Kalavasta
Climate Neutral Strategies

Impact local heating and cooling choices

Documentation

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Contents

1 Introduction

In this documentation, the models used for the analysis in the main report (Impact lokale warmte-koude keuzes, Kalavasta 2026) will be discussed in more detail. Most of this document will focus on the Infrastructuur Transitie Model (ITM) and its inputs, with one section focusing on the smaller backup tool, which calculates the required capacity of backup.

Inputs to the Infrastructure Transition Model (ITM)

In this section, we will discuss the inputs to the Infrastructure Transition Model (ITM), which is used to calculate the electricity grid load, and how it links to the backup tool developed to calculate the required backup capacity. These are: the Startanalyse for the built environment, the Netbeheer Nederland (NBNL) scenarios for the remainder of the energy system, and the Energy Transition Model (ETM) for hourly demand curves.

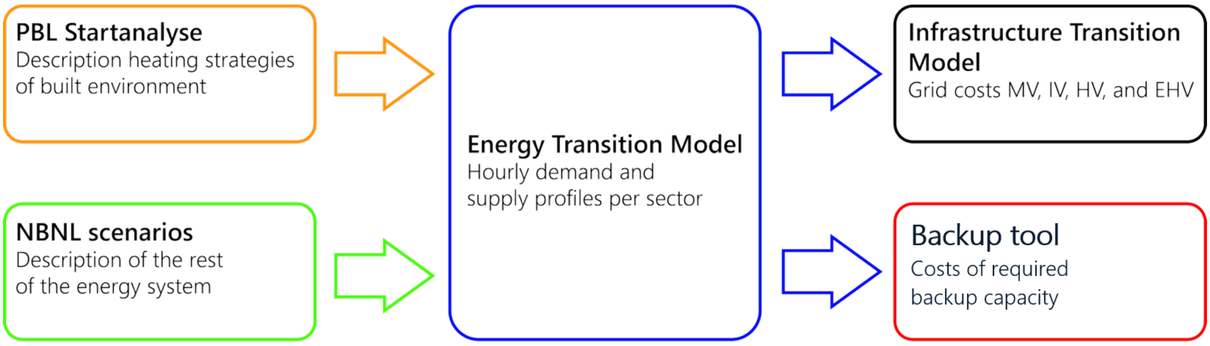


Figure 1. A schematic overview of the analysis process. From the inputs (Startanalyse, orange, and NBNL scenarios, green), via the ETM (blue) to generate hourly demand curves, to the ITM (black) for the cost of the electricity grid and the backup tool (red) to calculate the required backup capacity.

The reference scenarios used in this analysis consist of two parts. Technology choices in the built environment are based on the Startanalyse, which describes heat demand, electricity demand, and local heating costs for various heating strategies at neighbourhood level. The remainder of the energy system is described using the most recent NBNL scenarios, available in the ETM. These NBNL scenarios include their own representation of the built environment, which is overwritten with data from the Startanalyse. A number of additional adjustments are made to the scenarios which will be expanded upon later. The resulting "Startanalyse – NBNL scenarios" in the ETM serve as the reference scenarios for this study.

These reference scenarios provide the input for two analytical tools. The ITM translates the scenarios into regionalized demand and supply profiles, links these to a network topology derived from publicly available asset data provided by the network operators and subsequently uses PyPSA to calculate the peak load per cable and transformer. The backup tool uses residual demand curves from the same scenarios to determine how much dispatchable generation capacity is required to cover the remaining electricity demand – after optimal deployment of storage – at every point in time. Together, these tools produce the network costs and backup costs that are used in the analysis.

The building blocks of the ITM

The Infrastructure Transition Model (ITM) comprises several building blocks: the input ETM scenarios discussed above, the regionalization of the hourly demand and supply curves from these scenarios, a description of the electricity network structure, and a network calculation tool, PyPSA.

The hourly profiles from the ETM national scenarios – covering hourly electricity demand and supply – are regionalized to a location (municipality, neighbourhood, MV/LV station, or exact location) and voltage level. The network topology is derived from publicly available spatial data of cables and substations across the MV, IV, HV and EHV networks. Hourly power flows per cable and substation are then calculated using PyPSA, yielding a peak load per network component that is subsequently translated into national costs.

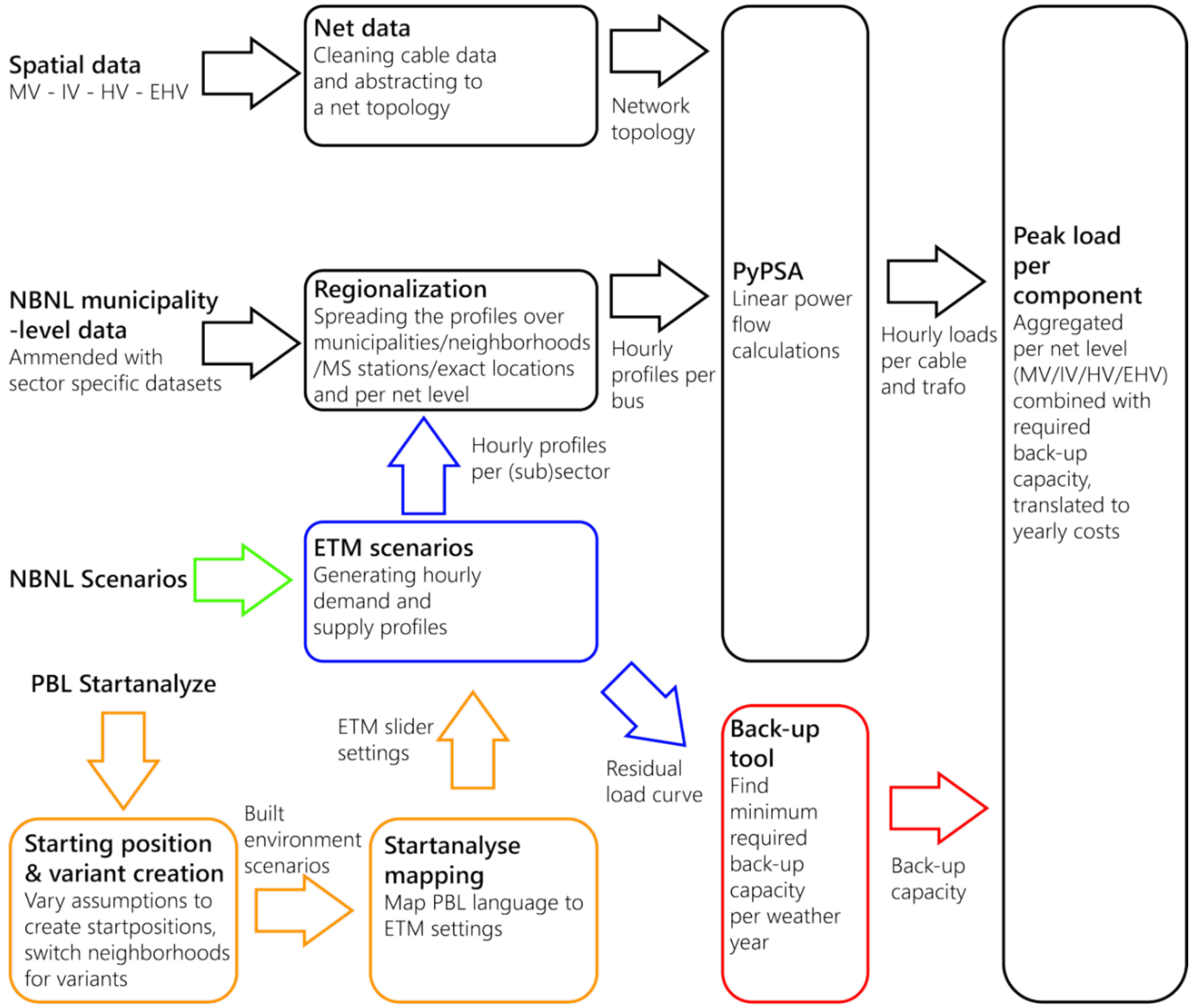


Figure 2: An overview of the subparts of the ITM and their interconnectivity.

Each of these blocks are summarized briefly below. Then, each section will dive deeper into these parts.

- Starting position & variant creation
  This part processes the Startanalyse to make it ready for use. This means concatenating all the data, figuring out the split of heating strategies between houses & utilities, and calculating the share of the Netherlands that uses each heating strategy.
- Startanalyse mapping
  This part maps the Startanalyse calculations onto ETM inputs. This is done for housing stock, heating strategies, coefficient of performances (COPs) and more. A mapping to use the Startanalyse as the regionalization of the built environment demand is also applied here.
- ETM scenarios
  In this part, we combine the NBNL scenarios with the Startanalyse mapping into ETM scenarios. From these scenario's we get the hourly supply and demand curves per sector.
- Regionalization
  The regionalization uses many data sources to 'regionalize' the national hourly electricity supply and demand curves using weights for each individual consumer/supplier.
- Net data
  The electricity network topology is created by processing open data from the Regional Grid Operators and from TenneT. Regionalized consumer/suppliers are connected to this topology.
- PyPSA
  Finally, we calculate powerflows through the network topology, resulting in hourly loadcurves per cable and transformer. Peak loads per asset are then aggregated and used to calculate grid costs.

In preparing this documentation, an AI tool was used as a writing aid. The resulting text has been reviewed and revised for content by the authors.

2 Starting position & variant creation

To create our inputs for the ITM, we process Startanalyse data. We also create different starting positions by changing Startanalyse assumptions and create variants by 'switching' certain neighbourhoods from one heating strategy to another.

2.1 Summary

- We download all the Startanalyse data per municipality and concatenate this.
- We calculate the so called starting position, in which each neighbourhood is assigned the heating strategy that corresponds to the lowest national costs
- We create three additional versions of these starting positions by using different Startanalyse assumptions. Two of which are created by PBL (expensive & scarce climate neutral gas, and insulation B+) and one of which we added (higher electricity price). The latter uses an electricity price that is 50% higher than the average price used in the Startanalyse.
- From these starting positions, we create variants, where neighbourhoods are purposely 'switched' away from the heating strategy with the lowest national costs as calculated by PBL. These will allow us to study the impact of these switches on the electricity network.

2.2 Data sources

- Startanalyse (PBL): https://startanalyse.pbl.nl/gemeentedata

2.3 Detail

The heating and cooling mix for the built environment is based on the Startanalyse, which describes for every neighbourhood in the Netherlands the number of homes and buildings, including heat demand, electricity demand, and local heating costs for different strategies. Local heating costs cover elements such as insulation, heat pumps, electricity, climate-neutral gas, and district heating. The Startanalyse distinguishes four heating strategies:

Strategy 1: Individual air-water or ground-source heat pump

Strategy 2: Medium-temperature (MT) district heating network using residual heat or geothermal energy

Strategy 3: Partial district heating (a combination of (Z)LT district heating with an individual heat pump, or MT district heating with a central heat pump), combined with individual heat pumps (strategy 1)

Strategy 4: Hybrid heat pumps using climate-neutral gas

For each neighbourhood, the Startanalyse calculates the costs of multiple heating strategies and selects the option with the lowest national costs. The reference situation uses these outcomes as-is. Three additional variants recalculate the strategy with the lowest national costs using different inputs: the higher electricity price variant scales up the electricity price by 50% and recalculates costs per strategy per neighbourhood; the expensive and scarce gas variant applies a different cost column and a different climate neutral gas availability column; and the insulation B+ variant only considers B+ strategies.

Beyond these starting positions, strategy switches are applied as variants. These switch specific strategies to an alternative – for example, replacing an air-water heat pump (strategy 1a) with a ground-source heat pump (strategy 1b), or switching from strategy 1 to strategy 2, 3A, or 3B. A switch to the hybrid heat pump is excluded, as its deployment is constrained by the availability of climate-neutral gas.

Where a switch is made to strategy 3, it is only applied to neighbourhoods where the additional local costs are no more than 20% higher than under the original strategy. Without this limit, a relatively small number of neighbourhoods with disproportionately high-cost increases would skew the comparison between network costs, backup savings, and local heat costs. For switches from air-water to ground-source heat pumps, or to a district heating network with geothermal energy, this 20% threshold is not applied, as the cost increase in these cases is considerably larger and applying the threshold would leave too few neighbourhoods making the switch. Furthermore, when switching to strategy 3, sufficient (Z)LT heat is not always available to connect all homes and buildings to a district heating network; homes and buildings for which no connection is feasible remain on an air-water or ground-source heat pump (strategy 1).

Table 1 provides an overview of all heating strategies, including the grouping of sub-strategies, with the sub-strategy with the lowest national costs always selected within each strategy. Table 2 describes the assumption variants used in the Startanalyse: two are based on PBL sensitivity analyses (expensive and scarce gas, and insulation B+), while the higher electricity price variant was added by Kalavasta. Figure 3 shows, per neighbourhood, the aggregate heat demand and number of connections per heating strategy across the Netherlands based on the lowest societal additional costs, as well as the spatial distribution of heating strategies. Table 3 provides an overview of the strategy switches applied, with their effects on heat demand and number of connections shown in Figure 4.

Table 1. Overview of all heating strategies, including the grouping of sub-strategies. Some of these parameters are taken directly from the Startanalyse. Cooling is not included in the Startanalyse, so the cooling strategy was determined by Kalavasta. The peak electrical demand is derived from Startanalyse data combined with heat pump profiles from the ETM. Heat demand depends not only on the building envelope label but also on parameters such as dwelling size and construction year. The housing mix differs per strategy.

Strategy Kalavasta	Heating technology Startanalyse	Insulation Startanalyse	Cooling Kalavasta	Tap water Startanalyse	Input – output heat pump Startanalyse	Label Startanalyse	SCOP heating Startanalyse except S3A 1-3: assumption Kalavasta	Heat demand (GJ/weq/year) Startanalyse	Peak electricity demand (kW/weq) Kalavasta (via ETM profiles)	Share peak boiler Startanalyse
1 A	Air-water heat pump	B+	Heat pump/AC	Heat pump	Lucht – 50 °C	B+	4.25	33	2.1	-
1 B	Ground heat pump	B+	Heat pump	Heat pump	Bodem – 50 °C	B+	5	33	0.9	-
2 A	MT district heating rest heat	B+/D+	AC	Network heat	-	B+	-	23	0.0	15%
2 B	MT district heating geothermal	B+/D+	AC	Network heat	-	B+	-	30	0.0	15%
3 A1	(Z)LT district heating with individual heat pump per house	B+	Heat pump	Heat pump	15 – 50 °C	B+	5.25	30	0.7	-
3 A2	(Z)LT district heating with individual heat pump per house	B+	Heat pump	Heat pump	15 – 50 °C	B+	5.25	35	0.8	-
3 A3	(Z)LT district heating with individual heat pump per house	B+	Heat pump	Heat pump	15 – 50 °C	B+	5.25	29	0.6	-
3 A4	(Z)LT district heating with individual heat pump per house	D+	Heat pump	Heat pump	15 – 70 °C	D+	3.5	34	1.1	-
3 A eHP	*Strategy 1 for the portion of the neighbourhood for which insufficient (Z)LT heat is available*									
3 B1	MT district heating – source (Z)LT –with central heat pump	B+	AC	District heating	15 – 70 °C	B+	3.5	31	0.36	15%[1]
3 B2	LT district heating – source (Z)LT - with central heat pump	B+	AC	District heating	15 – 50 °C	B+	4.5	34	0.36	15%[1]
3 B3	MT district heating – source (Z)LT - with central heat pump	D+	AC	District heating	15 – 70 °C	D+	3.5	30	0.35	15%[1]
3 B4	MT district heating – source (Z)LT - with central heat pump	D+	AC	District heating	15 – 70 °C	D+	3.5	29	0.34	15%[1]
3 B eHP	*Strategy 1 for the portion of the neighbourhood for which insufficient (Z)LT heat is available*									
4 A	Hybrid heat pump	B+	Heat pump/AC	Gas boiler	15 – 70 °C	B+	4	34	1.3	-
4 B	Hybrid heat pump	D+	Heat pump/AC	Gas boiler	15 – 70 °C	D+	3.6	39	1.7	-

[1] The Startanalyse prescribes 10%. This value was transcribed incorrectly and noticed too late for adjustment. As a result, the savings on grid and back-up costs for a strategy shift to S3B are somewhat overestimated in this analysis.

Table 2. The four Startanalyse starting positions.

Startanalyse starting position	Description
PBL reference assumptions	The standard assumptions applied by PBL, see PBL (2025)
Expensive & scarce gas	The price of climate-neutral gas increases and availability decreases
Expensive electricity	The electricity price paid by the built environment for heat generation rises by an average of 50%
Insulation B+	Only heating strategies with building envelope label B+ are included, reflecting a situation in which autonomous insulation has led to this minimum label.

Table 3. Description of the heating strategy switches that get used as variants in this work.

Name	Switch	Description
Lowest national costs		This is the reference strategy, in which the heating strategy with the lowest national costs is selected for each neighbourhood. The exception is the hybrid heat pump, whose total deployment is also limited by the availability of green gas
More ground heat pumps	S1A → S1B	The air-water heat pump in neighbourhoods following strategy S1 is replaced by a ground heat pump. As local additional costs in most neighbourhoods exceed 20% above those of the air-water heat pump, all neighbourhoods with an air-water heat pump are switched to ground heat pumps.
More (Z)LT district heating	S1 → S3A	The air-water heat pump in neighbourhoods following strategy S1 is replaced by a (Z)LT district heating network with an individual heat pump. Only neighbourhoods where local additional costs are no more than 20% higher than for the air-water heat pump are switched.
More MT district heating, with central heat pump	S1 → S3B	The air-water heat pump in neighbourhoods following strategy S1 is replaced by an MT district heating network with a central heat pump. Only neighbourhoods where local additional costs are no more than 20% higher than for the air-water heat pump are switched.
More MT district heating, with central 'net neutral' heat pump	S1 → S3B*	Variant of S1 → S3B in which thermal storage and/or additional peak boilers are added, allowing the heat pump to operate in a theoretically grid-neutral and backup-neutral manner. Only neighbourhoods where local additional costs are no more than 20% higher than for the air-water heat pump are switched.
More MT district heating with geothermal	S1 → S2	The air-water heat pump in neighbourhoods following strategy S1 is replaced by an MT district heating network with geothermal energy. As local additional costs in most neighbourhoods exceed 20% above those of the air-water heat pump, all neighbourhoods with an air-water heat pump are switched to geothermal.

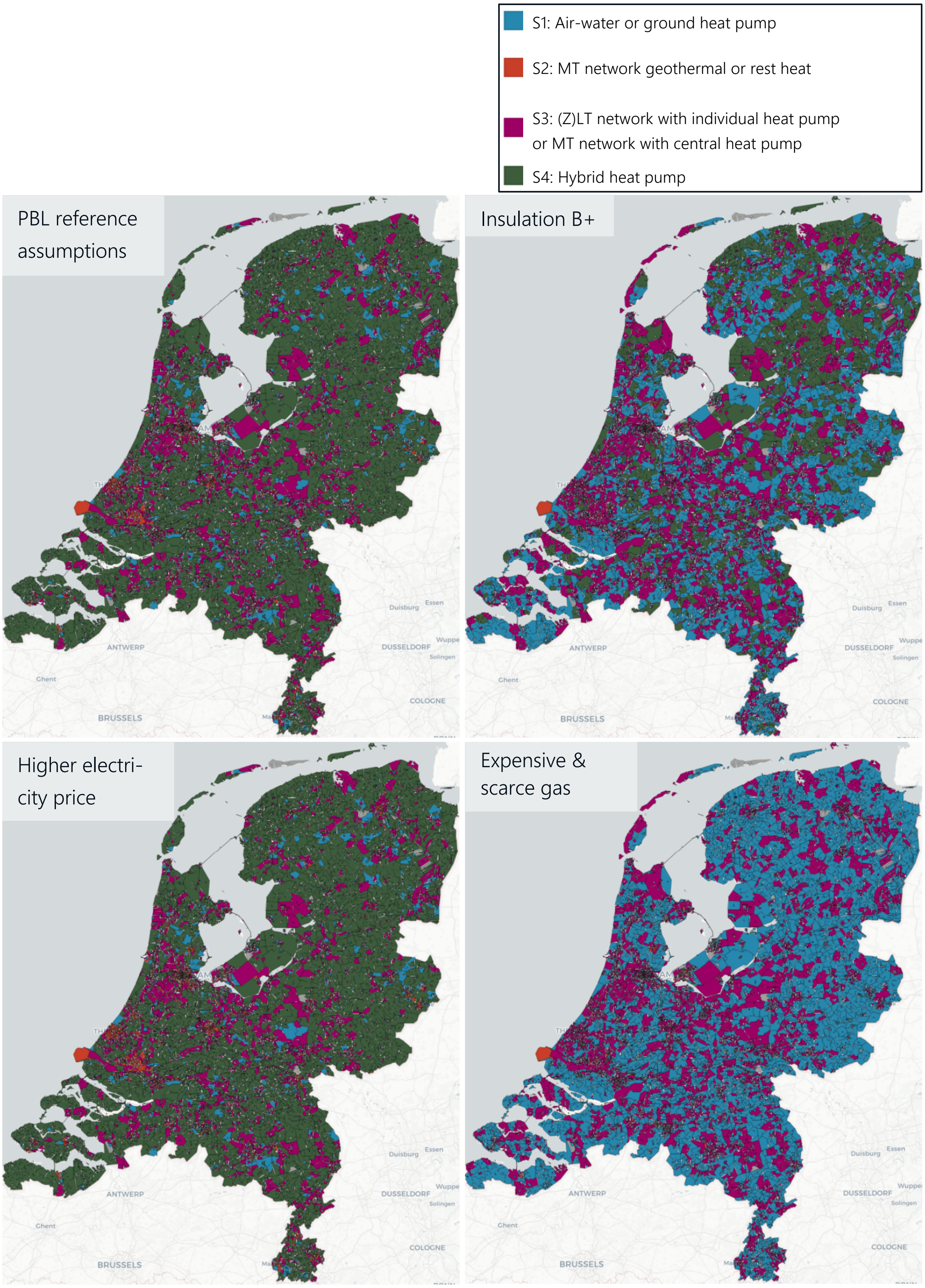


Figure 3. Spatial distribution of the selected heating strategy per neighbourhood for each calculation (based on Startanalyse data; for some neighbourhoods no Startanalyse data is available).

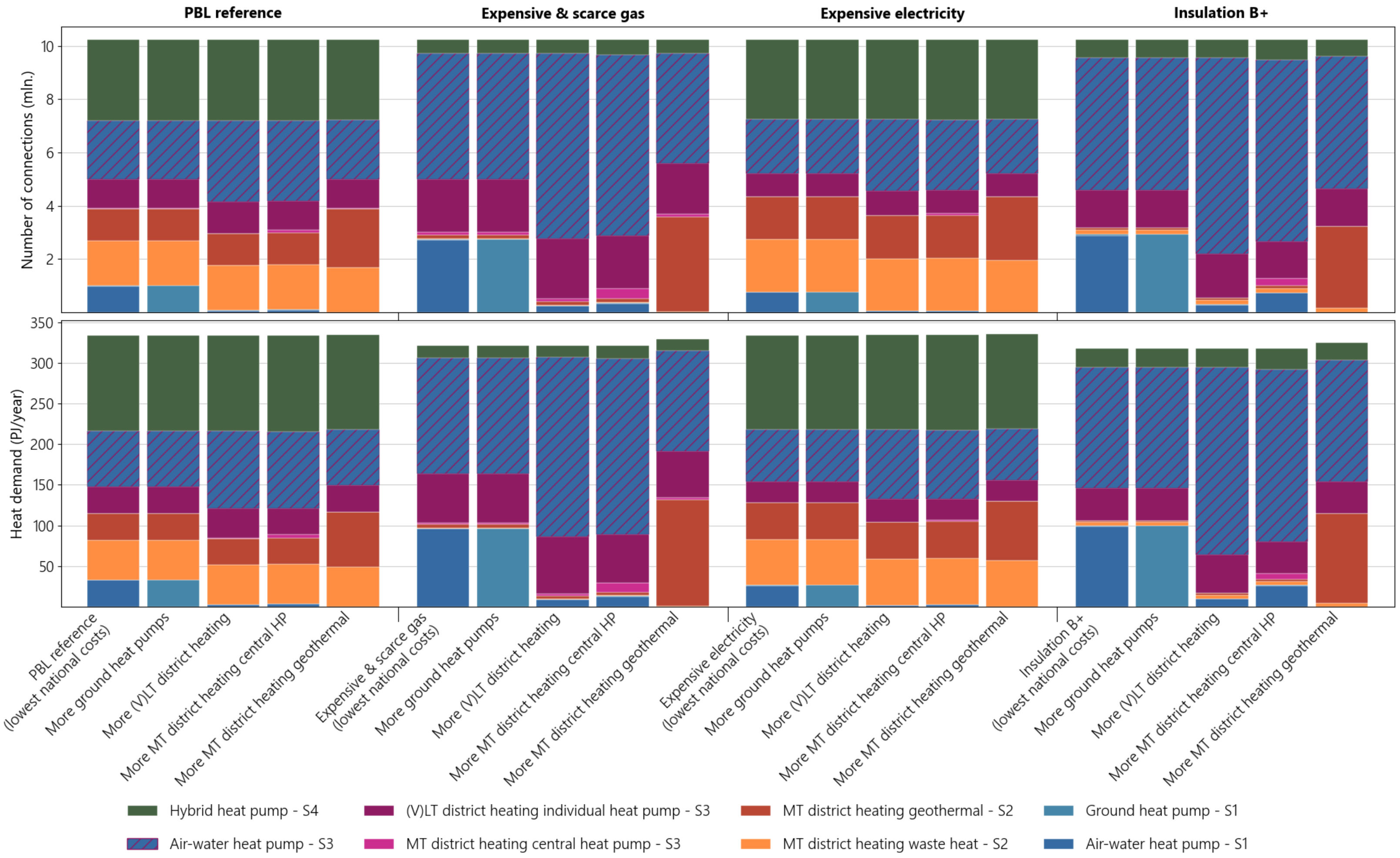


Figure 4. Annual heat demand and number of connections per heating technology for the different Startanalyse assumptions and for the various strategy switches.

3 Startanalyse mapping

We combine the NBNL scenarios with the Startanalyse starting positions and variants by mapping the Startanalyse data per neighbourhood onto ETM sliders on a national level. One of the main challenges is to figure out how the heating technologies (as defined by PBL: air-water or ground heat pump, different types of district heating and hybrid heat pump) are split over buildings and households (since PBL only specifies them per neighbourhood). Additionally, PBL technology terminology is mapped onto ETM input sliders. Finally, Startanalyse data is used for the regionalization of the heating related electricity demand of the built environment.

3.1 Summary

- For each neighborhood, we calculate the GJ/year/connection heat demand value per heating technology and per building type (households vs utilities).
- We sum these nationally to get a heat demand per heating technology / strategy combination.
- We map each unique strategy / heating technology combination to an ETM category. We also assign a COP to each unique strategy / heating technology combination and then obtain an average COP for that ETM category.
- We use the per neighbourhood values to calculate a relative share of each neighbourhood in the total demand of a certain ETM category. This will be used to regionalize the electricity curve of that category later.
- Additionally, we also obtain information about this specific variant / starting position situation, such as the number of household equivalent (weq) with each strategy / heating technology combination.

3.2 Data sources

- Startanalyse (PBL): https://startanalyse.pbl.nl/gemeentedata

3.3 Detail

The Startanalyse only reports on the heating technologies and total heat demand per neighbourhood, and thus, we need to calculate which part of this heat demand is fulfilled by which technology and whether it is supplied to households or utility buildings. To do so, we first split the assigned heating technologies between households and utilities. In a second step, we calculate the GJ/year/connection heat demand value for MT district heating and electric heat pumps per neighbourhood from the individual all electric heat pump (s1) and residual heat/geothermal heat district (s2) strategies. This is possible since these are calculated for each neighbourhood, although it may not correspond with the lowest national costs. This intermediate step is necessary because a neighbourhood can have up to three heating technologies, and this allows us to isolate the GJ/year/connection values of two common technologies. Finally, we use this to calculate the GJ/year/connection heat demand value per heating technology per neighbourhood for the chosen strategy in each neighbourhood.

Due to the Startanalyse data having integer values, we need to take into account uncertainty on the values to prevent negative values showing up sometimes. If this still happens, we enforce a minimum heat demand GJ/year/connection. While this is an inaccuracy, over the whole dataset, this isn’t much more than a few percent of the total.

We map these strategy / heating technology combinations to an ETM slider, and then we sum all the values nationally to obtain total demand for that slider and also calculate shares for each heating technology. For each neighbourhood, we track its relative importance each of the ETM sliders, which will allow us to regionalize the built environment heat demand later. We also store information about the number of home-equivalent (weq) that are in each strategy / technology, which will allow us to calculate the costs per weq.

For the COPs, we use the COP as defined in the Startanalyse for each heating technology for a specific strategy. However, for some technologies, we use alternative COPs, as already shown before in Table 1. We validate the choice of these COPs to see if the total demand changes as seen in the PBL data for a specific switch matches the total electricity demand change as obtain later via the ETM hourly demand curves.

4 ETM scenarios

The NBNL scenarios and processed Startanalyse data are combined within the ETM to generate the hourly demand curves required for the load flow calculations. Some parts of the NBNL scenarios are changed, a weather year is selected, and the built environment settings are replaced by the Startanalyse mapping, after which the hourly demand curves are exported. In addition, the inputs required for the backup tool are also saved at this stage.

4.1 Summary

- We start with a blank 2025.01 version ETM scenario
- We extract all scenario inputs from the NBNL scenarios, including slider settings, merit order settings and custom hourly supply and demand profiles. Except for the weather related profiles, such as renewable generation, heating and cooling profiles. These are based on the weather year 2012, which is a different weather year than is used by the ITM and backup tool.
- We create new cooling profiles for weather years 1987, 1997 and 2019 by reverse engineering the NBNL 2012 cooling profile. We do this because the cooling profiles in the 2025.01 version of the ETM are incorrect.
- We upload the slider settings and merit order settings, together with the NBNL profiles and external model coupling settings from the NBNL scenarios.
- We overwrite interconnection settings.
- We pick our weather year (1987/1997/2019).
- We match the ETM housing stock to the Startanalyse.
- We match the total heat demand of the Startanalyse by changing the kWh/m2 values in the ETM. We keep the ratio between them for different types of housing the same, but just scale them up/down together.
- We match the Startanalyse tap water demand by scaling the population in the ETM.
- We match the share of heat supplied by different heating technologies to match the previous Startanalyse calculation. We keep the merit order as modeled by the ETM in mind here.
- We repeat this same process for buildings, after the above was done for households.
- We also set the heat sources for the district heating networks, which also includes a decision on how much of the heat is sources from peak boilers.
- We also set the cooling demand of the built environment. We follow the NBNL assumption that 65% of cooling with be done by AC, the rest split using the ratios found for heating strategy.
- We also set the COP of the heating technology. For some strategies, this involves using the season COP (SCOP), which are then matched as closely as possible to the PBL data.

- After all this, we download the ETM hourly demand curves for further use and store slider settings for future use by the backup tool.

4.2 Data sources

- Energy Transition Model (ETM): https://2025-01.energytransitionmodel.com/

4.3 Detail

Netbeheer Nederland (NBNL) scenarios

Since the built environment does not operate as an energy island, a description of the overarching energy system is also required. Network load and the deployment of dispatchable backup capacity are determined by the distribution of electricity demand and supply – across both space and time – from all sectors combined.

The NBNL scenarios are used to describe the remainder of the energy system. These scenarios provide context for the total electricity demand from other sectors, the volume of renewable generation, and the availability of flexibility resources such as storage and dispatchable power plants. Table 4 presents an overview of the NBNL Scenarios 2025, with a brief description of each scenario.

Table 4. Scenarios available in the ETM used to describe the non-built environment portion of the energy system.

NBNL Scenarios 2025	Description
Koersvaste Middenweg (KM)	Follows the current policy trajectory. Strong, rapid electrification of end-use, supplemented by gas and hydrogen.
Eigen Vermogen (EV)	Maximum focus on energy autonomy. Strong growth in solar and wind, green hydrogen, and rapid electrification of industry and mobility. Strong government steering.
Gezamenlijke Balans (GB)	European cooperation takes centre stage. Hybrid decarbonization: electrification combined with gas (natural gas, green gas, blue hydrogen). Gas infrastructure remains important.
Horizon Aanvoer (HA)	Large-scale import of sustainable energy. Energy-intensive industry partially relocates abroad, low domestic consumption. Limited domestic generation, minimal government steering.

The original scenarios have been adjusted on several points for this study. The most significant adjustment concerns the heating and cooling choices for the built environment, which have been replaced by the settings from the Startanalyse. Concretely, the heating/cooling mix and insulation level in the ETM have been aligned with the Startanalyse. For the period 2025–2040, a gradual transition path is applied in which the heating/cooling mix shifts from the current situation towards the 2050 end-state described by the Startanalyse. The share of high-efficiency boilers in the scenarios is maintained throughout, with the remaining heating mix distributed proportionally based on the Startanalyse heating mix.

In addition, the weather-dependent demand and supply profiles from the NBNL scenarios (weather year 2012) have been replaced by the weather profiles available as standard in the ETM (weather years 1987, 1997, and 2019).

The annual electricity demand and installed capacities of the Netbeheer Nederland scenarios as adjusted by Kalavasta are shown in Figure 5.

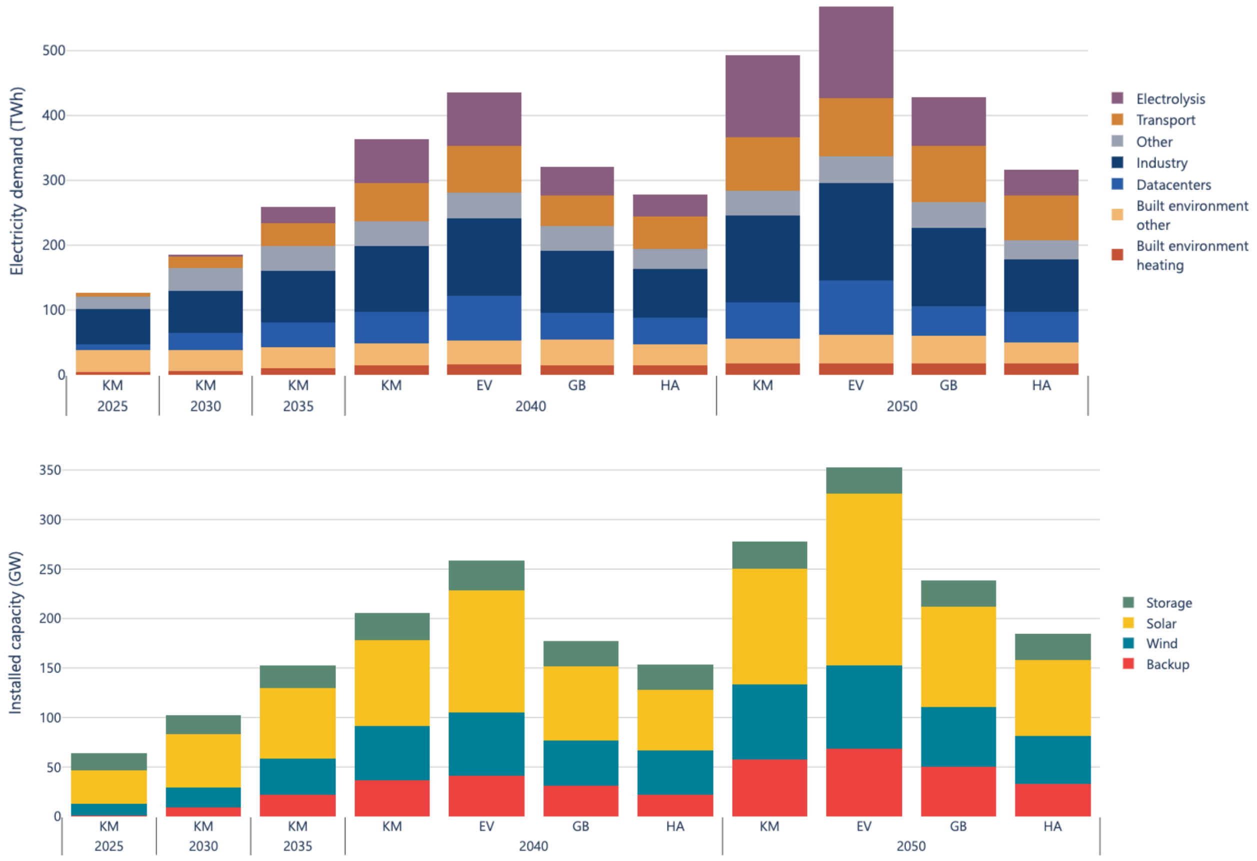


Figure 5: Electricity demand (top) and installed capacity (bottom) per adjusted NBNL scenario.

Interconnection settings

The Netbeheer Nederland (NBNL) scenarios include interconnection price and availability curves for several interconnectors, each representing interconnection capacity with a neighbouring country. These curves are derived from ENTSO-E TYNDP scenarios and rely on weather year 2012, which makes them unsuitable when other weather years are applied. Constructing new curves for alternative weather years proved impractical, and the interconnection modelling in the ETM does not adequately represent the functioning of actual electricity markets.

For these reasons, the interconnection settings have been adjusted when moving from weather year 2012 to 1987, 1997 and 2019. Export availability has been disabled entirely, while import availability is set to a fixed percentage that differs per interconnector, based on the TenneT Monitor Leveringszekerheid 2025. The import price profile has been replaced by a fixed electricity price of 500 EUR/MWh, ensuring that imports are only drawn upon during scarcity hours when domestic production capacity is insufficient.

Cooling profiles

Because we remove all weather related custom NBNL profiles, we need cooling profiles that correspond to 1987, 1997 and 2019 weather conditions. However, the native ETM cooling profiles are incorrect in the 2025.01 version of the ETM. Therefore, we reverse engineered the 2012 NBNL cooling profiles for houses and buildings, and created new cooling profiles for weather years 1987, 1997 and 2019.

Merging NBNL & Startanalyse

While the NBNL scenarios are saved within the ETM, due to technical reasons that don't allow us to change some parts of this saved scenario, we start with a blank 2025.01 ETM scenario and then reproduce a NBNL scenario by filling in all the values associated with the NBNL scenario. However, there are some parts that we leave out, such as the interconnection settings, the weather-related profiles, and the built environment settings.

After having reproduced the NBNL scenario, we start adding the Startanalyse values. First, we match the housing stock to the Startanalyse, both in number of houses, and in the heat demand of the houses. We achieve the heat demand match by tuning the kWh/m^2 values in the ETM. To do so, we scale all the kWh/m^2 by one value until the heat demand matches – we do not change the values of apartments relative to detached houses or new versus old homes. We also match the tap water demand by setting the population in the ETM.

Having matched the total demand, we move on to the heating technologies. Here, we need to set the share of houses with a certain heating technology, which is applied by the ETM via a merit order (with newest houses getting priority). Thus, we pick the share of houses with a certain heating technology so that we exactly match the heat demand supplied by that heating technology according to the Startanalyse. This whole process is done separately for houses & utility buildings. For district heating, we also set the heat sources to match the split between geothermal and rest heat from the Startanalyse. Here, we also take into account the percentage of peak boilers as shown in Table 1.

For cooling demand, we keep the NBNL assumptions in place. We also keep the NBNL share of ACs in place. The remaining cooling is done with air heat pumps with a COP similar to that of ACs, or ground heat pumps with a much higher COP. The share of ground heat pumps is based on the share of individual ground heat pumps and individual water-water heat pumps.

Finally, we also fill in the (seasonal) COP values that we have determined for each heating technology to match the Startanalyse, before saving the hourly electricity demand curves from the ETM.

A detail on COPs

Since the ETM does not allow the COP for tap water heating to be set explicitly, no adjustment is made for this parameter. As noted earlier, the total electricity demand is therefore checked against the Startanalyse to verify that it changes as expected. In addition, the electricity demand curves per home equivalent (weq) as obtained from the ETM are checked.

Weather years

Both heat demand and generation from solar, and wind is strongly dependent on weather conditions. Electricity infrastructure and backup provisions must, however, be dimensioned to meet demand even during extreme weather. The adjusted NBNL scenarios are therefore calculated under three different extreme weather years which are already present in the ETM:

- 1987: A year with cold winter weeks in January coinciding with a period of low wind and solar output (Dunkelflaute), and the fifth lowest number of sunshine hours recorded since 1901.
- 1997: A year with multiple low-wind periods during the heating season and cold days extending into spring and autumn.
- 2019: The year with the warmest heatwave ever recorded, during which the national heat record was broken on 25 July.

5 Regionalization

Based on the ETM scenarios that have been described earlier, national hourly electricity demand and supply profiles are generated. For the grid calculations, this national data is translated into local profiles and mapped onto the electricity grid.

5.1 Summary

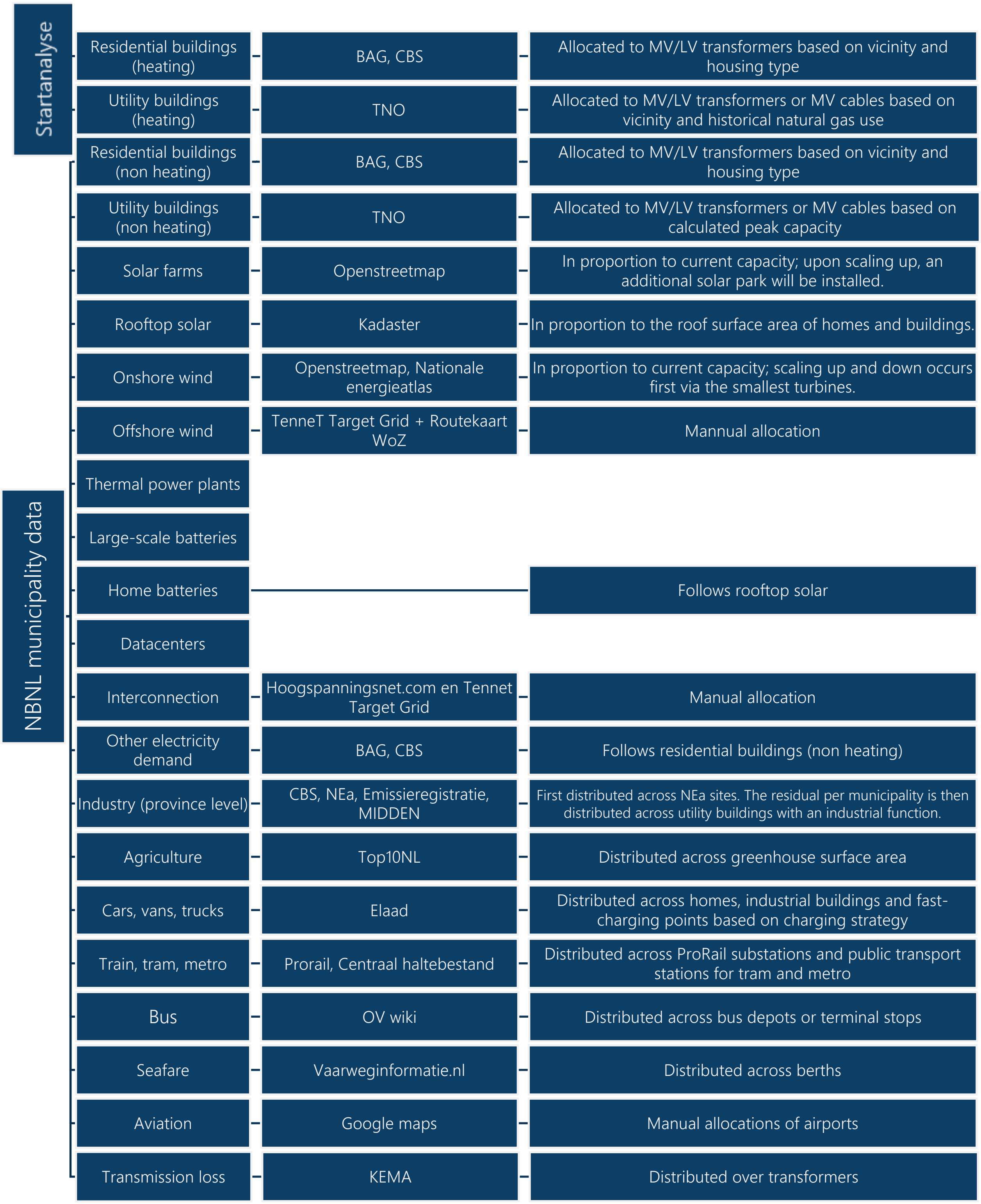
This regionalization happens in two steps: first to the municipal level using NBNL data and to neighbourhood level for Startanalyse data, then further regionalized within municipalities or neighbourhoods where needed. Various datasets are used for this. While many of these datasets are detailed enough to be used for regionalization on their own, they are only used here to distribute the NBNL demand and supply figures within each municipality. The datasets therefore act as distribution weights rather than absolute values.

The grid level connection to which consumers and suppliers are connected to, is determined by the peak power per consumer; the connection categories are shown in Table 5.

Figure 6 gives an overview of the datasets and approach per sector. The level of detail in each category depends on the data available for that sector. A detailed description per sector is provided in the sections below.

Table 5. Connection categories used for grid connection.

Grid Connection Type	Peak capacity
MV/LV station	< 0.3 MW
MV cable	0.3 - 3 MW
MV or IV side of a HV/MV or HV/IV station	3 - 80 MW
HV side of a HV/MV, HV/IV or EHV/HV station	80 - 800 MW
EHV side of an EHV/HV station	> 800 MW



Startanalyse	Residential buildings (heating)	BAG, CBS	Allocated to MV/LV transformers based on vicinity and housing type
	Utility buildings (heating)	TNO	Allocated to MV/LV transformers or MV cables based on vicinity and historical natural gas use
NBNL municipality data	Residential buildings (non heating)	BAG, CBS	Allocated to MV/LV transformers based on vicinity and housing type
	Utility buildings (non heating)	TNO	Allocated to MV/LV transformers or MV cables based on calculated peak capacity
	Solar farms	Openstreetmap	In proportion to current capacity; upon scaling up, an additional solar park will be installed.
	Rooftop solar	Kadaster	In proportion to the roof surface area of homes and buildings.
	Onshore wind	Openstreetmap, Nationale energieatlas	In proportion to current capacity; scaling up and down occurs first via the smallest turbines.
	Offshore wind	TenneT Target Grid + Routekaart WoZ	Mannual allocation
	Thermal power plants		
	Large-scale batteries		
	Home batteries		Follows rooftop solar
	Datacenters		
	Interconnection	Hoogspanningsnet.com en Tennet Target Grid	Manual allocation
	Other electricity demand	BAG, CBS	Follows residential buildings (non heating)
	Industry (province level)	CBS, NEa, Emissieregistratie, MIDDEN	First distributed across NEa sites. The residual per municipality is then distributed across utility buildings with an industrial function.
	Agriculture	Top10NL	Distributed across greenhouse surface area
	Cars, vans, trucks	Elaad	Distributed across homes, industrial buildings and fast-charging points based on charging strategy
	Train, tram, metro	Prorail, Centraal haltebestand	Distributed across ProRail substations and public transport stations for tram and metro
	Bus	OV wiki	Distributed across bus depots or terminal stops
	Seafare	Vaarweginformatie.nl	Distributed across berths
	Aviation	Google maps	Manual allocations of airports
	Transmission loss	KEMA	Distributed over transformers

Figure 6. Overview of regionalization data and brief description of methodologies per sector

5.2 Data sources

- Netbeheer Nederland (NBNL): https://www.netbeheernederland.nl/toekomstscenarios/regionale-scenarios-en-datasets-van-de-netbeheer-nederland-scenarios-editie-2025
- Basisregistratie Adressen en Gebouwen (BAG): https://www.pdok.nl/introductie/-/article/basisregistratie-adressen-en-gebouwen-ba-1
- Centraal Bureau de Statistiek (CBS): https://www.cbs.nl/en-gb/our-services/open-data
- PBL Startnalyse: https://startanalyse.pbl.nl/gemeentedata
- TNO: https://publications.tno.nl/publication/34641408/vsKfxB/TNO-2023-P10648.pdf
- OpenInfraMap: https://openinframap.org/#2/26/12
- OpenStreetMap: https://www.openstreetmap.org/#map=8/52.154/5.295
- Esri Netherlands ArcGIS: https://services.arcgis.com/nSZVuSZjHpEZZbRo/arcgis/rest/services/Windturbines/FeatureServer/0/query
- Basisregistratie Topografie (BRT): https://www.pdok.nl/introductie/-/article/basisregistratie-topografie-brt-topnl
- Nederlandse Emissieautoriteit (NEa): https://www.emissieautoriteit.nl/publicaties/ets-stationair
- Manufacturing Industry Decarbonisation Data Exchange Network (MIDDEN): https://www.pbl.nl/en/middenweb/the-database
- Elaad: https://outlook.elaad.nl
- ProRail ArcGIS Basiskaart: https://maps.prorail.nl/arcgis/rest/services/Energievoorzieningsysteem/FeatureServer/7/query
- Centraal Haltebestand (CHB): https://data.ndovloket.nl/haltes/
- Vaarweginformatie (Rijkswaterstaat): https://www.vaarweginformatie.nl/wfswms/dataservice/1.3/
- GTFS Nederland: https://gtfs.ovapi.nl/nl/gtfs-nl.zip
- OV Wiki: https://wiki.ovinnederland.nl/wiki/Overzicht_van_stallingen
- Onderzoek naar methodologie voor de verdeling van kosten van netverliezen (KEMA): https://zoek.officielebekendmakingen.nl/blg-114695.pdf
- Hoogspanningsnet.com: https://webkaart.hoogspanningsnet.com/index2.php#8
- Target Grid (TenneT): https://www.tennet.eu/nl/target-grid#kaart

5.3 Detail

Residential buildings

The electricity consumption of residential buildings excluding solar home systems, batteries, EVs, is broken down into two categories for regionalization: non-heat-related and heat-related electricity demand.

Non-heat-related electricity demand, covering appliances, lighting and other general consumption is spatially refined using two data sources. First, the BAG dataset, which provides geographical data on all residential buildings in the Netherlands, including the number of households per building ('verblijfsobjecten'). This is used to distribute demand within a municipality and connect buildings to their nearest appropriate transformer station.

The second accounts for the fact that electricity consumption varies by housing type. Two categories are distinguished: apartments and non-apartments. The relative consumption per category is derived from a CBS dataset on average electricity consumption by housing type in the Netherlands. These values are used as weights when distributing the NBNL municipality data, alongside the number of households per building and their geographic location.

Heat-related electricity demand is central to this study, as it varies depending on the starting position and heating strategy being examined. Its regionalization is therefore based on the PBL Startanalyse, which assigns a heating strategy and associated electricity demand to each neighbourhood. This is described in further detail in Section 2. There is also a CBS dataset on the average heat demand of apartment and non-apartment which is used as weights to distribute the PBL Startanalyse data among residential buildings within a neighbourhood.

Grid connection: All residential buildings are connected to the nearest MV/LV transformer station.

Utility buildings

Utility buildings encompass a broad range of non-residential, non-industrial buildings primarily in the service sector for example offices, shops, schools, or healthcare facilities. As with residential buildings, utility buildings are connected to the nearest transformer station or cable using a geographical approach.

However, rather than the standard BAG dataset, a refined version provided by TNO is used. This TNO dataset includes estimated electricity consumption values per utility building. Rather than being applied directly these estimates are used as weights to distribute the municipality-level NBNL demand data across individual utility buildings, allowing the electricity demand and connection capacity to be assessed at building level.

Heat-related electricity demand is central to this study, as it varies depending on the starting position and heating strategy being examined. Its regionalization is therefore based on the PBL Startanalyse, which assigns a heating strategy and associated electricity demand to each neighbourhood. This is described in further detail in Section 2. The TNO enriched data BAG provides data on the estimated gas consumption of utility buildings, which is used as a weight to distribute the PBL Startanalyse data among utility buildings within a neighbourhood.

Grid connection: The peak capacity of each building is calculated by combining heat-related, non-heat-related electricity demand, estimated rooftop solar generation, battery storage capacity and additional coupled demand such as EV chargers or industrial electricity use. Based on this calculated peak capacity, each building is then connected to the appropriate grid level.

Solar Farms

Solar farms already make-up a considerable portion of electricity production, but they are forecasted to grow in the future. There is available data on the location of currently active solar farms which were collected via OpenInfraMap and OpenStreetMap. Within each municipality the area of the solar park is used as weight when distributing the NBNL data. For future scenarios rather than guessing the location of future parks the existing parks are scaled up proportionately to match the NBNL municipality data.

Grid connection: The peak capacity of solar farms is calculated from their geographical area, and each solar farm connects to the grid at a voltage level for their specific capacity. Solar capacity allocated to a municipality without solar farms currently, MV/LV transformer and MV cable connections are excluded; only connections at MV or HV substation level or higher are permitted.

Rooftop solar

Rooftop solar generation is not included in the electricity demand of residential or utility buildings but is instead assigned in a separate step. This distribution is based on the ground area of the buildings, which can be found in the BAG data. The NBNL data provides separate rooftop solar generation values for residential and utility buildings. Within each category, generation is distributed equally across all rooftops for that category within the municipality.

Grid connection: Rooftop solar is coupled to the building it is installed on. Residential rooftop solar is therefore always connected to MV/LV transformer stations. For utility buildings, the grid connection level varies according to the calculated peak capacity of the building, as described above.

Onshore wind

The location and capacity of each onshore wind turbine in the Netherlands is retrieved from the ESRI Netherlands ArcGIS dataset. The dataset is filtered to include only turbines on land and inland waterways; offshore turbines are addressed in the following section.

To assign turbines to wind parks, OpenStreetMap is used as a complementary source. Individual turbine coordinates and associated wind farm boundaries are queried, and turbines located within a wind farm boundary are assigned to that park. Turbines that cannot be matched to a named park through OSM are subsequently clustered based on geographic proximity: turbines located sufficiently close to one another are grouped into a single synthetic park, while isolated turbines are retained as standalone units.

To match the NBNL onshore wind capacities per municipality, the installed capacity is adjusted depending on whether the scenario requires more or less capacity than is currently present. When the scenario capacity for a municipality exceeds the reference capacity, the smallest turbines are scaled up first, reflecting the practice of replacing older, small turbines with larger ones. When the scenario capacity for a municipality falls below the reference capacity, turbines are removed starting from the smallest, continuing until the required reduction is reached. For municipalities that currently host no turbines but have allocated capacity in the NBNL data, this capacity is distributed across the substation locations within the municipality.

Grid connection: The grid connection of a turbine depends on whether it is part of a wind park. Turbines within a park share a single connection point, located at the centroid of all turbines in that park. The grid connection type depends on the total wind park capacity. Standalone turbines connect individually, with the connection level determined by the turbine's capacity. For capacity newly allocated to municipalities without existing turbines, MV/LV transformer and MV cable connections are excluded; only connections at MV or HV substation level or higher are permitted.

Offshore wind

The offshore wind capacities in the NBNL dataset are specified at municipality level, where each municipality represents the location of the landing substation. Within each municipality, the capacity is assigned to exact landing points manually. These points correspond to the substation locations identified in current offshore wind landing plans and are stored with their exact coordinates.

Grid connection: The regionalisation assigns each landing location to the exact coordinates of the corresponding TenneT substation, to which the offshore cable connects.

Thermal power plants, large scale batteries and datacenters

This category covers a wide range of power plants, large scale batteries and datacentres. These sectors are regionalised only using the NBNL municipality data. Within each municipality these are simply distributed evenly among the relevant substations.

Grid connection: The municipality capacity from the NBNL data is used. However, grid connections to MV/LV transformers or MV cables are not allowed. Only direct connections to substations.

Home batteries

Batteries are generally installed alongside solar panels, therefore home batteries within municipalities are distributed based on the same logic as rooftop solar. The area of the building determines the amount of home battery capacity assigned which is deduced from the BAG data.

Grid connection: Home batteries are coupled to buildings, therefore in the case of residential building it is always distributed to MV/LV stations and for utility buildings it varies with the calculated capacity of the building (see above).

Interconnection

Interconnections are manually coupled to the substations where interconnection capacity is currently based on Hoogspanningsnet.com, or where this is planned based on Target Grid.

Grid connection: due to the high capacity per interconnection line, a connection is always made to a EHV station.

Industry

Within industrial demand the following industry categories are distinguished: steel, aluminium, other metals, refineries (also PtH), chemicals (also PtH), food (also PtH), paper (also PtH), industrial CHP methane, industrial CHP hydrogen.

NBNL data is not available per municipality but only per province. Regionalisation within each province is done using several steps:

- Current industrial electricity demand is regionalised to:
    - Large industrial sites based on the NEa emissions per site combined with electricity typical electricity demand per ton CO_2 emissions for the production processes at that specific site based on the MIDDEN database.
    - The remaining electricity demand per industrial sector is calculated by subtracting the electricity demand of large sites from the sector totals from the CBS energy balance. This is then regionalised to municipality level using another CBS dataset.
- Extra industrial electrification is regionalised to:
    - Large industrial sites based on the current NEa emissions
    - Additional electrification is assigned to steam crackers based on assumed electric cracking percentages per NBNL scenario
    - Smaller industrial sites are assigned based on residual emissions on a sector level. This is then regionalised to municipality level using CBS data.
- Smaller industrial sites are then regionalized within municipalities using the TNO enriched BAG dataset to utility buildings with function type “industry”.

Grid connection: Large consumers connect to the relevant grid level based on their calculated peak capacity. The residual consumption coupled to utility buildings is connected to the grid level based on the calculated peak capacity for that specific building, but the minimum connection type is an MV cable, meaning that MV/LV connections are upgraded to MV cable.

Agriculture

Electricity demand in agriculture is primarily associated with greenhouses, and also includes demand related to PtH (power-to-heat) and CHP (combined heat and power) installations. The geographical distribution of greenhouses is derived from the BRT dataset, which is used to connect agricultural demand to the nearest MV cable. Within each municipality, NBNL demand data is distributed across greenhouse facilities in proportion to their surface area.

Grid connection: The calculated peak capacity combining traditional, PtH and CHP electricity demand is based on area for agricultural consumers is also used to determine the grid connection level.

Mobility – Cars, Vans, Trucks

Mobility related electricity demand covering cars, trucks and vans is delivered through charging infrastructure. Several charging strategies are distinguished, including but not limited to home charging, workplace charging, public charging and fast charging. The share of each strategy varies by vehicle type and NBNL scenario.

To refine the spatial distribution beyond the municipality level, separate Elaad datasets are used for cars and for trucks and vans. These datasets forecast charging demand and the distribution of charger types per neighbourhood, enabling a more granular regionalization than the NBNL data alone provides.

Grid connection: Home and public chargers are distributed among MV/LV stations within the neighbourhood. Workplace chargers are coupled to utility buildings and are therefore connected to the electricity grid at the level appropriate to that building's calculated peak capacity. Fast chargers are connected directly to MV cables.

Mobility – Rail, Tram, Metro

Track-bound public transport is powered continuously via overhead lines for example. The task is to identify the points where these lines latch onto the electricity grid. For trains the connection is more explicit with fewer dedicated substations for this purpose, while for the other two the connection is more frequent sometimes even at stations. Therefore, the two categories are tackled separately, with specific datasets:

- Rail: From the ProRail ArcGIS FeatureServer, the location of substations are used to distribute the municipality level data evenly, which are then connected to the closest appropriate gride element. In a case of no available substation in a municipality where NBNL specifies consumption (for example future scenario), a consumer is placed in the centroid of the municipality bearing the specified load.
- Tram, Metro: Rather than designated substations, tram and metro lines are modeled to latch onto the electricity grid at stations. The CHB dataset was accessed via NDOV Loket and the geographic location of tram and metro stations are extracted. The consumption specified in the municipality NBNL data is distributed among all relevant stations in the municipality for trams and metros separately, and these stations are connected to the appropriate grid elements.

Grid connection: All track-bound public transport connection points occur on the MV cable.

Mobility – Bus

Electric buses are assumed to charge primarily at depots where they are parked overnight, and secondarily at terminal stops where fast charging is possible during layover time.

Depot locations are collected via OV Wiki. Terminal stops are identified from GTFS data by selecting the final stop of each trip.

In municipalities with depots, all capacity is allocated to the depots. In municipalities without depots but with terminal stops, the capacity is assigned to the terminal stops. Municipalities without any bus infrastructure receive the capacity at the municipal level.

Grid connection: For depots, the connection type depends on the peak capacity per depot. For terminal stops, the minimum connection type is an MV cable, meaning that MV/LV connections are upgraded to MV cable. For data regionalised to municipality level, MV/LV transformer and MV cable connections are not allowed and only connections to MV or IV substations or higher are allowed.

Shipping

Electricity used for shipping vessels is concentrated at berths in ports and along waterways. The regionalisation distributes the capacity across known berth locations.

Berths are retrieved via Vaarweginformatie. Per municipality, the NBNL capacity is distributed evenly across the berths.

Grid connection: The connection type depends on the peak capacity per berth, the minimum connection type is an MV cable, meaning that MV/LV connections are upgraded to MV cable.

Aviation

Electrification of aviation is concentrated at airports, where ground operations, ground power units and potentially future electric aircraft will require electricity.

NBNL municipality data is simply allocated to exact coordinates of five Dutch airports: Amsterdam Airport Schiphol, Rotterdam The Hague Airport, Eindhoven Airport, Maastricht Aachen Airport and Groningen Airport Eelde.

Grid connection: The connection type depends on the peak capacity.

Transmission Losses

Electricity transmission losses must be accounted for in the regionalization for two reasons. First, they are part of the ETM scenarios, and if skipped would result in a supply and demand imbalance. Second, the linear power flow method used to calculate power flows does not model network losses explicitly as explained in a later chapter. Transmission losses are therefore modelled as additional electricity consumption.

Table 6 shows the distribution of network losses per voltage level. Within each voltage level, losses are distributed evenly across all transformers.

Grid connection: Network losses are introduced to the grid at the appropriate transformer stations for each grid voltage level.

Table 6. Distribution of transmission loss among voltage levels (KEMA).

Voltage level	Loss Weight
EHV (extra high voltage)	0.09
HV (high voltage)	0.09
MV_IV (medium/intermediate voltage)	0.42
LV (low voltage)	0.4

6 Net data

We create a national power grid topology of all Dutch MV, IV, HV and EHV grids so we can connect all regionalized consumer and supplier load profiles to the correct location within the grid topology and then perform power flow calculations. Starting from public grid operator data from the regional grid operators and from TenneT, we create a net topology that describes all transformers and the connections between transformers, including cable length, number of parallel cables and the voltage level.

6.1 Summary

- We process the cable and transformer location data from each regional DSO and TenneT per net level (meaning, TenneT for EHV and HV – Liander, Stedin, and Westland Infra for IV – Liander, Stedin, Coteq, Enexis, and Westland Infra for MV) separately.
- We combine the smaller cable segments into cables that run from one transformer to another, add connections and junctions, and remove junk data. We add transformer locations and attach all cables to transformers. We remove cables that go from a transformer directly to a consumer or supplier instead of another transformer.
- We combine all these into one combined Dutch grid, still based on the geographical data.
- We remove 'islands', isolated pockets of cables, which are less than 0.1% of the total cables at this point, ensuring that we have a 100% connected grid.
- To this 100% connected grid, we attach the regionalized suppliers/consumers. Suppliers/consumers with large grid connections are attached directly to stations using artificial cables, while low capacity consumers get attached to the closest MV cable or MV/LV transformer.
- We abstract from the pure geographical data to a topology, remembering the voltage and length of the cables. In this step, we also check for parallel cables such as different phases of TenneT cables, resulting in an abstracted topology between stations, where each connection has voltage, number of parallel cables, and length information.
- We do not model any topological development of the grid in the future.
- The lowest voltage in our topology is 10 kV.

6.2 Data sources

The spatial data from each DSO.

Coteq: https://coteqnetbeheer.nl/open-data (2025 version)

Enexis: https://www.enexis.nl/over-ons/waar-staan-wij-voor/open-data (2026 version, requestable via form)

Liander: Liander via ArcGIS (Nov 2025 version)

Stedin: https://www.stedin.net/zakelijk/open-data/liggingsdata-kabels-en-leidingen (2025 version)

TenneT: TenneT Assets via ArcGIS (Feb 2026 version)

Westland Infra: https://westlandinfra.nl/over-westland-infra/duurzaamheid-innovaties/open-data/ligging-van-het-elektriciteitsnet/ (June 2025 version)

For validation:

Hoogspanningsnet.com map: https://webkaart.hoogspanningsnet.com/

Hoogspanningsnet.com topology maps: https://www.hoogspanningsnet.com/netschema/regionaal/

6.3 Detail

The regionalized electricity demand and supply profiles are connected to the network topology, for which a description of the electricity grid is required. This topology is built up in a number of steps:

1. Process cable and transformer locations from regional grid operators and TenneT separately per voltage level
2. Combine them to a national grid
3. Abstract the grid to a topology
4. Connect consumers/suppliers

Each of these steps will be discussed in more detail below.

General procedure per grid operator

This is repeated separately per voltage level (MV, IV, HV and EHV):

1. Load all the data. For Liander IV & TenneT also take above ground cables into account
2. Merge the tiny individual segments into big cables where it's obvious
3. Add the stations to the dataset by attaching them to cable endpoints
4. Add junctions
5. Clean out cables that don't contribute to the topology

Validation & Combination

The IV and TenneT datasets are validated separately against data from Hoogspanningsnet.com. After this, we combine all separate grids one Dutch grid. The resulting combined grid is shown in Figure 7.

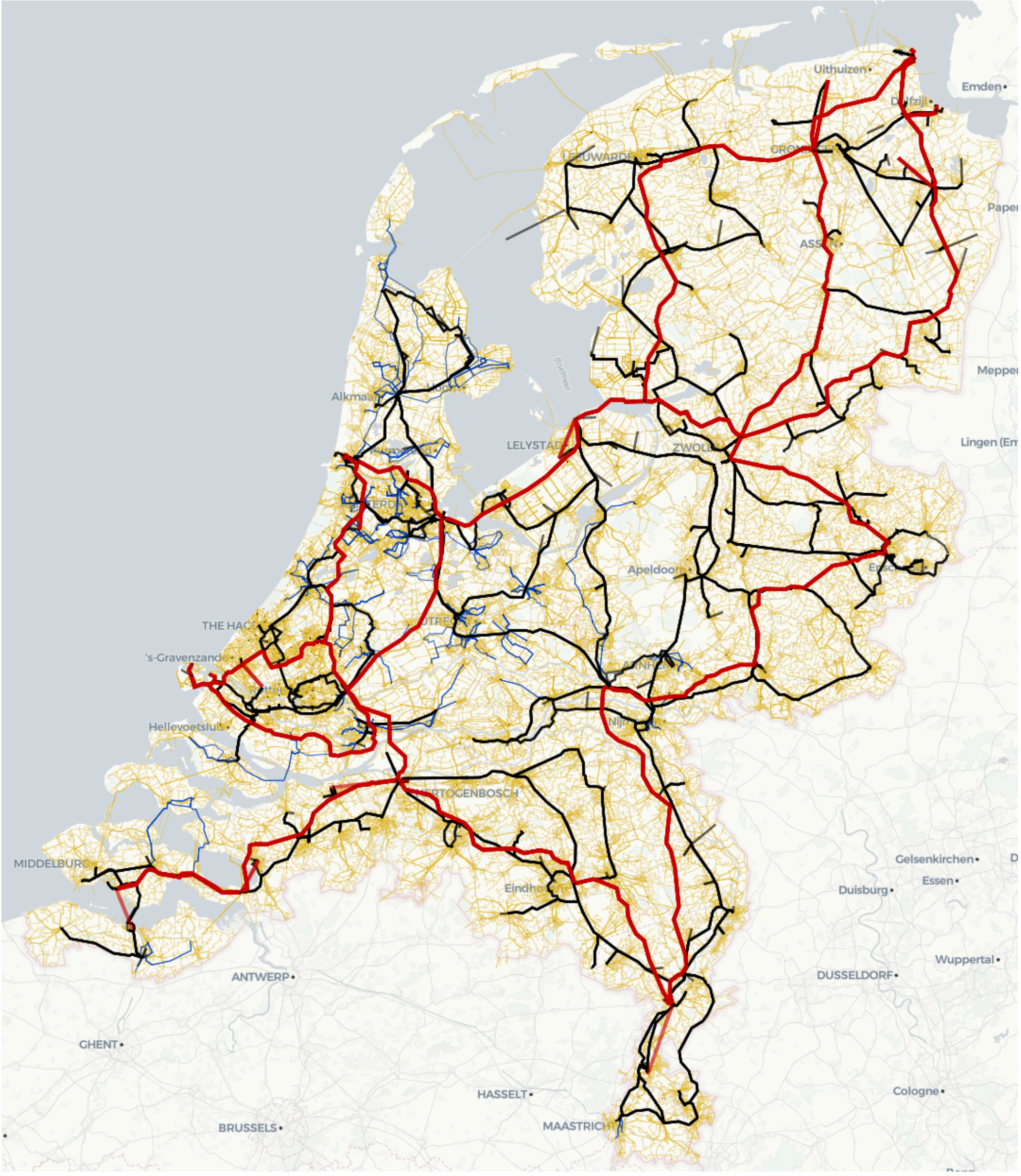


Figure 7. Cleaned location data of the EHV- (red), HV- (black), IV- (blue) en MV-nets (yellow).

Abstraction

We abstract this grid and then check for islands. Around 0.1% of the cables are in islands. We remove these for the next step, since we don't want our consumers/suppliers to be attached to islands.

The abstraction results in a network topology in which all connections are reduced to a set of core parameters: the two endpoint connections per cable (transformer or a junction), the voltage level, the length, and the number of parallel connections. This abstraction is performed after the combination step and the addition of consumers and suppliers described in the next section. Network development over time is not incorporated in the analysis. The figure below illustrates part of the MS-network of Almere as an example of the result.

Figure 8. Illustration of the resulting network topology for a part of Almere.

This abstraction step has two main advantages:

- It captures the true topology of the network without unnecessary complexities
- It allows us to simplify many cable connections (such as 6 1-phase TenneT cables) to a single connection. This doesn't just improve ease-of-use, validation efficiency, but also improves simulation speed in PyPSA

In this step, a lookup table is also created that identifies which cables must be upgraded jointly, referred to as the 'true cables'. This applies, for instance, to two cables linked by a bus at a consumer within an MV loop. Although these cables remain separate entities in the model, treating them independently would not reflect operational practice. The 'true cables' lookup therefore ensures that such cables share the same maximum load, as will be further specified below.

Consumer/supplier connection

Finally, we add the consumers/suppliers from the regionalization to the grid. Depending on their peak voltage, they get a dedicated artificial cable to a nearby transformer of the correct voltage level (depending on connection capacity) or are connected to MV cables or MV/LV transformers.

After this step, the grid is abstracted again, now with the consumer/suppliers added to it, and prepared for PyPSA. In this step, transformers are placed at for every bus that has multiple voltages, which only occurs at transformer stations in the topology.

7 PyPSA – power flow calculations

In this part of the ITM, all pieces come together, and we calculate the hourly load profiles of each individual cable and transformer. First, we take the power grid topology, with the consumers/suppliers attached to it, and use the hourly demand curves as obtained from the ETM and the regionalization to assign a load/supply to each individual location in our topology. Then, we use PyPSA for linear power flow calculations. Finally, we process this data to obtain the required capacities in terms of MW for transformers and MW·m for cables. These are then used to calculate national grid costs based on average €/MW or €/MW·m cost figures for transformers and cables respectively.

7.1 Summary

- From the regionalization, we have a share of each regionalized consumer/producer in a specific category. From the ETM, we have the hourly demand curve for those categories. Thus, we combine these to obtain hourly demand curves per regionalized consumer/producer.
- We place a 'slack bus' on the network, which is responsible for balancing the system. Since our system is already balanced, very little load falls to the slack bus, however, it has to be present for numerical reasons and allows for an explicit check of the regionalization.
- We run a linear power flow calculation to get the loads per station / cable per hour
- We find the peak load per cable / station for all the weather years. We also check if certain cables have to be upgraded together (such as the three phases of a TenneT HV cable), in which case we ensure they have the same peak.
- These values per cable / station are summed nationally to obtain MWm (for cables) values per net level and MW values for stations per net level. These are then converted to € to obtain a cost figure for net investments.

7.2 Data sources

None.

7.3 Detail

Based on the regionalization and the ETM hourly demand curves, we calculate an hourly demand/supply curve for each specific consumer/supplier, which can also be MV stations in the case of the built environment. Then, using the network topology described above, electricity flows are pushed through the network. These calculations are performed using the Python package PyPSA, an open-source and widely used tool for this type of analysis, applying a simplified linear power flow method. This approach offers the advantage of high computational speed and requires only a limited set of electrical parameters, though it also carries certain limitations, which are discussed later in this section.

To make the simulation work, one needs to add a 'slack bus' to the network. This slack bus gathers all the remaining imbalance in the system. Since the ETM hourly demand curves are inherently balanced, this can only be caused by missing consumers/suppliers from the regionalization. Thus, this slack bus is checked to ensure it is negligible and does not impact the simulation.

Each weather year is simulated using linear power flow separately, after which the results for 1987, 1997, and 2019 are combined to obtain a single highest peak load per network component. Where cables must be upgraded together as a set, the peak of the entire set is used. The outcome is an hourly load curve per cable and transformer, with the peak load across the three weather years determining the required capacity of each network component. Capacity is therefore an output of the model, not an input.

The results are then aggregated at the national level. For transformers, the peak load in MW is summed per category, defined by the upper and lower voltage levels of the transformer. For cables, the peak load is multiplied by the cable length to produce a total value in MW·m, which is then summed per category. These aggregated values are combined with unit cost figures – expressed in €/kW·m for cables and €/kW for transformers – to convert peak loads into investment costs. Cable costs thus reflect both load and length. Cost figures differ per voltage level, as shown in Table 7. Investment costs are summed per voltage level and subsequently converted to annualized costs.

Table 7. Unit cost figures for electricity infrastructure, applying a WACC of 2.25% in line with the Startanalyse.

	CAPEX	Typical capacity	After n-1 redundancy	OPEX[7]	Costs	Yearly costs
EHV/HV transformer	260 €/kW[1]			1,5 % CAPEX/year	260 €/kW	13,8 €/kW/year
HV/IV transformer	160 €/kW[1]			1,5 % CAPEX/year	160 €/kW	8,5 €/kW/year
HV/MV transformer	160 €/kW[1]			1,5 % CAPEX/year	160 €/kW	8,5 €/kW/year
IV/MV transformer	112 €/kW[2]			1,5 % CAPEX/year	112 €/kW	6,0 €/kW/year
EHS cable	7500 €/m[3]	√3 · 4,00 kA[7] · 380 kV = 2635 MVA	1845 MVA 70%[7]	1,0 % CAPEX/year	4,1 €/kW·km	0,2 €/kW·km/year
HS cable	3500 €/m[3]	√3 · 1,35 kA[7] · 150 kV = 350 MVA	250 MVA 70%[7]	0,5 % CAPEX/year	14,3 €/kW·km	0,6 €/kW·km/year
TS cable	650 €/m[3]	√3 · 0,785 kA[4] · 50 kV = 70 MVA	35 MVA 50%[7]	0,5 % CAPEX/year	19,1 €/kW·km	0,8 €/kW·km/year
MS cable	250 €/m[3]	√3 · 0,390 kA[5] · 10 kV = 7 MVA	3,5 MVA 50%[7]	0,5 % CAPEX/year	74,0 €/kW·km	3,2 €/kW·km/year
Discount rate	2,25%[6]					
Lifespan	40 jaar[7]					

[1] CE Delft (2024). Analysis and calculation of feed-in tariff

[2] Midpoint value from Netbeheer Nederland (2019), scaled by the HV/MV transformer cost different from CE Delft (2024)

[3] Midpoint value from 'Netbeheer Nederland (2019). Basisinformatie over energie-infrastructuur'

[4] 40/69 (72.5) kV Aluminium Conductor with Copper Wire Screen - trefoil formation https://www.alfanar.com/catalogs/cables_wires/HV_cables.pdf

[5] 6.35/11 (12) kV Three Core unarmoured aluminium conductors - 3x240 mm2 https://www.powerandcables.com/wp-content/uploads/2016/12/Nexans-6-33kV-Medium-High-Voltage-Underground-Power-Cables.pdf

[6] Same discount rates as used in the Startanalyse

[7] Assumptions

Cable & transformer types

To run the linear power flow calculation, you need to specify several properties of the cables and transformers. For cables, the only required property is the reactance per kilometre cable in Ω/km, representing the inductive impedance of a cable per unit length; multiplied by cable length to get total reactance. We assign this property based on a typical cable at this voltage level. For transformers, you must specify the short-circuit voltage (as a percentage of its voltage), which determines the transformer's reactance, and the nominal power in MVA, which is also used to calculate the reactance. Here, we assign the properties based on a typical transformer between the two voltage levels of the transformer. The properties assigned to the cables and transformers can be seen below in Table 8.

Table 8. Properties of cables & transformers used in the PyPSA calculations.

Voltage(s) (kV)	Reactance X (Ω/km)	Short-circuit voltage vsc (%)	Assumed nominal power for pu impedance base (MVA) – not enforced as a capacity limit in the ITM	Reasoning
380/220 transformer	-	14	1000	Based on TenneT Geertruidenberg
380/150 transformer	-	15	500	Based on TenneT Vierverlaten
380/110 transformer	-	12	315	Based on standard PyPSA values
380/10 transformer	-	16	63	Rare & estimated to fall in line with other values
220/110 transformer	-	12	400	Based on TenneT Meeden
220/10 transformer	-	14	63	Rare & estimated to fall in line with other values
150/50 transformer	-	12	200	Estimated based on Hoogspanningsnet numbers
150/25 transformer	-	12	160	Estimated based on Hoogspanningsnet numbers
150/20 transformer	-	12	100	Based on Phase-to-Phase numbers
150/10 transformer	-	12	66	Based on Phase-to-Phase numbers
110/20 transformer	-	11	80	Based on standard PyPSA values
110/10 transformer	-	10	63	Based on standard PyPSA values
50/25 transformer	-	8	63	Rare & estimated to fall in line with other values
50/20 transformer	-	8	63	Estimated based on Hoogspanningsnet numbers
50/10 transformer	-	10	40	Estimated based on Hoogspanningsnet numbers
25/10 transformer	-	8	25	Rare & estimated to fall in line with other values
20/10 transformer	-	4	25	Estimated to fall in line with other values
380 overhead line	0.26	-	-	Based on PyPSA HTLS 4-bundle 380.0
220 overhead line	0.301	-	-	Based on PyPSA Al/St 240/40 2-bundle 220.0
150 cable	0.11	-	-	Estimated based on TenneT 2500 mm^2 Al XLPE
110 cable	0.115	-	-	Estimated based on 1200 mm^2 Cu 110 kV cable specs
50 cable	0.1	-	-	Estimated based on typical ~500 mm^2 Al XLPE
25 cable	0.112	-	-	Based on PyPSA NA2XS2Y 1x240 RM/25 12/20 kV
20 cable	0.112	-	-	Based on PyPSA NA2XS2Y 1x240 RM/25 12/20 kV
10 cable	0.105	-	-	Based on PyPSA NA2XS2Y 1x240 RM/25 6/10 kV

On the use of linear power flow

In our simulations, we use linear power flow, as compared to non-linear power flow, for two main reasons:

1. We cannot run non-linear power flow due to a lack of data on the cables and transformers
2. But more importantly, linear power flow gives adequate results without overcomplicating the simulation.

This second statement deserves some more detail. The advantages of linear power flow (LPF) include that it is well suited to the 3x8760-hour simulations that we are running and that it typically can reach reasonable accuracies. However, LPF becomes weaker as you apply it to lower voltages. This has to do with three key assumptions that LPF depends on:

- The network should have a flat voltage profile, with no voltage drop.
- X should be much larger than R, which means that reactance should be larger than resistance. This is the case for HV lines, where X is often 3-10x larger than R.
- The angle between the voltage on different lines should be small.

The validity of these assumptions is questionable for a MV network, at 10 kV, as the resistive voltage drop can become ~5% and because the X/R can be near to 1.

However, given that this study is structured as a delta analysis, the implications of these limitations are mitigated. Although the absolute errors in the MV network are difficult to quantify precisely, they could plausibly range from 5% to 20%, particularly in meshed MV configurations. Such errors are largely structural and systematic in nature. For a given fixed topology, they remain broadly consistent, which means that when two cases with identical topology, but differing loading conditions are compared – as is the case for the variants considered here – these errors are expected to largely cancel out.

Load-dependent errors in the linear power flow (LPF) method may also occur. However, because the loading differences between the compared variants are relatively modest – only a portion of the built environment is adjusted, while the broader electricity system remains unchanged – the associated effects are expected to be limited.

On this basis, the application of the linear power flow method appears to be a reasonable approach within the scope of this study, given the constant topology across scenarios and the relatively small variation in loading between the comparison variants.

8 Backup tool

The backup tool is separate from the ITM, however, it is still explained in this documentation report, as it is part of the analysis chain to obtain the final results (grid costs and backup costs). The backup tool is always run immediately after obtaining the hourly electricity demand curve from the ETM.

Using the hourly electricity demand curve for a specific weather year and the known properties of the batteries for a specific NBNL scenario, the backup tool calculates the minimum required backup capacity, which is limited by a single most-extreme weather event.

8.1 Summary

- From the hourly demand curve, we calculate the residual demand that has to be filled using batteries or backup capacity (which for the purpose of the backup tool, includes interconnects).
- Using the hourly demand curves for the three weather years (1987, 1997 and 2019), we find a single value for backup capacity that ensures that demand is always met and batteries stay within their minimum and maximum state of charge.
- This is dictated by the most extreme weather event, often with a duration of several days in which the full backup capacity must be dispatched.

8.2 Data sources

Hourly supply and demand profiles from the ETM.

8.3 Detail

From the ETM hourly demand curves, we calculate the residual load (must-run electricity generation versus baseload demand) that has to be met using batteries or backup capacity.

The model applies perfect foresight to determine at which moments batteries would charge and discharge, with the aim of shaving the highest residual demand peaks. As long as higher residual demand coincides with higher electricity prices, this represents a realistic approximation of actual battery deployment. In this way, the minimum backup capacity required to cover the shaved portion of the demand curve can be determined. Battery charging is also modelled, so that two weather events in quick succession can in principle also become the limiting factor, though this was not observed for the 1987, 1997, or 2019 weather years. Since the model assumes perfect foresight, the calculated backup capacity should be regarded as a lower bound. However, as the analysis focuses on differences between scenarios rather than absolute values, this does not affect the conclusions.

An example is shown in Figure 9, which illustrates that a single weather event – in this case the period from 17 to 23 January in weather year 1987 – is the determining factor for the required backup capacity.

The required backup capacity is calculated for both an energy system using the heating strategy with the lowest national costs per neighbourhood and for a system in which a strategy switch has been applied. The difference in total backup capacity between this reference calculation and the strategy switch is then multiplied by the annual costs of backup capacity. For this a value of €1,350/kW is used, based on the all-in costs of an open-cycle gas turbine (OCGT), with an assumed lifetime of 25 years and fixed annual maintenance costs of 3% of CAPEX and a WACC of 2.25%.

In practice, backup needs are met by a combination of dispatchable generation, storage, demand response, and imports, all of which would be utilized to varying degrees in a well-functioning electricity market. However, marginal changes in backup requirements will largely translate into more or fewer peaking power plants. The cost of a gas turbine therefore serves as an appropriate and conservative unit cost figure for changes in backup capacity needs.

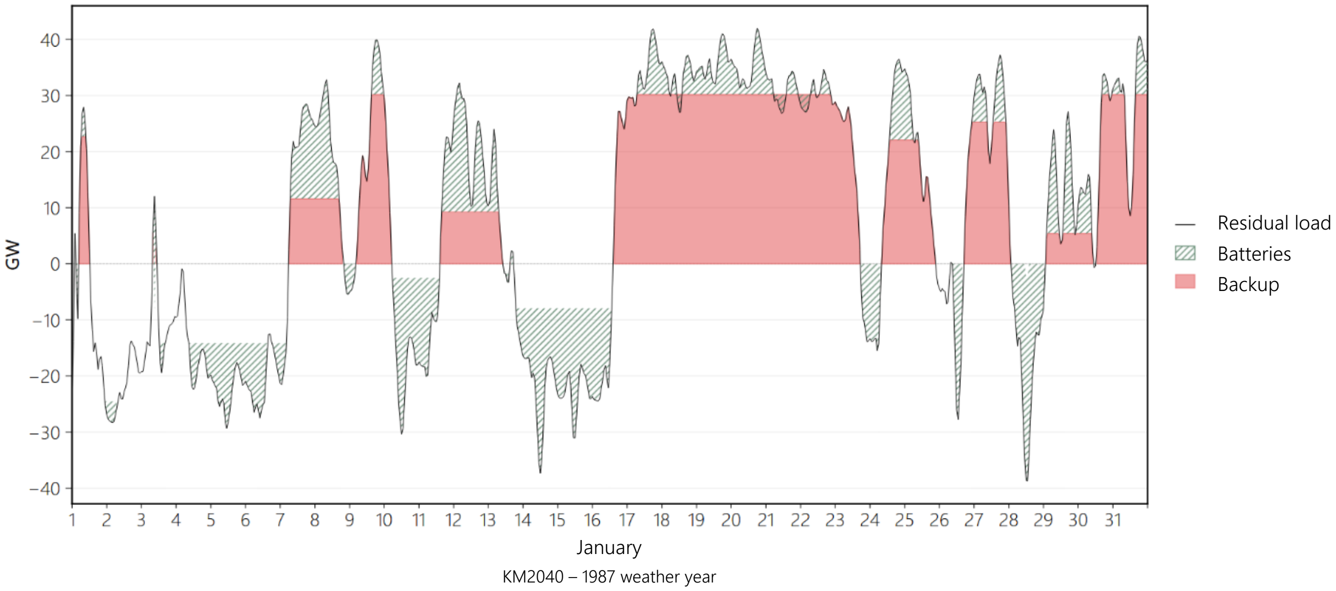


Figure 9. Example calculation of backup deployment in January, weather year 1987, for the KM2040 scenario.