each model district, with the current situation in 2013 and the future scenarios for 2040.

Percentage of overloaded transformers				
Model district	**2013**	**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 - Pk 1	1%	1%	9%	92%
Urban >1940 groundbased - Pk 2	1%	1%	1%	94%
Green urban - Peak 1	1%	1%	1%	90%
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%

Table 5: Differences between PC4 (four digit postal code), 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

6. Conclusions and discussion

6.1 Conclusions

The energy transition is expected to stretch the limits of the distribution grid capacities. Increases in the peak load and the fluctuations of demand and supply provide difficulties for the distribution network operators. The regional differences are so far not included in the future load forecasting methods. The aim of this article was to construct model districts that can be used in a scalable manner, in order to determine the future load demands of the distribution transformers. The method has been applied in a case study to the operating area of the Dutch network operator Stedin, and applied on the time horizon of 2040.

A total of 18 model districts are used to divide the operating area. Applying the scenarios reveals that in most districts in the Paces and Tides scenarios the current capacity of the transformers is sufficient to deal with the peak demand, which occurs during the winter and the increase is caused by additional heat pump deployment. However, in the village and rural accessible districts, as well as in all districts in the Circles scenario, the summer peak becomes dominant and results in an increased overloading of the transformers. Especially the high deployment rates of PV in the Circles scenario cause nearly all transformers to have an insufficient capacity.

6.2 Discussion

There are however some limitations to the approach taken. Firstly the size of the model districts are relatively large. This causes the districts to be similar in relation to each other due to the large number of connections within a district. If a smaller area size is chosen it could be that an area previously classified as e.g. centrum-urban plus, actually contains multiple model districts for which centrum-urban plus is merely the average classification. Also the smaller areas sizes better align with the number of buildings that each transformer serves (see Table 5), making the analysis more detailed. Secondly, the commercial buildings are not further specified by using different types of reference buildings. Therefore the demand of each commercial buildings is the same in the different model districts. Including commercial reference buildings would substantially increase the confidence in the findings. Thirdly, the scenarios have been under construction throughout the research. The scenarios are not substantially validated against other scenarios (as far as this is even possible). The findings of this article can be used to improve the scenarios on the elements that show the largest influence on the peak demand, namely the regional differences in deployment of PV and heat pumps.

The results can be used to determine the main focus for future research, on which it is recommended to provide additional attention to the more rural districts since these are expected to be the earliest and largest affected by the energy transition. However, this research did not include electric vehicles and cooling by heat pumps. Including these additional demands might change the solutions since the summer peak can be lowered. Additional research on the impact of these technologies is therefore recommended.

Overall this method provides an additional tool to the load forecasting toolbox. Although surrounded with uncertainty, the inclusion of an intermediate aggregation level provides policy makers in the energy sector with additional insights into the effect of the differing regional deployment rates.

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Appendix – Model districts characteristics

Model districts	Description on categorising postal areas
City	**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	**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.