Investment and Operation Co-Optimization of Integrating The Regional Plans of The Netherlands at High Spatial and Temporal Resolution

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Summary

Energy transition goals to reduce carbon emissions are a driver key for an increase share of variable renewable energy sources (vRES). To achieve 49% of CO_2 reduction by 2030 compared to 1990, the Netherlands set a plan to generate 84 TWh of electricity from renewable energy sources, where 35 TWh need to be generated exclusively from onshore renewable energy sources (large-scale solar PV and wind onshore). Since large renewable energy projects require inter-municipal decision-making rather than a decision-making at a local level, the Netherlands introduced an instrument called regional energy strategy (RES) in the climate agreement. RES consists of dividing the country into thirty regions, in where each region needs to identify the necessary installed capacity of vRES and storage units along with the necessary investments in the grid. So far, the energy regions set their vRES plans, where 26 TWh of electricity generation from large-scale solar PV and wind onshore is expected.

The regional transition entails many uncertainties. On one side, the electrification of different sectors such as industry and transport will lead to an increase in electricity demand. On the other side, the electricity grid has reached it's maximum capacity in some regions. Therefore, the vRES plans (large-scale solar PV) set by the energy regions might not be achieved as planned. Therefore, in order to implement the energy region's plans into the Dutch power system optimally, uncertainties in electricity supply and demand need to be taken into account.

The approach adopted in this thesis consists first of the modelling of the Dutch power system as a thirty-region power system reflecting both the electricity grid and the energy regions. Second, developing a high spatio-temporal resolution electricity supply and demand profiles. Third, creating different scenarios to capture uncertainty in electricity supply and demand, where a two-phase scenario planning is developed. Generation type and capacity uncertainty (achievement of 50% and 100% of large-scale planned solar PV projects by the energy regions) are presented in the first phase and the allocation of the installed capacities to segments of two different electricity load shapes (medium growth and high growth) as a second phase decision. Last, optimizing the investment costs in generation and transmission expansion with energy storage units under the different

scenarios.

The optimization problem is formulated as a two-stage optimization problem. In the first stage, the investment costs in energy storage units along with the transmission lines to incorporate the 26 TWh planned electricity generation are minimized under the different scenarios in electricity supply and demand. In the second stage, the outcomes of the first optimization problem (the required energy storage and transmission lines capacities) are used as input in the second optimization problem, where the investment costs in generation, transmission and storage units to meet the 35 TWh electricity generation are minimized under the same scenarios. The generation expansion consists of expanding the generation from large-scale solar PV and wind onshore from 26 TWh to 35 TWh.

The results of the first optimization problem show that under a medium growth of electricity demand, the target to reduce CO_2 emissions by 49% can be reached under the achievement of both 50% and 100% of planned large-scale solar PV. However, under a high growth of electricity demand, the national target to reduce CO_2 emissions by 49% by the achievement of 50% of large-scale solar PV is not reached. Both transmission lines (at different voltage levels) and storage units (battery and hydrogen) need to be expanded to incorporate the 26 TWh electricity generation. The best technology to generate the remaining 9 TWh according to the results of the second optimization problem is wind onshore. Moreover, the best location is Rotterdam-Den Haag region. As a result, the 35 TWh electricity generation can be integrated into the electricity grid in a cost-optimal way by using energy storage systems, flexible gas supply and the expansion of several transmission lines at the 380kV and 150kV voltage level. This work can be extended to explore other directions such as the variations of both CO_2 cap and price, the coupling to other sectors such as gas network and the interconnection between surrounding countries.

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List of Abbreviations

AC	Alternating Current
CARMA	Carbon Monitoring for Action
CBC	Coin-or Branch and Cut
CBS	Centraal Bureau voor de Statistiek
COROP	Coördinatiecommissie Regionaal Onderzoeksprogramma
DC	Direct Current
ECN	Energy Research Centre of the Netherlands
ED	Economic Dispatch
EHV	Extra High Voltage
ENTSO-E	European Network of Transmission System Operators for Electricity
ESS	Energy Storage Systems
ETM	Energy Transition Model
GEO	Global Energy Observatory
GLPK	GNU Linear Programming Kit
HESS	Hybrid Energy Storage Systems
HV	High Voltage
ICT	Information and Communications Technology
JRC	Joint Research Centre
KEA	Klimaat en Energieakkoord
KEV	Klimaat- en Energieverkenning
LMP	Locational Marginal Price
LOPF	Linear Optimal Power Flow
LP	Linear Programming
MV	Medium Voltage
NEV	Nationale Energieverkenning
NP RES	National Program Regional Energy Strategy
OPF	Optimal Power Flow
OPSD	Open Power System Data
OSM	OpenStreetMap
OWEZ	Windpark Egmond aan Zee
PBF	Protocolbuffer Binary Format
PBL	Netherlands Environmental Assessment Agency
PF	Power Flow
PME	Energy Saving Monitoring Protocol
PV	Photovoltaics
PyPSA	Python for Power System Analysis
RES	Regionale Enegie Strategie
RM	Reserve Margin
RVO	Rijksdienst voor Ondernemend Nede
TSOs	Transmission System Operators
SDE+	Stimulation of Sustainable Energy Transition
vRES	variable Renewable Energy Sources
WOL	Welvaart en Leefomgeving

1 Introduction

1.1 Objectives for a sustainable future

The share of renewable energy sources in the European energy mix is increasing due to a strong commitment and effective energy transition policies of member states [49]. This increase is expected to continue in order to achieve at least a reduction of 50% of CO_2 by 2030 compared to 1990 [81]. According to [42] renewable energy resources; namely large/small-scale photovoltaics (PV), wind onshore and offshore; accounts for 17.5% of the energy mix in 2017 and they are expected to reach 34% by 2030. The Netherlands set a goal of 14% of variable renewable energy sources (vRES) consumption share by 2020 under 2008 Energy and Climate package in contrast to 6.6% in 2017 [55]. The country noticed at early stage that these targets are unlikely to be achieved under the 2008 Energy and Climate package. Therefore, new policies were introduced to address the potential compliance gap and new targets were set [46].

A national climate and energy accord was announced by the national government in 2017, with a stronger energy ambitions. The target is to reduce emissions of greenhouse gases by almost 49% compared to 1990 [76]. The approach adopted in conceiving the climate energy accord follows the Trias Energetica theory of Duijvenstein [17], which consist of three main steps:

- Improving the energy efficiency in different sectors.
- Increasing the share of renewable energy sources.
- Using the remaining fossil fuels sources in a cleaner way.

These steps will contribute to reduce both electricity demand and emissions of greenhouse gases.

The total electricity production target by 2030 is set to 84 TWh in Klimaatakkoord [64]. 49 TWh need to be generated by wind offshore and 35 TWh by onshore energy resources (Figure 1.1). Regarding wind offshore, a 2030 Road-map is already set, where installed capacity, turbines specification and locations are defined. The 35 TWh need to be exclusively generated from wind onshore and large-scale solar PV (>15kW). Regarding small-scale solar PV (<15kW), a 7 TWh of electricity production is expected by 2030.

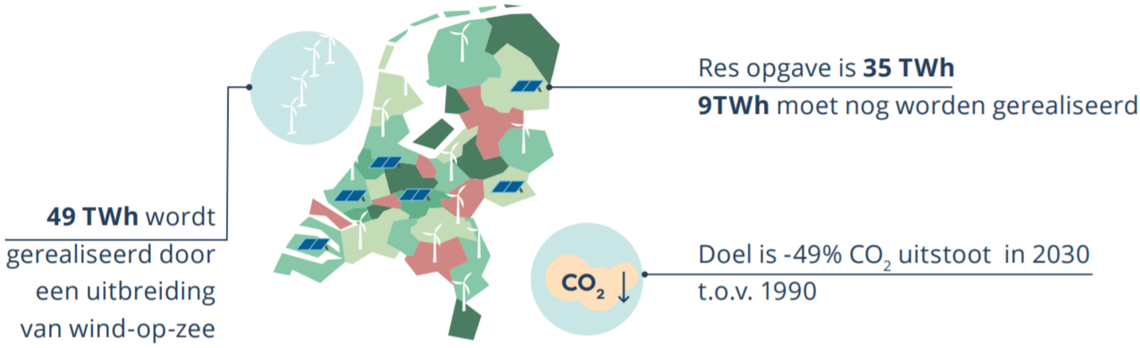

Figure 1.1: Renewable electricity generation targets by 2030 [64]

1.2 Strategy to define the energy regions

The introduction of large-scale onshore renewable energy technologies incorporates many challenges. On one hand, these projects are subject to social acceptance because different stakeholders will be affected by the placement of these production facilities [98]. On the other hand, when planning renewable energy projects locally "their cross-jurisdiction implications requires inter-municipal decision making" [37]. According to [37], the inter-municipal collaboration is necessary to avoid an unfair distribution of costs and benefits within local administrations, in where large sized municipalities with larger capacities and investment room harvest all the benefits. As a result, in order to make more deliberated decisions regarding the large-scale onshore technologies, Klimaatakoord presented a package of measures and instruments; with the active support of as many contributing parties as possible; to engage participation at regional level. The drafted instrument is called Regional Energy Strategy (RES), where the country is divided to thirty energy regions (Figure 1.2). Each region is represented by several stakeholders among others civil organization, business community, municipalities and water authorities [25].

Figure 1.2: Energy regions

1.3 Energy regions objectives

The objective of these regions is to deliver their strategy of energy transition such as the necessary renewable energy sources installed capacity and storage units, the location of the technologies and the needed infrastructure [76]. These strategies will be assessed on both feasibility and ambitiousness. Once the energy regions deliver their strategies, the Netherlands Environmental Assessment Agency (PBL) will add up the electricity production of each region. If the total sum of the electricity produced by the energy regions is not equal to 35 TWh, the remaining electricity production will be divided over the regions by the national government. However, the criteria for the division of the remaining 9 TWh are not set yet. A definite RES (RES 1.0) needs to be presented by each energy region the first of July 2021, after both the Netherlands Environmental Assessment Agency and the National Program Regional Energy Strategy (NP RES) have delivered their final analysis regarding RES-drafts presented the first of June 2020 (Figure 1.3) [25].

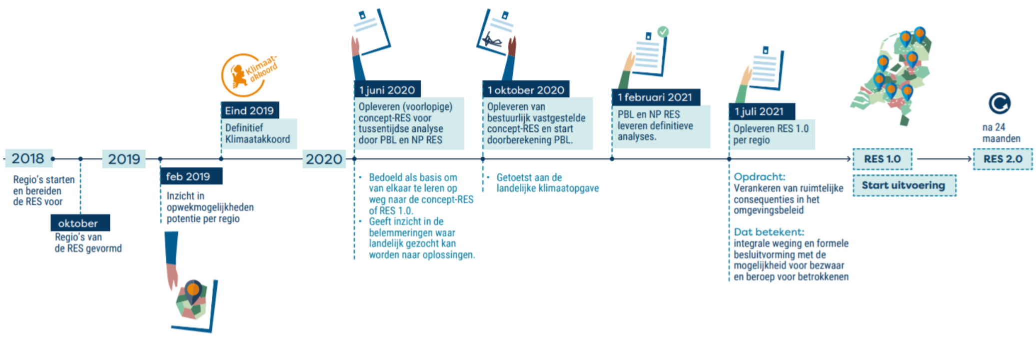

Figure 1.3: RES process [25]

While implementing the Regional Energy Strategy, there has been no clear picture of sustainable generation already realized and planned projects by each energy region [63]. Therefore, NP RES provided a factual and transparent picture of:

- Which part of the 35 TWh of electricity generation has been realized and planned by wind onshore and large-scale solar PV (> 15 kWp) projects.
- Which projects have been realized and planned for electricity generation from small-scale solar PV (< 15 kWp).

1.3.1 Large-scale solar PV and wind onshore

Large-scale projects for solar PV and wind onshore for the year 2030 are based on the Stimulation of Sustainable Energy Transition (SDE+) decisions [63]. These projects are translated into electricity generation in TWh per energy region based on the calculation rules used by the Central Agency for Statistics (CBS), PBL and the Netherlands Enterprise Agency (RVO) described in [63].

Both the current installed capacity in MW and the realized production in TWh of wind onshore are given by the Central Agency for Statistics in accordance with the EU Renewable Energy Directive (2009) [63]. At the beginning of 2019, 6.6 TWh electricity generation was achieved from wind onshore with a total installed capacity of 3400 MW [48]. Based on the methodologies drawn by PBL to determine the installed capacity of wind onshore per region, 17.7 TWh (Approximatively 7000 MW installed capacity) of electricity generation is expected by 2030 [63]. The installed capacity of solar PV (in MW) and production (in TWh) on the other hand were calculated by CBS using data from different organizations [63]. This approach makes it possible to very accurately determine the installed capacity (in MWp) per energy region. At the end of 2018, 1.5 TWh electricity generation was achieved from large-scale solar PV (>15 KWp) [48]. By 2030, 8.5 TWh (9450 MWp) electricity generation is expected.

It is difficult to consider all factors that influence the future realization of large-scale solar PV and onshore wind projects. Regarding wind onshore projects approximatively 95% of realization is expected (16.8 TWh) by 2030 due to their size and implementation period [63]. However, regarding large-scale solar PV projects, only 50% of the 8.5 TWh is assumed by 2030, since the limitations already applied for actual projects that cannot be connected to the electricity grid that reached its maximum capacity in some areas [63]. Figure 1.4 shows the production already achieved (until the end of 2018) and the expected electricity generation by 2030. Based on the realized production and the forecast projects, 26 TWh of onshore renewable energy is expected by large-scale solar PV and wind onshore in 2030.

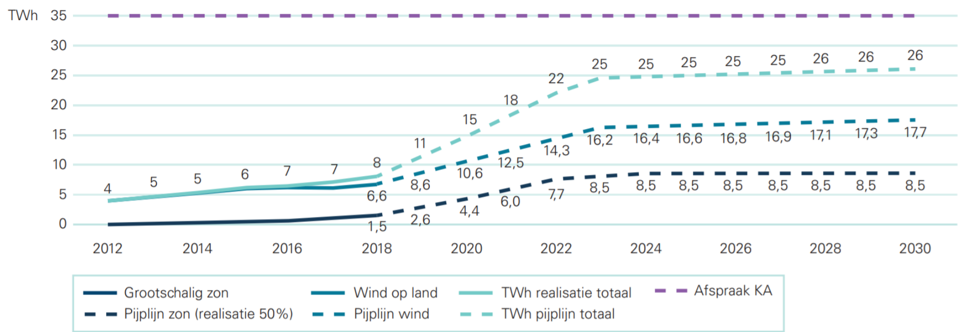

Figure 1.4: Wind onshore and large-scale solar PV electricity growth 2012-2030 [63]

1.3.2 Small-scale solar PV

In addition to the 35 TWh of electricity generation from large-scale renewable projects, 7.5 TWh of electricity generation from small-scale solar PV (solar roof) is estimated by 2030 based on CBS data. NP RES estimates that the electricity generation growth between 2016 and 2018 continue linearly till 2030 as shown in Figure 1.5.

At the end of 2018, a total installed capacity of 2300 MWp of solar PV (<15 KWp) in residential houses was achieved [48]. The expected installed capacity by 2030 is at least 8600 MW corresponding to 7.5 TWh of sustainable electricity generation [63]. According to [63], this is possible because currently only 4% of all roofs in the Netherlands are used. Figure 1.5 shows the expected growth for small-scale solar PV.

As a result, by 2030 the energy regions have as objectives: 16.8 TWh of electricity generation from wind onshore, at least 5.25 TWh of electricity generation from large-scale solar PV and an extra 7.5 TWh electricity generation from small-scale solar PV. Figure 1.6 gives an overview of the realized and expected electricity generation from large/small-scale solar PV and wind onshore by each energy region. Regarding large-scale solar PV, only

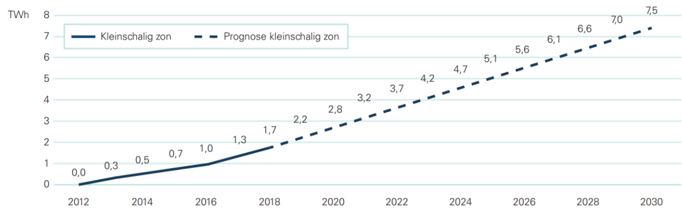

Figure 1.5: Small-scale solar PV expected electricity growth 2012-2030 [63]

50% of the electricity generation is displayed.

Huidige- en verwachte opwek per RES-regio (in TWh)	Grootschalig zon-pv			Wind op land			Kleinschalig zon-pv		
	Huidig 2018	Pijplijn 2030 (50%)	Totaal zon-pv groot	Huidig 2018	Pijplijn 2030	Totaal wind op land	Huidig 2018	Prognose 2030	Totaal zon-pv klein
Achterhoek	0,03	0,07	0,10	0,05	0,08	0,13	0,05	0,16	0,21
Alblasserwaard	0,01	0,04	0,05	0,02	0,01	0,03	0,01	0,02	0,02
Amersfoort	0,02	0,04	0,06	-	0,03	0,03	0,03	0,11	0,14
Arnhem / Nijmegen	0,03	0,13	0,16	0,03	0,14	0,17	0,07	0,26	0,33
Cleantech regio	0,02	0,10	0,12	0,01	0,02	0,03	0,04	0,13	0,16
Drechtsteden	0,01	0,08	0,09	0,02	0,05	0,06	0,02	0,05	0,07
Drenthe	0,08	0,39	0,47	0,04	0,77	0,81	0,10	0,32	0,42
Flevoland	0,09	0,19	0,27	2,22	1,71	3,92	0,05	0,18	0,23
Foodvalley	0,03	0,11	0,14	0,01	-	0,01	0,04	0,14	0,17
Friesland	0,10	0,25	0,36	0,43	1,61	2,04	0,09	0,37	0,46
Goeree-Overflakkee	0,02	0,02	0,05	0,15	0,48	0,63	0,01	0,03	0,03
Groningen	0,11	0,37	0,49	0,95	1,67	2,62	0,09	0,23	0,32
Hart van Brabant	0,04	0,15	0,19	0,04	0,16	0,21	0,04	0,13	0,17
Hoeksche Waard	0,00	0,04	0,05	0,10	0,08	0,18	0,01	0,02	0,03
Holland Rijnland	0,03	0,06	0,08	0,04	0,06	0,10	0,04	0,15	0,19
Metropoolregio Eind-hoven	0,08	0,20	0,29	0,02	0,12	0,15	0,08	0,32	0,41
Midden-Holland	0,01	0,06	0,07	0,02	0,01	0,03	0,02	0,07	0,08
Noord- en Mid-den-Limburg	0,07	0,18	0,25	0,02	0,22	0,24	0,09	0,29	0,38
Noord Holland Noord	0,08	0,13	0,21	0,37	1,22	1,59	0,09	0,27	0,36
Noord Holland Zuid	0,08	0,24	0,31	0,19	0,13	0,31	0,11	0,37	0,47
Noord Veluwe	0,01	0,02	0,03	0,00	0,05	0,05	0,02	0,07	0,09
Noord-Oost Brabant	0,07	0,13	0,20	0,00	0,09	0,09	0,07	0,25	0,32
Rivierenland	0,03	0,09	0,12	0,04	0,18	0,21	0,03	0,11	0,15
Rotterdam-Den Haag	0,07	0,14	0,20	0,48	1,14	1,61	0,11	0,35	0,46
Twente	0,05	0,20	0,26	-	-	-	0,07	0,19	0,26
U10/U16	0,05	0,06	0,11	0,06	0,07	0,13	0,08	0,25	0,33
West Overijssel	0,08	0,20	0,28	0,06	0,13	0,19	0,08	0,21	0,28
West-Brabant	0,05	0,18	0,23	0,29	0,61	0,90	0,06	0,20	0,26
Zeeland	0,08	0,15	0,22	0,93	0,22	1,15	0,07	0,20	0,27
Zuid-Limburg	0,02	0,14	0,16	0,00	0,02	0,02	0,09	0,33	0,42
Totaal	1,46	4,17	5,63	6,58	11,08	17,65	1,74	5,75	7,50

Figure 1.6: Planned & realized projects for electricity generation from large/small-scale solar PV and wind onshore per energy regions in TWh [63]

1.4 Challenges in the energy transition

To ensure a successful energy transition, the renewable energy planned projects need to be fully integrated into the electricity grid. However, the high integration of renewable energy sources (wind and solar) into the electricity grid entails many challenges. The stochastic and intermittent behavior of vRES poses several problems to the electricity grid operator, among others, grid imbalance in terms of supply and demand.

1.4.1 Electricity demand

By 2030, the Dutch electricity demand is expected to increase. However, this increase can take different shapes. In [88], three different scenarios (KA30, AT30 and FSI30) are presented, where the electricity demand is divided into different sectors: transport, industry, services, households and other (Figure 1.7). All scenarios have relatively a stable growth of electricity demand in the different sectors compared to the year 2020 (KA20). However, the electrification of transport sector and the development of power to gas/heat and heat pumps would lead to different growth within the different scenarios. The use of power to gas/heat and heat pump will increase the electricity demand respectively in industry, services and households sectors.

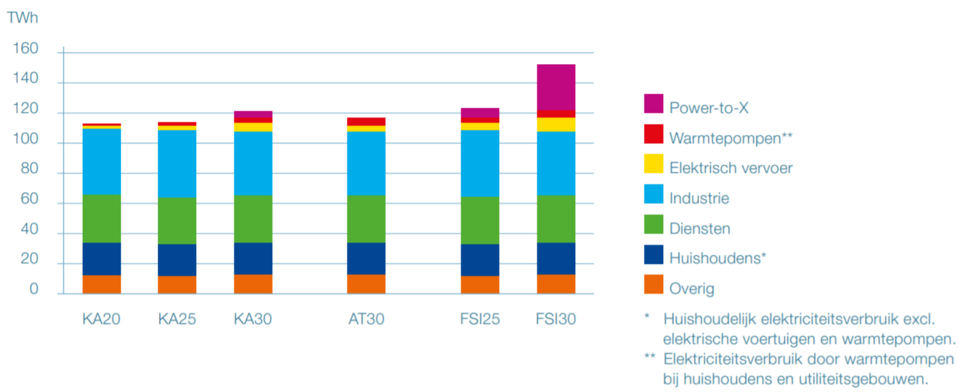

Figure 1.7: Development of the Dutch electricity demand by 2030 [88]

1.4.2 Electricity supply & peak demand

By 2030, the Dutch electricity supply is expected to have different evolution as well. The Energy Research Centre of the Netherlands (ECN) together with Alliander analysed the Dutch electricity security of supply by 2030 based on the reserve margin (RM) [93]. RM can be defined as the difference between the available and reliable production capacity and the peak demand in a year. In this study renewable energy installed capacities are not considered as reliable.

To capture the uncertainty in electricity supply from fossil fuel resources, two scenarios are considered for the year 2030 (KAS-basis and KAS-alternatief). The results of this study shows (Figure 1.8):

- For the year 2017 (NEV 2017), the RM is small because the Dutch electricity system was based mainly on fossil fuel resources.
- For the year 2030, the RM is too large compared to the year 2017. On one side, the electrification of the energy demand will result in a higher electricity peak. On the other side, phasing out coal and reducing the use of gas power plants will lead to a significant decrease in the reliable installed capacity.

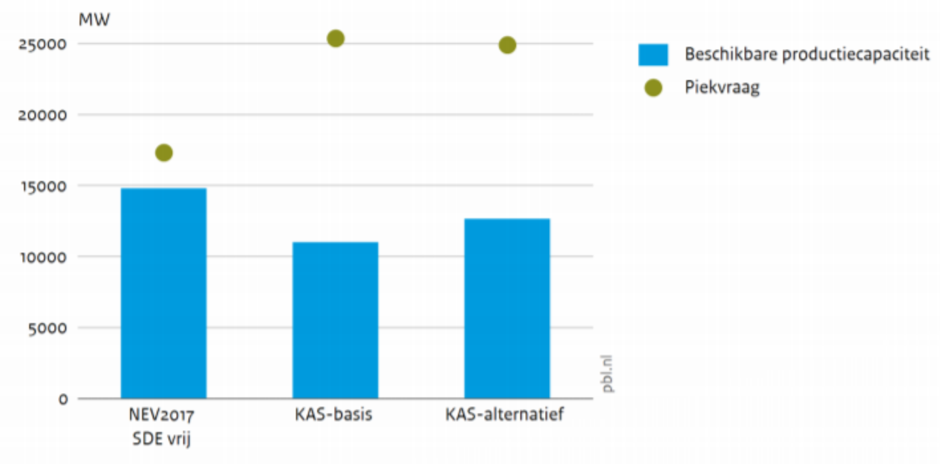

Figure 1.8: Available production capacity in the Netherlands in relation to peak demand in 2030 [93]

As a result, maintaining the production/consumption balance will become a very challenging task to the grid operator with the integration of vRES. First, the electricity demand can have different growth shapes, due to the use of heat pumps, the conversion of power to heat/gas and the electrification of transport sector. Second, fossil fuel installed capacity is expected to decrease significantly. This decrease can have different forms, since no decisive policy is defined yet. Last, the peak electricity demand is expected to increase due to additional electrification that is assumed to not be flexible.

1.5 Problem statement

So far only 26 TWh of large-scale solar PV and wind onshore electricity generation is planned within the energy regions for 2030. To optimally integrate this electricity production into the grid, the energy regions need to define the necessary storage capacities along with their locations. However, the uncertainty prevailing the Dutch electricity system in terms of supply and demand for 2030 might lead to an over-investment or under-investment problem. Moreover, the increase in peak demand might cause overloading of the transmission lines, which might require reinforcement of the transmission grid. Therefore, the goals of this thesis are:

- To find out the necessary installed capacity and location of storage units along with the necessary transmission expansion to adequately accommodate the 26 TWh of electricity generation from large-scale solar PV and wind onshore under uncertainty in supply and demand in a cost optimal way.
- To determine the least-cost investment in large-scale solar PV and wind onshore to meet the 35 TWh electricity generation under uncertainty, while incorporating the 26 TWh regional plans.

The incorporation of these uncertainties in power expansion planning can be done using stochastic programming [99]. The most common technique for solving the stochastic optimization problems is the formulation of its deterministic equivalent which can be done through scenario construction [99]. According to [47], analyzing the power system using different scenarios allow energy system modelers achieving their objectives in deriving robust trends. Moreover, by considering different scenarios, the real world complexity can be decreased to develop power system models that can be solved within appropriate computation time. Therefore, different deterministic scenarios will be constructed to capture the different evolution the Dutch electricity supply and demand can follow for the year 2030.

The following research question therefore is formulated to pursue this problem statement: **Given multiple scenarios in the Dutch electricity supply and demand, what is the cost-optimal power system expansion considering energy storage systems to incorporate the regional plans by 2030?**

To answer this question, several sub-questions are formulated:

1. Which components are important to model the current power system ?
2. How to model the Dutch electricity power system ?
3. How to model different scenarios in electricity supply and demand ?

4. What types of energy storage systems can be used and how can they be modelled ?
5. What is the cost-optimal investment in energy storage and transmission lines to accommodate the 26 TWh regional plans by 2030 under uncertainty ?
6. What is the cost-optimal power system expansion to meet the extra 9 TWh electricity generation from large-scale solar PV and wind onshore?

1.6 Relevance

1.6.1 Scientific relevance

The scientific relevance of this thesis is the modelling of the Dutch electricity demand at high spatial-temporal resolution. In order to analyse the energy system (e.g. on an hourly basis), high temporal and spatial demand profiles that describe the fluctuations of electricity demand in a specific area are needed [94]. In literature, the modelling of the Dutch electricity demand is performed in low granularity. In [9], only temporal demand variations are considered based on the mean and peak consumption. [96] adopted a high spatial approach to model the electricity demand for different regions by scaling down the national electricity demand. However, the scaling of the national electricity demand to regional electricity demand was based solely on the population in each region. [8] regionalized the Netherlands into four different regions. However, no information was given on how the electricity demand was distributed within the regions. In this thesis, high spatio-temporal demand profiles will be developed and used to model the Dutch electricity demand (the approach is described in detail in Chapter 4).

1.6.2 Societal relevance

The over/under-investments that might result from imperfect power system expansion with energy storage underline the social relevance of this thesis.
The 35 TWh electricity generation from large-scale solar PV and wind onshore requires enormous investments, namely in storage units, power lines and power generation. Through assessing the uncertainty in both electricity supply and demand in the energy transition of the Netherlands, the energy regions along with the Transmission system operators (TSOs) will be able to ameliorate their investment strategies and minimize the risk of inadequate

investments (over/under-investment).

- An over-investment in transmission capacities will lead to a negative impact on the TSO, since the regulatory framework penalizes any over-investment. Moreover, over-investment in generation capacities will result in a sub-optimal allocation of economic resources.
- An under-investment in transmission capacities will lead to congestion problems. Moreover, planned renewable projects won't be able to connect to the grid. In addition, under-investment in renewable power generation might lead to problems regarding security of supply and more use of fossil fuel resources.

The development of spatio-temporal demand profiles to forecast electricity demand and the use of the actual regional plans of electricity generation from renewable energy sources will help to model the electricity supply and demand of the year 2030 in a realistic way. Therefore, uncertainty in electricity supply and demand is better captured in the power system expansion decision-making process. As a result, network investments can be optimized under uncertainty and thereby long-term investment strategies can be formulated that are able to adapt as the future unfolds.

1.7 Research methods

The research methods chosen for this thesis are a combination of qualitative and quantitative approaches. The combination of different methods is essential to solve socio-technical problems.

- Desk research:
  To address the first and fourth research question, desk research is performed in the form of literature review, where relevant literature regarding power system expansion with storage units was reviewed. Therefore, the important components of the power system were identified together with the different types of storage units.
- Modelling and simulation:
  After the components of the power system are defined, a modelling and simulation method is used, which enables the analysis and the design of complex systems [92].

In this thesis, the modelling and simulation method is used to model the Dutch power system components and run several experiments to analyze the performance of the power system under different scenarios.

- Scenario Analysis:
  This method is defined as the process to analyse future events by considering different possible outcomes [4]. To answer the third research question scenario analysis is applied, where different scenarios are considered to capture uncertainty in electricity supply and demand.
- Linear Programming (LP):
  Linear programming is used to perform the Optimal Power Flow (OPF). The OPF is considered as the primary tool used to model the operation of electrical power networks [71]. OPF will be used to address the fifth and sixth research question, where generation, transmission and storage units expansion costs are optimized.

1.8 Outline

In Chapter 2, a literature review to define the research gap is performed. The methodology is presented in Chapter 3. Chapter 4 is divided into two main parts: "Pre-processing of data" and "Modeling of the power system components". In Chapter 5, Pypsa model is presented along with the mathematical formulation of the optimization problem. In Chapter 6, the scenario chart is presented, in which scenarios are defined. The results of the regional and national targets are presented respectively in Chapter 7 and Chapter 8. In Chapter 9 and Chapter 10, the discussion and the conclusion are provided respectively.

2 Literature review

In this chapter, a literature review is performed to first determine the most adequate models to model the Dutch power system components. Second, to define the most appropriate method to optimize the expansion of the Dutch power system. Last, to identify the research gap.

2.1 Modelling the Dutch electricity grid

The electricity grid incorporates different components. Based on the model chosen, the components require different input data. In this section, the different models, components and input data are identified. Moreover, a discussion regarding data availability is carried out.

2.1.1 Grid models

Modelling the power system requires energy system models that are conceptualized using both theoretical and analytical methods [56]. The models involve "modelling the electricity grid in a suitable manner using grid models" [31]. These models have several applications, among others, modelling, optimisation and extension of the electrical grids using different scenarios [30]. Therefore, [56] clustered the objectives of grid models into two main categories:

- The analysis of the technical and physical behaviour of the electrical grid.
- The planing, extension of the electricity systems and the management of the electricity supply and demand.

Besides the optimization of the expansion of the Dutch electricity system, an analysis regarding the loading on the power lines connecting the energy regions will be performed (see Chapter 3). Lines loading will give insights regarding the most loaded lines after expending the electricity power system. Therefore, in this thesis the model chosen will be used for the analysis of the technical behaviour of the electricity grid along with its extension. Grid models are categorized into different types [31]:

- Single-node models that assume "an unconstrained electrical grid and mostly used in economical models".

- Transshipment models, where exchange power is possible between different regions or nodes. In this model the physical power flow principles are not supported only the net transfer capacity between the regions.
- Direct current (DC) models, where "a network of various nodes and power lines is established. In this model the active power flows can be determined based on both the resistance and the maximal capacity of the power line, following Kirchhoff's law".
- Alternating current (AC) models, where both active and reactive power are modelled.

AC models are considered as the most realistic way to model AC grids. However, they require the most input data [11]:

- Buses: Nominal voltage, coordinates (longitude, latitude), carrier (AC/DC), voltage magnitude.
- Generators: Nominal power, P,Q,V control strategy, active/reactive power, carrier (e.g. coal, gas, wind, solar).
- Power lines: Series reactance, series resistance, shunt conductivity, shunt susceptance, limit of apparent power, length of line.
- Transformers: Series reactance, series resistance, shunt conductivity, shunt susceptance, limit of apparent power.
- Load: Active/reactive power, power sign.
- Storage units: P,Q,V control strategy, nominal power, active/reactive power, carrier (e.g. battery, hydrogen), state of charge, maximum state of charge capacity, efficiency of storage, efficiency of dispatch.

The increase of details and accuracy in AC grids is accompanied with an increased complexity, which results in longer simulation time [56]. Therefore, for extending the system, managing the electricity supply and demand and planning long-term investment a DC model is more convenient (see Section 2.3 for a detailed analysis). However, for the analysis of the technical and physical behaviors of the electricity grid for a specific period (e.g. one hour) an AC model is advantageous.

2.1.2 Data availability

The accuracy of the results of energy systems modelling depends on the availability of the input data [30]. In grid modelling, this input data is called grid data and incorporate buses, power lines and transformers data. According to [56], both grid models and grid data are not publicly available in general. The issue of data in energy modelling has been discussed by [39], where the author stated that there is a lack of transparency in energy models regarding how the data is retrieved. Moreover, no data validation is performed to insure the reliability of the data used. [56] addresses the lack of transparency in both grid modelling and grid data. Last, [19] discusses the importance of data issue and transmission grid models in energy modeling.

The issue of grid data applies to the Netherlands as well, where no official database for grid data is available. However, different unofficial sources provide grid data. In literature these sources can be divided into two categories:

- Open grid data, where grid data such as the coordinates of the substations are provided by open source databases (e.g. OpenStreetMap (OSM) project ([78])).
- Open grid models, where grid data are provided by open source energy system models (e.g. open_eGo ([5]).

The data retrieved from these open source databases and models are not validated and might lack of essential data. Therefore, data pre-processing is necessary, where different extracted data from open sources can be compared and validated.

2.2 Modelling electricity supply and demand scenarios

In this section the different approaches to model the Dutch electricity demand and supply are delineated along with scenario analysis in the Dutch power system expansion.

2.2.1 Modelling electricity demand and supply

Other data that are necessary in energy systems modelling are electricity demand and generation capacities. Both the details and scale of the data used to model both components depend on the approach adopted. In this subsection, the different approaches will be discussed.

2.2.1.1 Electricity demand

Demand profiles are considered as a key data input for energy system models since they describe the fluctuations of electricity consumption in a specific region [94]. However, the definition of demand profiles in literature is done in different ways, particularly for the Netherlands. In [9], the resilience of the Dutch electricity transmission network to extreme weather was evaluated. Therefore, the Dutch electricity grid was modelled as a set of connected technical elements: generators, distribution grid, transformers, transmission lines, substations and inter-connectors. While modelling the electricity demand, the author "set the magnitude and geographical distribution of electricity demand in accordance with known peak and mean consumption values" [9]. The exact value of aggregated electricity consumption was set randomly between a defined max/min value and assigned to the appropriate substation. In [96], the expansion of the Dutch power system along with the storage units was performed. The Netherlands was divided into thirty regions, where electricity supply and demand were assigned to each region. The modelling of the hourly electricity demand of each region was done by scaling down the hourly power demand for the Netherlands according to the population of each region. In [8], the congestion management in the Dutch electricity transmission grid was evaluated. The Netherlands was divided into four regions, where the electricity supply and demand were aggregated to each region. While modelling the electricity demand, no information was giving regarding how the data was retrieved and divided within the four regions.

In [8], the approach adopted consists of leaving demand data out of scope since the author does not addresses the question of obtaining appropriate demand profile data. In [96], the approach addresses spatial demand variations, where cumulative annual data is taken into account without considering temporal demand variations. In [9], temporal demand variations are considered, while spatial demand variations are neglected. The approach adopted in this thesis consists of the development and the use of spatio-temporal demand profiles (See Chapter 4). The spatial demand variations are set by the division of the electricity demand within different regions. The temporal demand variations are developed by scaling down the hourly yearly demand data of the Netherlands according to the accumulative yearly demand of the energy regions.

2.2.1.2 Electricity supply

The performance of the electricity system with increased share of vRES is influenced by the fluctuating electricity generation from wind and solar power [80]. Therefore, the use of modeling tools to understand both the technical and economical impact of investing in solar and wind is required [47]. According to [12] these models need to reach a high spatio-temporal resolution to adequately address the fluctuation in vRES. [12] argues that the field of modelling vRES at a spatial and temporal scale is only at early developments stages. Moreover, the emphasis is either at a large spatial coverage (e.g. country level) or small areas. Similar to electricity demand, the Dutch generation profiles are not modelled at high granularity. In [9], both the magnitude and geographical distribution of the Dutch electricity generation were "set in accordance with the known capacities and geographical locations of large generators only". Regarding distributed generation, assumptions were made about their geographical distribution. In [96], wind and solar were modelled using hourly wind speed and solar irradiation for the whole year. In [8], generation capacities are allocated to four nodes.

None of the sources above have described how the generation installed capacity data were extracted and divided within the chosen regions. In [8] and [9], the high temporal resolution of vRES is not addressed and the spatial distribution of vRES is not well described. The approach adopted in this thesis consists of the development and the use of spatio-temporal generation profiles. To address the temporal resolution of the generation, wind and solar will be modelled using hourly wind speed and solar irradiation. To address the spatial resolution, generation resources will be clustered by fuel types and allocated to the appropriate energy region. The approach is described in detail in Chapter 4.

2.2.2 Scenario modelling

Scenarios in power expansion illustrate how the energy system will develop under different conditions. In literature, various studies were conducted on the Dutch electricity supply and demand forecast, where different scenarios were generated. In [96], various scenarios were developed to analyse the effect of different electricity generation mix, where electricity demand was considered constant in all scenarios. [100] created different scenarios to capture uncertainty in carbon prices, low-carbon generation options development and end-users' behavior. [8] developed scenarios to study the effect of different electricity generation costs and mix. In this thesis, the scenario analysis method is used to assess the energy regions vRES plans under different electricity demand forecast. Electricity supply scenarios are generated based on the actual plans of the energy regions, where uncertainty is expected in large-scale solar PV projects. The demand scenarios are generated by defining two alternative development trajectories, which represent the lower and upper expected electricity demand in the reviewed reports.

2.3 Optimization of the Dutch power system expansion

The main focus of the current research in power system expansion is the incorporation of renewable energy sources. With the increasing penetration of vRES in electricity supply, the stochastic characteristics of solar and wind became the main uncertain factors of power systems [24]. Their integration in the Netherlands is being accelerated by government mandates through Klimaatakkoord to reduce CO_2 emissions, where 32% of vRES installed capacity is expected by 2030 [76]. However, their intermittent nature may pose great challenges for maintaining both the stability and the reliability of the grid [61]. The operational challenges associated with these trends can be alleviated by insuring an appropriate amount of operating reserves, since vRES does not contribute to system reserve [15]. The operating reserves can come either from demand (load curtailment) or supply (thermal units or Energy Storage Systems (ESSs)) [2]. Increasing the number of thermal units in reserve would only increase system costs because these plants would run shorter time and need to recover their costs as a consequence electricity price will rise. Moreover, thermal plants in reserve won't mitigate against fluctuations in renewable energy generation [2]. Therefore, the integration of ESS can be considered the best option to integrate vRES. ESS have several benefits, among others, decreasing the need for new generation and transmission capacity, correcting power factors, voltage and frequency, improving maneuverability (load following), as well as environmental advantages [24]. In the Netherlands, the energy regions need to integrate optimally storage units into their generation expansion plans along with the necessary transmission lines reinforcement. The reinforcement of transmission lines is necessary because electricity has to be transported from remote areas where vRES are installed, to the load centers and this would poses significant challenges to the electricity grid. Therefore, generation, transmission and storage investment costs need to be optimized.

The set of optimization problems in power systems "is acknowledged as optimal power flow" [53], where a cost function is optimized over different variables, such as, voltages real/reactive power outputs [24]. The OPF concept was introduced first in 1962 by Carpentier, where power transmission constraint was included in a an optimal Economic Dispatch (ED) [53]. OPF can be formulated to find "the welfare-maximizing consumption and generation levels in a network given the physical load flow equations, branch loading limits and generator cost function"[38]. However, the full load equations are non-linear [53]. Therefore, the optimization problem resulting is non-convex, making it computationally challenging [38]. To overcome the computational difficulties, different solutions were proposed based on local and global solution methods. Local solution techniques generate solutions for large problems within a short computational period [3]. However, there is no guarantee that these solutions are optimal or feasible [3]. Global methods might lead to an optimal solution. However, they are computationally very expensive and only applicable for small networks [3].

One of the most accepted approximation of the optimal power flow is DC optimal power flow (DCOPF) [38]. DCOPF uses DC power flow formula, which is a matrix equation that can be solved with no iteration. DCOPF problem ignores active/reactive losses and reactive power in the transmission system [7]. The approximation assumes small phase angle differences and fixed voltage magnitudes. Therefore, the DCOPF consists of linear constraints only and the objective cost function is linear or convex quadratic [3]. In general the solution generated by DCOPF are fast but not so accurate compared to

AC optimal power flow (ACOPF) [23]. ACOPF problem is the full representation of the OPF, which need to be solved via iterative algorithm due to its non-linearity nature [101]. Therefore, ACOPF problems are time consuming for large-scale projects and practically impossible to use in the body of large iterative algorithms as planning processes [7]. As a result, DCOPF problem is more favourable due to its short run time and its heuristic solution that can be used by power system operators for large network topologies.

An additional challenge in OPF problems is that power systems are largely affected by uncertainty [3]. In particular, electricity demand profiles and vRES installed capacity. To guarantee network stability, the treatment of uncertain parameters must be included in the optimization models.

Research gap

In literature the majority of work done using the DCOPF or linear optimal power flow (LOPF) focuses only on economic dispatch optimization subject to network constraints [97]. Recently, the linear optimal power flow is amplified by an investment optimization. In [60] the LOPF is used to minimize investment costs in transmission lines, transformers and storage units throughout all voltage levels in Germany using an open-source and open-data based synthetic medium-voltage grid model for distribution power supply systems (eGo). The electricity demand was modelled at a high spatial resolution. Moreover, different scenarios were constructed to capture uncertainty in vRES installed capacity. However, the electricity consumption and the annual peak load were assumed to be constant throughout all scenarios. [97] and [72] optimized investment costs in storage and dispatch in both generation and storage using the LOPF without including grid extension. Similar to [60], [97] used spatial demand profiles and considered different scenarios in vRES installed capacity, while considering electricity demand and grid data constant throughout all scenarios. [72] used time series aggregation to reduce the LOPF computation time. The electricity demand was normalized with respect to the maximum load value at each grid bus to reduce temporal complexity. In both [60] and [97] data regarding the components of the grid are extracted from OpenStreetMap (OSM) open data.

The LOPF performed in the described literature was performed to optimize expansion costs following the energy transition using different models. On one side, data quality problems arose regarding the input data used in the proposed models especially that most data were extracted from OSM. On the other side, non of the literature above has modelled the electricity demand using a spatio-temporal approach. Moreover, the modelling of the vRES was done only at a temporal resolution, ignoring spatial planning at regional level. In this thesis, the LOPF will be used to optimize investment costs in generation, transmission and storage units, where spatio-temporal demand and supply profiles are developed. The use of spatio-temporal modeling would allow overcoming deficiencies identified in the previous methods and would contribute to decision-making in an integrated spatio-temporal and energy planning at regional level.

3 Methodology

The methodology used in this thesis provides a comprehensive approach to:

- Model the Dutch power system using spatio-temporal generation and demand profiles.
- Co-optimize the expansion of electricity generation, storage units and transmission lines considering uncertainty in electricity supply and demand.

Following the literature review performed in Chapter 2, this approach needs to address different requirements:

1. The definition of appropriate input data sources and level of detail to model the Dutch electricity grid with a regional resolution.
2. The development of procedure to integrate and re-sample spatio-temporal demand profiles into regional profiles.
3. The translation of the regional electricity generation planning (in TWh) into regional generation capacities (in MW).
4. The development of appropriate scenarios to capture uncertainty in electricity supply and demand.
5. The use of appropriate software toolbox and data structures suitable to handle and integrate large spatio-temporal data sets of electricity supply and demand.
6. The use of adequate method to solve the optimization problem while taking advantage of the high spatio-temporal data sets.

The methodology is graphically summarized in Figure 3.1 and described in the next subsections. This methodology is inspired from the research described in [90]. In [90] the Dutch High Voltage (HV) electricity grid is modelled to identify bottlenecks in the transmission lines under different scenarios in electricity supply and demand. Both electricity supply and demand are modelled in a high spatio-temporal resolution at a municipal scale. Moreover, the Netherlands is divided into different supply areas. These areas are defined by clustering different municipalities with regard to their distance from a HV substation (see Subsection 3.2). In this thesis, the spatio-temporal approach will be applied to the energy regions instead of municipalities, which would allow to assess the planning of the vRES at a regional scale and contribute to decision-making in integrated spatial and energy planning following the regional plans.

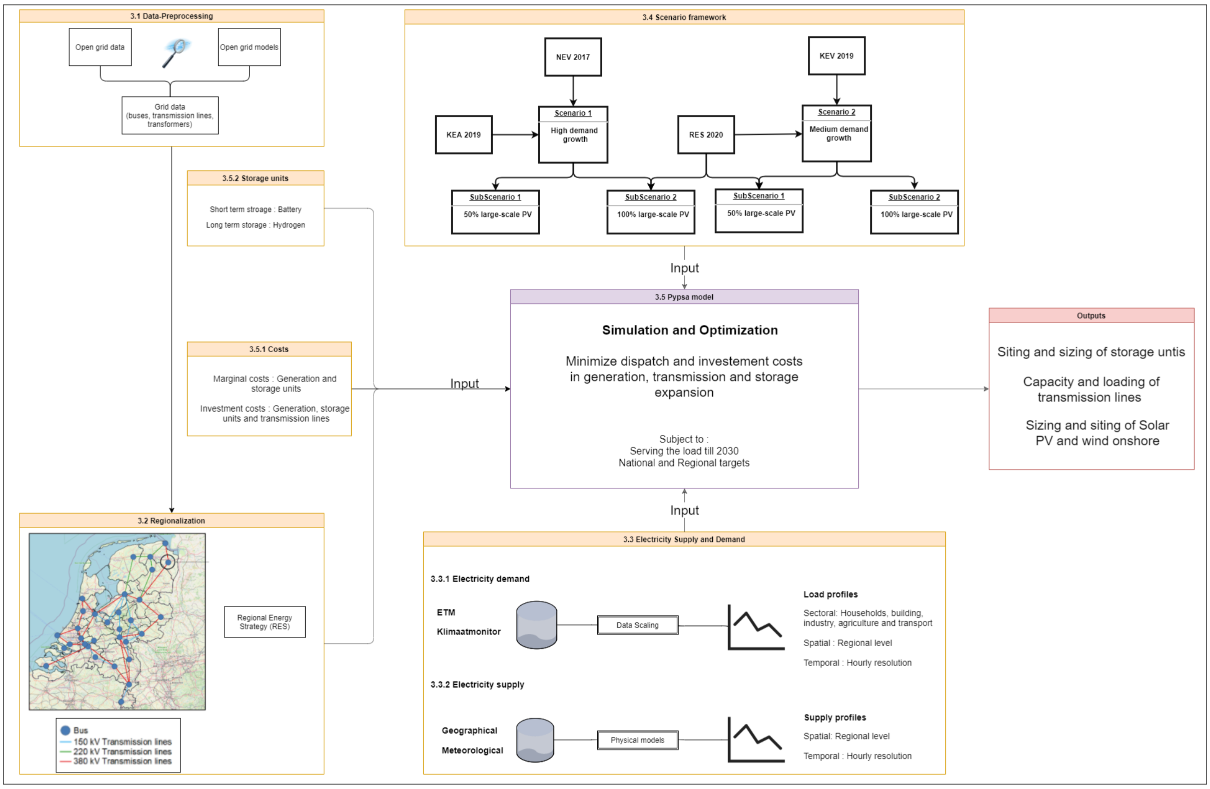

Figure 3.1: Methodology

3.1 Data pre-processing

The modelling of the Dutch electricity grid requires different input grid data. This data can be extracted either from open grid data or from open grid models (as discussed in Subsection 2.1.2). The advantage of grid models, is that grid data can be extracted easily and in a structured way. However, the data provided usually is not complete and not so accurate. Open grid data can contain a large set of grid data. However, the access to this data is difficult. Moreover, the data provided is not structured. As a consequence, the process of retrieving and structuring grid data from open grid data is time-consuming.

Both open grid data and models have benefits and drawbacks. Therefore, a sample of data will be extracted from both sources and then data pre-processing will be performed. Data pre-processing will allow to structure the extracted data from open grid data sources and then compare it to the data provided by open grid models. As a result, a final data set will be defined to be used in the modelling of the Dutch electricity grid (see section 4.1).

3.2 Regionalization

The modelling of the power system consists of the modeling of the electricity grid (based on grid data) and then the assignment of the electricity supply and demand to each bus (substation) in the electricity grid. The electricity supply and demand are usually given by municipality. The most common way to model the power system is the assignment of different municipalities to the nearest substation. As a result, the power system will be divided into different supply areas, where both electricity supply and demand are known. The use of this approach in this thesis is not feasible, because the vRES plans are given at a regional scale. Therefore, the electricity supply data need to be identified for each region and not municipality. Thus, to integrate the regional plans into the modelling of the Dutch power system, each energy region need to be represented by a substation, where electricity supply and demand are affiliated to.

Each energy region incorporates different substations as shown in Figure 3.2, where purple dots represent the 380kV substations, green dots represent the 220kV substations and blue dots represent the 150kV substations.

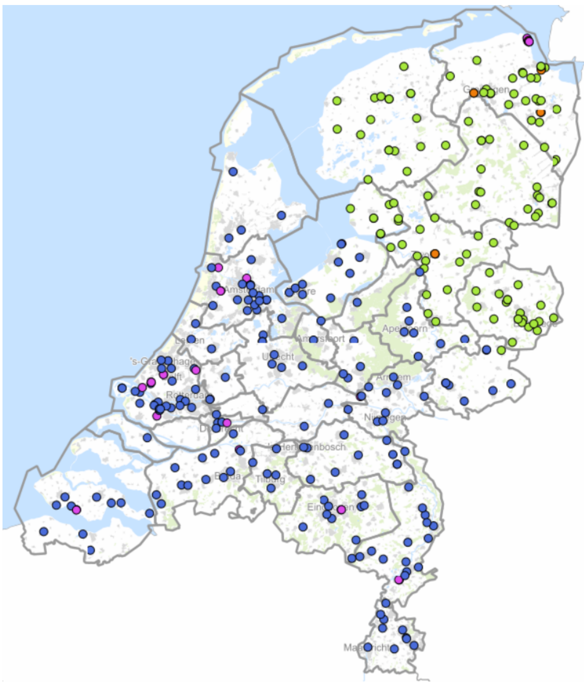

Figure 3.2: HV substations divided within the energy regions [74]

These substations are connected by different transmission lines at different voltage level (380kV, 220kV and 150kV). To represent the energy regions with the underlying topology of the electricity grid, each region will be affiliated to one main substation (see Section 4.2.1.1). The modelled electricity transmission lines connecting two substations incorporate merged transmission lines in series and in parallel (see Section 4.2). This approach, will allow the connection of the energy regions at different voltage levels, while preserving the electrical properties of the transmission lines of the electricity grid. Therefore, the transmission line expansion as well as line loading can be performed for each transmission line at different voltage levels. The next step consists of affiliating hourly electricity supply and demand to each substation.

3.3 Electricity demand and supply

3.3.1 Electricity demand

The approach adopted to model the Dutch demand profiles addresses both the spatial and temporal demand variations in the different energy regions (see Subsection 4.2.2).

- The spatial/sectoral demand variations are developed by dividing the electricity demand into different sectors (agriculture, households, transport, building and industry) within the thirty energy regions (regional level).
- The temporal variations are developed by scaling down the hourly sectoral electricity demand data of the Netherlands according to the accumulative yearly sectoral regional electricity demand. Therefore, hourly sectoral regional electricity demand profiles are conceived.

The hourly sectoral electricity demand is given by the Energy Transition Model (ETM) [22]. The accumulative yearly sectoral regional electricity demand is given by Klimaatmonitor [48].

3.3.2 Electricity supply

The modelling of the electricity supply addresses as well the spatio-temporal variations of the electricity supply in each region (see Subsection 4.2.3).

3.3.2.1 Spatial resolution

The spatial supply variations are developed by clustering generation resources by fuel types (e.g. solar, wind, gas). Then, the installed capacity within each fuel type is summed and assigned to the appropriate energy region. The assignment is done based on the location of the generation resources. Regarding vRES, Klimaatmonitor [48] provides the installed generation capacities for each energy region. Regarding conventional resources, the coordinates of the different power plants are identified and assigned to the appropriate energy region (see Subsection 4.2.3.5 and Subsection 4.2.3.6).

3.3.2.2 Temporal resolution

In order to create temporal supply profiles for wind, hourly wind speed need to be gathered first. These data can be obtained from measurement, computer tools like: Meteonorm [58] and MERRA-2 [10] or national data bases like: the Royal Netherlands Meteorological Institute [41]. Regarding solar profiles, solar irradiation need to be gathered. These data can be obtained as well from MERRA-2.

Since temporal supply profiles are weather dependent, an accurate parametrization is needed. In this thesis, this is done using MERRA-2 that is defined as "a global atmospheric reanalysis produced by the NASA Global Modeling and Assimilation Office"[26]. MERRA-2 offers a high spatial and temporal (hourly) resolution. The high spatio-temporal resolution would preserve inter-regional and inter-temporal dependencies [10]. The main advantage of MERRA-2 is its facility of use, the modelling of both wind and solar and the high resolution results it gives. By the aim of MERRA-2, hourly wind speed and solar irradiation for one year have been gathered for thirty locations within every modelled energy region.

3.4 Scenario framework

The main sources of uncertainties in the current system are related to the vRES, whose output changes remarkably in time, and to the electricity demand, that depends on technological and socio-economical components. This thesis considers uncertainty in both electricity supply and demand based on the different governmental energy reports, where the electricity demand can take different shapes, and the investment in vRES may not be achieved as planned as discussed in Chapter 1.

On one side, a medium and a high growth of electricity demand is expected by 2030 based on the National Energieverkenning (NEV) 2017 [18] and the Klimaat- en Energieverkenning (KEV) 2019 [67] reports. On the other side, only 50% of the planned large-scale solar PV projects is expected by 2030. In order to assess the impact of large-scale solar PV on the CO_2 reduction, the minimal (50%) and maximal (100%) values of the expected installed capacity are represented by the scenarios. Therefore, a two-phase scenario planning is developed, where generation type and capacity uncertainty (achievement of 50% and 100% of large-scale solar PV projects) are presented in the first phase and the allocation of the installed capacity to segments of two different electricity load shapes as second phase decision. Both the expected electricity supply and demand presented in the scenario planning are developed as spatio-temporal profiles and incorporated as input into the optimization model (see Chapter 6).

3.5 PyPSA model

3.5.1 Simulation and optimization

The simulation and the optimization of the Dutch electrical power grid is done using Python for Power System Analysis (PyPSA) model, which is a free software toolbox. The choice of PyPSA software is due to the free and open source distribution of the simulation platform, the conception in Python language and the dynamic response. Moreover, PyPSA is designed to scale well with large networks and high resolution supply and demand profiles.

In the model, each energy region is represented by a single bus with different electricity demand and generation portfolios. The power generation portfolio is represented by the combination of different generation technologies: gas, coal, biomass, waste, nuclear, wind onshore, wind offshore and solar. Two assumptions are considered concerning the modelling of renewable energy sources: (1) The availability of renewable energy resources power is derived from the installed capacity and weather conditions, (2) curtailment is allowed in case the surplus of electricity generated cannot be stored with the chosen storage units. To consider adequately the fluctuations in electricity generation from vRES, a whole year is simulated with an hourly resolution. In addition, the interconnection between other countries is not considered because the focus is whether the Netherlands can meet the national target in reducing CO_2 emissions without importing electricity from surrounding countries.

The optimization problem is a linear optimal power flow model, that minimizes the annual system costs. The linear problem computing the LOPF is implemented using PyPSA model. The latest data provided by Klimaatmonitor regarding the energy regions are for the year 2017, which is considered as the reference year in this thesis. For the reference year, the LOPF is used to optimize the dispatch of conventional and renewable energy generators based on their marginal costs.
Regarding the year 2030, the LOPF is used to optimize two problems. First, the optimization of the investment costs in the transmission lines and energy storage systems to incorporate the 26 TWh electricity generation from large-scale solar PV and wind onshore as planned by the energy regions. Second, the optimization of the investment costs in large-scale solar PV, wind onshore, energy storage system and transmission lines to meet the 35 TWh electricity generation. The second optimization problem will determine where the remaining 9 TWh of electricity generation will be installed based on the investment costs of solar PV and wind onshore. The outcomes of the first optimization problem (the required storage and transmission capacities) are used as an input for the second optimization problem (see Chapter 5).

3.5.2 Storage units

So far there is no installed capacity of energy system storage in the Netherlands. Therefore, the installation of unlimited storage capacities at all buses at a certain variable and capital costs is allowed in the optimization model. The model can build storage units while computing the LOPF. However, to better analyse the energy storage systems, a specification of the type of storage is needed. Most of the recent literature that optimizes power system expansion with storage units uses two types of storage units: short-term and long-term storage units. In this thesis, both types will be used following the specifications set in [97].

- Short-term storage can be represented by large-scale battery storage facilities that operate on an hourly scale with an energy to power ration of q = 6, meaning that the batteries can provide and store energy for 6h. Moreover, the round-trip efficiency chosen is 93%.
- Long-term storage units can be presented by compressed hydrogen stored in underground salt caverns operating as seasonal storage units. Hydrogen storage can provide and store energy for 168h with a charging efficiency of 0.725 and a discharging efficiency of 0.425.

3.5.3 Computational performance

One of the main challenges in solving the linear optimal power flow for large networks with high resolution electricity demand and supply profiles is the computational performance. Regarding PyPSA model, the computational performance relies strongly on the passive branch flow formulation, the solver type and the usage of pyomo.

- Passive branch flow formulation

  The power flow $f_{l,t}$ in the branch l at the time t in AC networks is expressed by "the difference in voltage angle $\Theta_{p,t}$ at bus0 and $\Theta_{q,t}$ at bus1 divided by the series reactance x_r" [11]:

$$f_{l,t} = \frac{\Theta_{p,t} - \Theta_{q,t}}{x_r} \tag{3.1}$$

  The power flow is limited by the capacity of the branch F_l

$$|f_{l,t}| \leq F_l \tag{3.2}$$

  PyPSA model proposes four different formulations of the linear power flow equations [11]:

  - Cycle formulation is based on the voltage angles described in equation 3.1.

– Ptdf is based on the power transfer distribution factor formulation

– Kirchhoff and cycles formulations are based on "graph-theoretic decomposition of the network flows into a spanning tree and closed cycles".

Even though these formulations are mathematically similar, they have different solving times.

In [38], the author solved a linear optimal power flow problem in a system with a high share of vRES using the four formulations. As shown in Figure 3.3, the Kirchhoff formulation is the fastest in all the cases. Therefore, Kirchhoff formulation is used to solve the LOPF problem in this thesis.

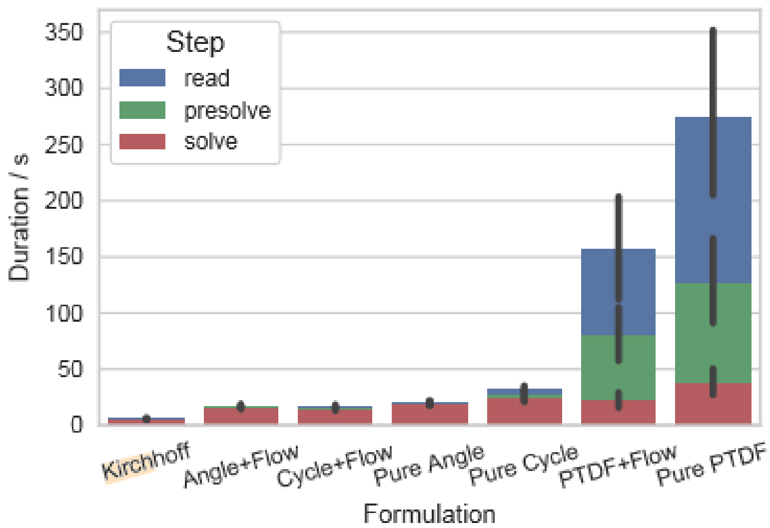

Figure 3.3: Performance of the different formulation to solve the LOPF [38]

- Solver type

PyPSA model solves the LOPF problem using different external solvers. These solvers can be either free (e.g. GNU Linear Programming Kit (GLPK) [54] and Coin-or branch and cut (CBC)) or commercial (e.g. Gurobi [29]). After different simulations using GLPK, CBC and Gurobi to solve the LOPF problem, Gurobi was the fastest. Therefore, Gurobi solver is used with an academic license.

- Pyomo usage

PyPSA uses the open-source optimization modeling language Pyomo for modeling structured optimization applications. In the most recent versions of PyPSA, the optimization can be enabled without the usage of Pyomo. According to [5] the non-use of Pyomo results in an efficient linear optimal power flow in terms of time and memory usage. However, setting Pyomo to false generates some errors since some constraints need to be set in advance. Therefore, Pyomo is incorporated to perform the LOPF.

3.5.4 Line loading and locational marginal price

3.5.4.1 Line loading

In the linear power flow (LPF), the modelling of the transmission lines requires only series resistance data. Therefore, only the active power through the transmission lines can be computed. However, in the non-linear Newton-Raphson Power Flow algorithm (PF) the series reactance/resistance and the shunt conductivity/susceptance data are needed. Therefore, both active and reactive power through the transmission lines can be calculated. Thus, the computation of the transmission lines loading is more accurate using the PF.
In this thesis, the LOPF led to results concerning dispatches and investments decisions. In the interest of simulating reactive power flows, the LOPF will be followed by the PF for a specific hour.

For each sub-scenario the transmission lines loading will be computed for three cases:

- High vRES/High electricity demand.
- Low vRES/High electricity demand.
- High vRES/Low electricity demand

The case where both electricity demand and vRES supply are low is not considered, because the loading on the transmission electricity lines is low. Therefore, no insights can be given regarding the most loaded lines in the network.

3.5.4.2 Locational marginal price

Locational Marginal Price (LMP) is defined as the marginal cost to the system operator to deliver an additional unit of energy to a particular bus in the network [43]. The LMP calculation will be followed by the computation of lines loading in the three cases at the different nodes in the network. Different LMP among the nodes in the network will give insights regarding congestion in the network in case there is surplus electricity production.

3.6 Summary

The methodology used in this chapter was conceptualized in a way that the six requirements defined in Section 3.1 are fulfilled. The fulfillment of the different requirements will allow the modelling of the Dutch power system components at high granularity resolution and the optimization of the expansion of the Dutch power system following the energy regions plans. The components of the Dutch power system will be modelled in the next chapter.

4 Modeling the Dutch power system

The Dutch power system will be modelled as a thirty-region power system reflecting both the national energy strategy (vRES plans of the energy regions) and the electricity grid using PyPSA model.

The physical building blocks of the model include buses, transformers and transmission lines. Since the Dutch electricity network operates at different voltage levels, the building blocks will be used to represent these variations. In this thesis three voltage levels will be considered (380kV, 220kV and 150kV). The electricity generation and the load will be affiliated to the different buses in the model. The model components are presented in Figure 4.1.

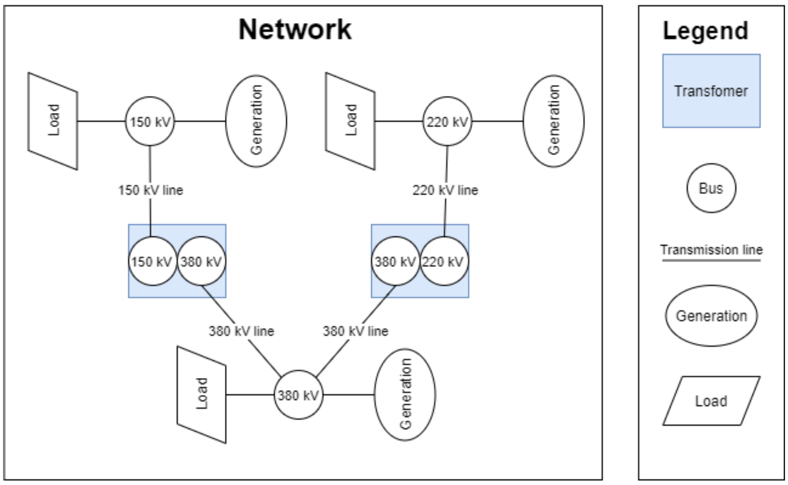

Figure 4.1: Model components

As discussed in Section 2.1, the components of the power system need different input data. The input data can be retrieved from different sources, especially the data needed to model the buses, transmission lines and transformers (called grid data).

In this chapter, a data pre-processing will be performed to determine the most accurate sources of grid data of the Dutch electricity grid. Then, the different components of the power system will be modelled.

4.1 Data pre-processing

As discussed in the literature review section, no official sources containing grid data are available. The only way to extract grid data is from open grid models or open grid data. On one side, extracting grid data from open grid models is more efficient in terms of time and data structure. However, the quality of data, the assumptions and the simplifications considered while deriving this data are being criticized. On the other side, extracting grid data from open grid data is time consuming. Moreover, the data provided is unstructured. To decide upon which grid data sources will be used to extract grid data, two different grid models will be compered with three different open grid data. A summary of the findings is presented at the end of this section.

4.1.1 Open grid data

Grid data are extracted from three different open grid data: the static grid model, HoogspanningsNet and Openstreetmap (OSM).

4.1.1.1 Static grid model

The transmission grid operator (TenneT) provides a document containing data of the HV grid (380kV and 220kV) for the Netherlands [86].
The data presented by the static grid model are:

- The electrical properties of the transmission lines (conductance, resistance and reactance).
- The transmission lines names, length and the maximum and minimum current.

4.1.1.2 HoogspanningsNet

HoogspanningsNet is an independent association that provides in-depth information about the electricity grid of the Netherlands and can be accessed through the website (https://www.hoogspanningsnet.com) [33]. HoogspanningsNet offers two important documents: “Netkaart Nederland” and “Netschema van Nederland”.
“Netkaart Nederland”: shows the high-voltage connections in the Netherlands that belong to the state network (see Appendix IV).

“Netschema van Nederland”: shows the Dutch interconnection network in a schematic graphic manner (network diagram), where the capacities of the lines and transformers are defined (Figure 4.2).

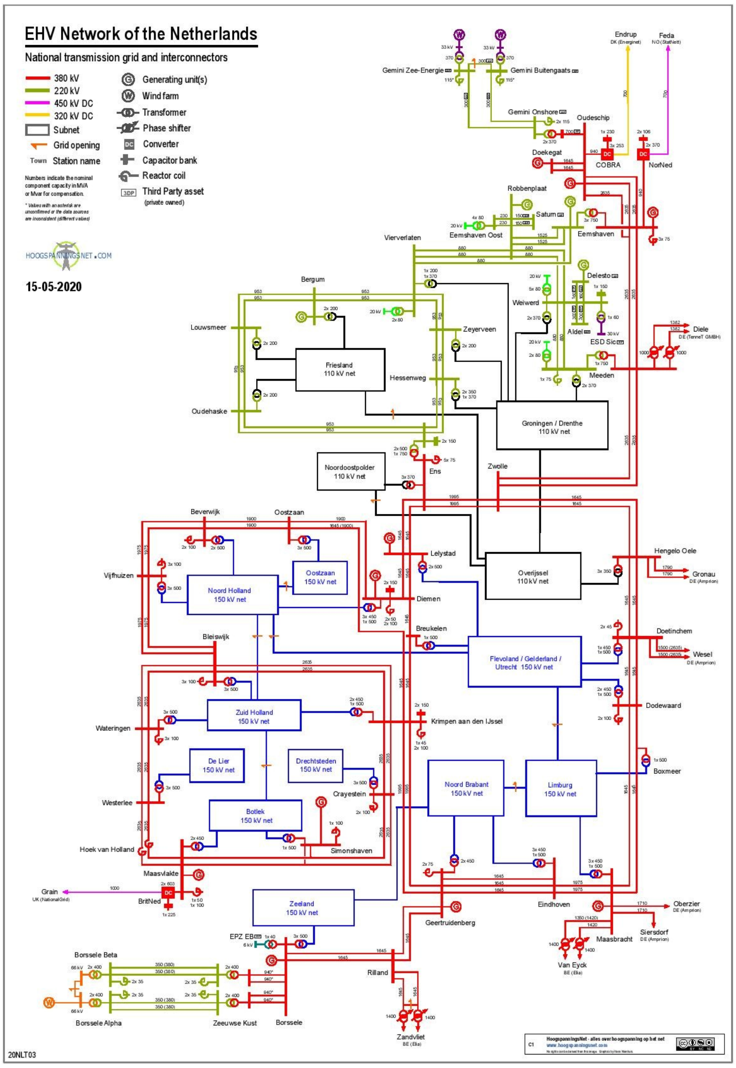

Figure 4.2: Network diagram [35]

4.1.1.3 OpenStreetMap

OpenStreetMap is a "collaborative project that creates and distributes geographic data for the whole world" [65]. It is considered as a massive free and open database, that contains all attributes about every single geographic characteristic [65]. Different methods are discussed in literature on the way of extracting OSM data. Therefore, the process in which the data can be extracted easily and efficiently is presented in this subsection.

4.1.1.3.1 Download data

The OSM data of the Netherlands is exported from GeoFabrik [27], which offers the data either in shape-file or raw OSM data. OSM electricity data Shape-files are offered as commercial data by GeoFabrik. Therefore, OSM raw data is used because it contains all the OpenStreetMap data, needs few memory storage and is freely accessible. This data covers all the Netherlands (Figure 4.3) and is downloaded with a Protocolbuffer Binary Format (PBF) format.

Figure 4.3: GoeFabrik data area coverage for the Netherlands [27]

Raw OSM data will be transformed into readable data through the free and open-source cross-platform QGIS [52] (see Appendix I). QGIS, allows viewing, editing, and analyzing geo-spatial data. Viewing OSM data in QGIS can be done through loading the data in the form of lines and points. The line and point forms can be used respectively to present the buses and the electricity transmission lines. However, a filtering of the loaded data is needed because the raw data loaded in QGIS contains data for different sectors (e.g. transport, railways, waterway and power)

4.1.1.3.2 Filtering data

Transmission lines

QGIS offers a filtering process, where fields and values need to be defined. For the power system, the fields correspond to power. However, values can have a different set of choices (e.g. transmission lines, buses). This process will enable to filter and display the electricity transmission lines of the Netherlands (Figure 4.4). To have a better visualization of the location of the lines, the thirty regions shape file is downloaded from [6] and implemented in QGIS (Figure 4.5).

Figure 4.4: Electricity transmission lines in the Netherlands made with QGIS

Figure 4.5: Electricity transmission lines following RES distribution made with QGIS

The voltage levels of the extracted transmission lines is between 50kV and 380kV. Therefore, the data is filtered again based on the voltage levels to include only 150kV, 220kV and 380kV transmission lines. This is done by setting the value of the voltage as: $"voltage" =' 380000 : 150000'$ or $"voltage" =' 380000; 220000'$ or $"voltage" =' 150000'$ or $"voltage" =' 220000'$ or $"voltage" =' 380000'$ (Table 4.1).

Voltage Level	Number of lines
150000	1679
380000	1872
380000;220000	8
380000;150000	5

Table 4.1: Electricity transmission lines filtered by voltage levels

Buses

The buses in OpenStreetMap are defined by the key words "generator" or "substation" and take the shape of a point (Figure 4.6).

QGIS illustrates the coordinates of the buses using the coordinate system EPSG: 3857, where EPSG code is used as a spatial reference system identifier by QGIS. PyPSA model uses EPSG: 4326.

Figure 4.6: Netherlands OSM buses data as a point made with QGIS

QGIS contains a different range of predefined coordinate reference system. Therefore, the coordinates are adapted as follow:

Coordinate reference system	Authority ID
WGS 84	EPSG: 4326

Where, WGS is the World Geodetic System.

Data analysis

Power data in OpenstreetMap is represented by different types: ways, relations and nodes. Nodes for example can identify the "electricity lines carrying towers and electrical poles"([?]). Overhead lines and underground cables can be identified by open ways. Power plants, stations, substations and generators are represented by close ways. To better illustrate the data OSM offers, Borssele substation is used as an example (Figure 4.7).

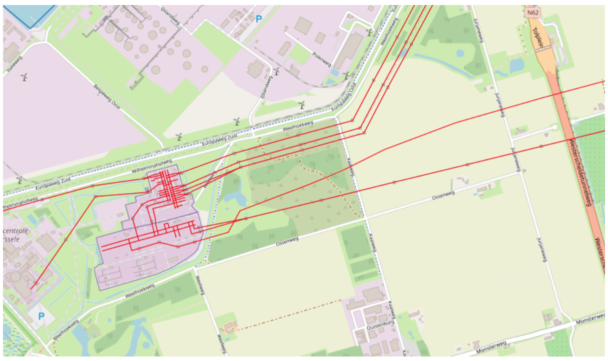

Figure 4.7: Borssele 380kV/150kV substation connected to transmission lines made with QGIS

The data of Borssele substation (380kV/150kV) and the 380kV transmission line connected to it as extracted from OSM are shown respectively in Table 4.2, Table 4.3. Regarding the transmission lines, OSM provides only the number of cables, wires and circuits.

$Full_id$	$w739937233$	$w87787238$
Osm_id	739937233	7787238
Osm_type	way	way
name	380kV Borssele	150kV Borssele
operator	TenneT	TenneT
power	substation	substation
substation	transmission	transmission
voltage	380000	150000

Table 4.2: Borssele 380kV/150kV substations

$Full_id$	$w414789591$
Osm_id	414789591
Osm_type	way
Cable	6
Frequency	50
power	line
wires	triple
voltage	380000
Circuit	2

Table 4.3: Borssele 380kV transmission

To calculate the electrical properties of the transmission lines: Resistance r_{ohmKm}, Capacitance c_{nFKm}, Reactance x_{ohmKm} and the maximum Current Thermal Limit $\bar{f}_A$, SciGRID approach can be adopted [57]. Where,

$$r_{ohmKm} = C_r/(\frac{wires}{wires_{typical}})(\frac{cables}{3}) \tag{4.1}$$

$$x_{ohmKm} = C_x/(\frac{wires}{wires_{typical}})(\frac{cables}{3}) \tag{4.2}$$

$$c_{nFKm} = C_c/(\frac{wires}{wires_{typical}})(\frac{cables}{3}) \tag{4.3}$$

$$\bar{f}_A = C_l/(\frac{wires}{wires_{typical}})(\frac{cables}{3}) \tag{4.4}$$

$wires_{typical}$ represents the number of wires in a transmission line, that takes the value of 2 for a 220kV transmission line and the value of 4 for a 380kV transmission line [57].

C_r, C_x, C_r and C_l are the electrical coefficients of a transmission line as described by SciGRID (Table 4.4).

Voltage levels	$C_r(ohm/km)$	$C_x(ohm/km)$	$C_c(nF/km)$	$C_l(A)$
380kV	0.025	0.25	0.0137	2.6
220kV	0.080	0.32	0.0115	1.3

Table 4.4: Electrical properties coefficients [57]

Now that the open grid data sources are presented along with the data they provide, the open grid models will be discussed in the next subsection.

4.1.2 Open grid models

Two different open grid models are chosen: Transnet-model and PyPSA-Eur. Both models contain grid data for the Netherlands.

4.1.2.1 Transnet-model

The Transnet project consists of "a set of Python and Matlab scripts for the automatic inference of high voltage power grids based on crowd-sourced OpenStreetMap data" [51]. Transnet offers grid data with a voltage level in the range of 110kV to 380kV. The data provided are:

- Buses: coordinates, voltage level, name, operator.
- Transmission lines: coordinates, voltage level, number of cables, type of lines, length, resistance, reactance, shunt capacitance and nominal current.

4.1.2.2 PyPSA-Eur

PyPSA-Eur is "an open model data-set of the European power system at the transmission network level that covers the full ENTSO-E area" [40].
The data set of the electricity grid is represented by a "grid model that is based on a modified GridKit extraction of the ENTSO-E Transmission System Map and takes into account alternating current lines at and above 220kV voltage level" [40]. The data of the transmission lines of the Netherlands consist of the location of the lines, their voltage, number of circuits and the length.
To visualize the electricity transmission lines provided by PysPSA-Eur, the model was customized to include only the Netherlands instead of all European countries. The HV lines implemented in the model cover the whole Netherlands as shown in Figure 4.8.

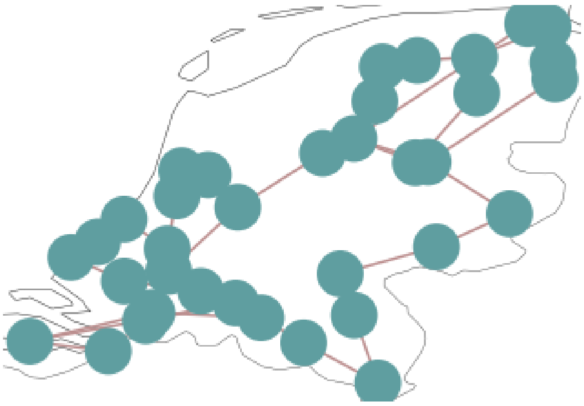

Figure 4.8: The HV network of the Netherlands based on PyPSA-Eur model made with PyPSA-Eur

4.1.3 Summary

Both open grid data and model grid data offer a different set of information regarding the electricity grid of the Netherlands. This data is summarized in Table 4.5.

	Open grid data			**Grid models**	
	Static grid model	**HoogspanningsNet**	**OpenStreetMap**	**PyPSA-Eur**	**Transnet-model**
Scope	Netherlands	Netherlands	Europe, North Africa, USA, parts of Asia and South America	Europe	Europe, North Africa, USA, parts of Asia and South America
Voltage level	220kV and 380kV	20kV - 380kV	50kV – 380kV	220kV and 380kV	110kV - 380kV
Capacity of the lines	No	Yes	No	No	No
Electrical properties of the lines	Conductance, resistance /reactance and maximum/ minimum current	Number of circuits	Number of wires and cables	number of circuits	Cables, type, resistance, reactance, shunt capacitance and nominal current
Lines length	Yes	Yes	No	Yes	Yes
Lines type	Yes	Yes	Yes	Yes	Yes
Location	No geo data	No geo data, A detailed map	Georeferenced locations	Georeferenced locations	Georeferenced locations
Transformers capacity	No	Yes	No	No	No
Data extraction	Data is provided in Pdf file	Manual	Geospatial tools	Simulation	Simulation

Table 4.5: Summary of the different grid data

PyPSA-Eur provides a limited set of data compared to Transnet-model, where different voltage levels are described with their characteristics. However, the data generated by Transnet-model is mainly based on OpenstreetMap approximation. Moreover, the capacity of the lines and the transformers is missing. Even though in both models data can be extracted easily and in a structured way, the data provided is not very accurate and is incomplete. The findings show that the criticism regarding data used from open grid models is relevant. Therefore, the grid data of the Netherlands will be extracted from open grid data sources only (Table 4.6).

Components	Data	Voltage level	Sources
Transmission lines	Coordinate	380kV/220kV/150kV	OSM
	Length	380kV/220kV	Static grid model
		150kV	HoogspanningsNet
	Capacity	380kV/220kV/150kV	HoogspanningsNet
	Electrical Properties	380kV/220kV	Static grid model
		150kV	PyPSA model (see Section 4.2.1.2)
Buses	Coordinate	380kV/220kV/150kV	OSM
Transformers	Coordinate	380kV/220kV/150kV	OSM
	Capacity	380kV/220kV/150kV	HoogspanningsNet

Table 4.6: Open grid data sources used to extract the Dutch grid data

4.2 Modelling of power system components

In this section the Dutch electricity grid is modelled based on the data pre-processing preformed in the previous section and adjusted to incorporate the energy regions, where each region is represented by one main bus (substation). Then, the electricity demand and the generation of each energy region are defined and assigned to the appropriate bus. A summary of the different distribution keys to model the electricity demand and generation along with their sources is presented in Appendix VIII.

4.2.1 Power grid

The underlying topology of the Dutch power grid incorporates three main components: buses, transmission lines and transformers, which operate at different voltage levels. In this section, the electricity grid will be modelled to incorporate the thirty energy regions. Therefore, the necessary buses representing the energy regions need to be defined along with the necessary transmission lines connecting the regions.

4.2.1.1 Buses

Buses are considered as physical nodes, to which all the physical components (e.g. transformers, transmission lines) as well as the electricity demand and generation are connected to. In order to assess the vRES plans set by the energy regions, the energy regions need to be defined by a main bus, where the electricity generation of each energy region is assigned to. The process of buses selection is defined as follow:

1. Filtering the grid buses of the HV network (380kV/220kV).
2. Validating and adjusting manually the location of the HV buses using real grid map.
3. Incorporating the 150kV infrastructure, in case the 380kV/220kV buses are missing from a region.

Filtering the grid buses of the HV network

The HV buses of the Netherlands are extracted from the grid map of TenneT [85], in where they are divided into 380kV and 220kV high-voltage buses. The 380kV buses (purple dots) are spread all over the country with a total number of 28. However, the 220kV infrastructure is located in the North-East of the Netherlands and incorporates 11 buses (orange dots) (Figure 4.9).

The location of the buses within the thirty regions is found using RES analysis map "RES Analysekaarten versie 2.0" [74], which is represented in Figure 4.9. This map shows that the 380kV and 220kV buses are located in 16 regions only. The remaining 14 regions incorporate 150kV and 110kV buses.

The 380kV buses are connected with each other by 380kV transmission lines that pass through almost all the regions. Therefore, in the next step an in-depth investigation regarding the location of the buses will be done to see if possible adjustment of the locations of the modelled buses is possible.

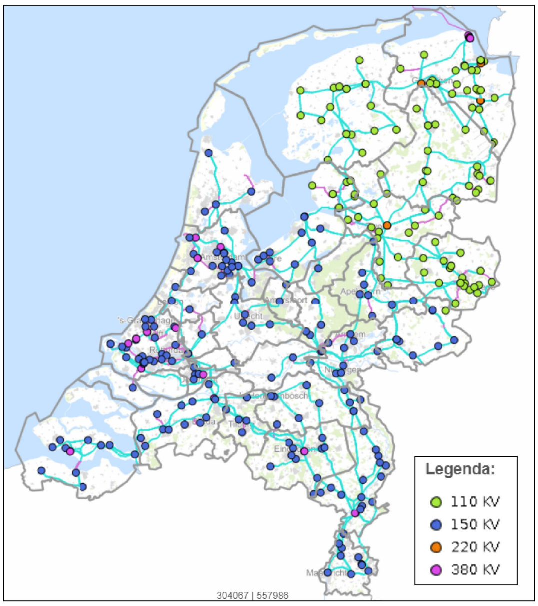

Figure 4.9: HV buses of the Netherlands [74]

Manual validation and adjustment using a real grid map

Different cases need to be taking into account, while affiliating a bus to a region:

1. Regions that contain only one 380kV or 220kV bus.

2. Regions with more than one 380kV/220kV bus.

3. Regions with no 380kV/220kV bus, but that have a 380kV/220kV bus nearby.

4. Regions with no 380kV/220kV bus and without a 380kV/220kV bus nearby.

In the first case, the HV buses are immediately affiliated to a region (e.g. West-Brabant and Eindhoven regions).

In the second case (an example of Zeeland region is illustrated in Appendix VI), the choice of one main bus among the available buses within the same region is based on two criteria:

- The buses location should preserve the shape of the HV network (mainly buses located at the edges).

- The transmission lines connecting two regions can be added in series and in parallel to form only one main transmission line, without losing their electrical properties.

Following these criteria, fifteen regions that incorporate 380kV and/or 220kV buses have been affiliated to one main bus, except for Groningen region. Even though Groningen region incorporates many 380kV and 220kV buses, the criteria to affiliate only one bus cannot be met. Three main buses are located at the edge of Groningen region: Vierverlaten, Meeden and Eemshavem as shown in Figure 4.10.

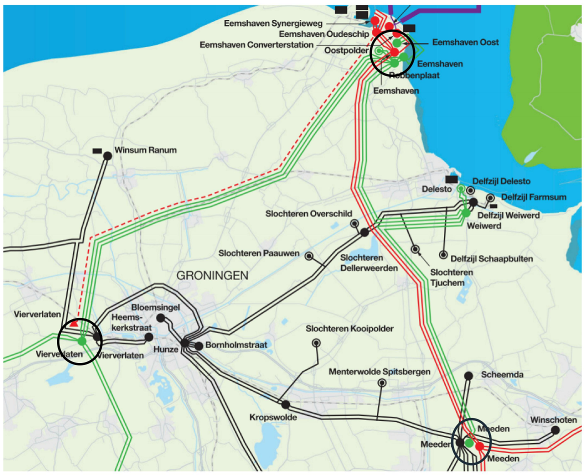

Figure 4.10: HV buses in Groningen region [34]

The connection between Meeden and Eemshaven incorporates two transmission lines: 220kV and 380kV transmission lines. The 380kV transmission line connects Groningen to Drenthe. However, the 220kV is within Groningen region only. Therefore, to represent the 220kV transmission line in the model, both Meeden and Eeemshaven are considered as buses in the model.

Vierverlaten bus is located at the edge of Groningen and connect Groningen to Drenthe and Friesland. To represent the 220kV transmission line connecting Vierverlaten to Eemshaven with the real electrical properties of the line, both buses need to be considered. Therefore, Groningen region is represented by three buses instead of one: Vierverlaten, Meeden and Eemshavem.

The third case consists of regions that does not contain any 380kV/220kV buses, but the 380kV/220kV buses are nearby their borders (e.g. the region Hoekse Waard does not contain any 380kV/220kV buses, but near to its border a 380kV bus is located Figure 4.9). In this case, a relocation of these buses within these region will be performed to maximize the representation of the thirty regions by the HV grid in the model.

Figure 4.11 shows the relocation of the 380kV substation Simonhaven from Rotterdam-Den Haag region to Hoekse Waard region as an example. The coordinates of the buses are retrieved from QGIS to calculate the distances between the old and the new location.

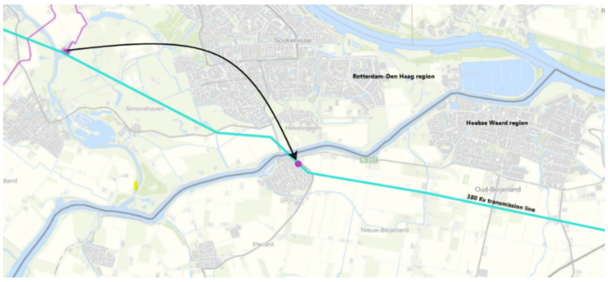

Figure 4.11: Relocation of Simonhaven substation

The same process is done for the four remaining regions. The Table 4.7 gives an overview of the regions, associated substations an their new coordinates.

Regions	Buses	Old Coordinates	New Coordinates
Regio Midden-Holland	Krimpen a/d Ijssel	4.63059024959,51.9143988216	4.64931,51.90824380
Regio Hoekse Waard	Simonshaven	4.2659700303, 51.8393451834	4.3494,51.8127
Regio Holland Rijnland	Bleiswijk	4.53038040704, 52.0362245399	4.56215,52.06582
Regio Noord-Holland Noord	Beverwijk	4.67928839348, 52.4728590695	4.71355,52.51410
Regio U10/U16	Diemen	5.01533821368,52.337160338	5.01777,52.2989

Table 4.7: Relocated buses

The last case, is presented in the next subsection.

150kV infrastructure inclusion

Since the 380kV and 220kV electricity grid cannot capture the connections between all the regions, 150kV buses were incorporated to connect the remaining regions where no substation is within their borders or nearby. The process to choose a substation to connect the remaining regions is as follow:

- Localize all the 150kV buses within a region (Figure 4.12),
- Calculate the distance between the 150kV buses and the nearest 380kV/150kV transformer, and choose the nearest one (using the nearest neighbor join approach),
- Select the substations that are connected directly with a power line to the 380kV/150kV transformers.

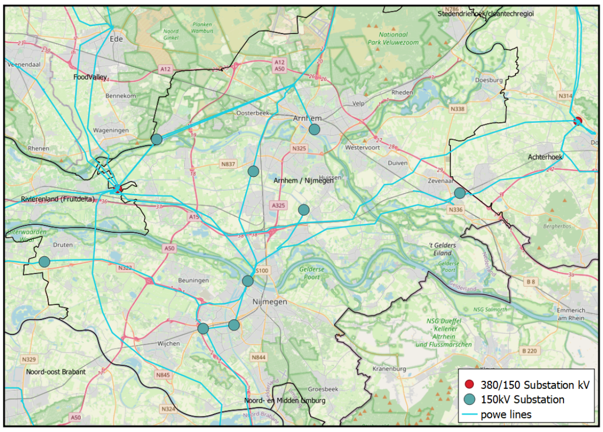

Figure 4.12: 150kV substations within Arnhem/Nijmegen region

4.2.1.2 Transmission lines

Electrical power transmission lines are considered as the edges in the network that connects several buses to each other, therefore establishing the network shape [82]. Each line have different characteristics; length and electrical components, that determine its performance. In this model, 380kV/220kV/150kV transmission lines are included.

380kV

380kV high-voltage lines are the largest high-voltage lines in the Netherlands, with a transport capacity that exceeds 1000 MVA [33]. They connect the entire country and in some regions they cross the border so that electricity can be traded internationally (Figure 4.13). As discussed before, in this study the interconnection between other countries is not taken into account.

380kV transmission lines play an important role in the development and position of large cities and industrial areas. Moreover, they make areas attractive for investment because of their reliable electricity supply. In order to prevent any malfunctioning in the network, the high voltage grid is designed in such a way all 380kV lines are redundant (almost all lines have at least two circuits) [34]. In general the two circuits are used at half capacity only: the power is distributed on both sides of the joint [33]. However, when one of the two circuits needs to be out of service for maintenance, the circuit is used at full capacity to transport the same amount of power [33]. In this case, an overload of up to approximately 15% is usually permitted if it does not take too long [33].

Figure 4.13: 380kV transmission lines [33]

220kV

The North of the Netherlands have a different voltage level because of historical reasons, namely related to Germany [32]. They are designed in the Northern part of the country as a ring and they are redundant [35]. The 220kV transmission lines have the same function as the 380kV transmission lines and play an important role to transport wind offshore generation from the North Sea coast [32].

The 220kV grid is considered as an interconnection network. Therefore, ring shapes, redundancy, short repair times and reliability are essential [32]. The capacity of each line is equal to 953 MVA. The HoogspanningNet's webkaart [36] can be used to retrieve more information regarding the 220kV transmission lines.

150kV

The 150kV connections are used to link the 9 regions chosen in the previous subsection to the HV infrastructure. The 150kV transmission lines are connected to the 380kV grid through a transformer, and their capacity is between 60MVA and 800MVA.

The capacity of the lines and their length can be found using HoogspanningNet open source as discussed in Section 4.1. The electrical properties of the lines can be calculated either by using OSM approximation or by using a set of standards lines offered by PyPSA model, where the resistance, reactance and shunt capacitance are defined for every type. Computing the electrical properties of the lines using OSM data is time consuming. Therefore, the electrical properties provided by PyPSA model will be used. The line chosen is N2XS(FL)2Y 1x120 RM/35 64/110 kV [11], which have a capacity up to 845 MVA. The electrical parameters of the lines are shown in Table 4.8. In the model this parameters need to be multiplied by the length of the lines.

Name	**Frequency**	**Resistance per length**	**Reactance per length**	**Shunt capacitance per length**	**Nominal current**	**Mounting**	**Cross section**
N2XS(FL)2Y 1x300 RM/35 64/110 kV	50	0.06	0.144	144	0.588	cs	300

Table 4.8: 150kV transmission line electrical parameters [11]

For 150 kV transmission lines in series, the average capacity is taken into account.

4.2.1.3 Transformers

The transformers are used to connect the bus with the highest voltage to the lower voltage. Multiple transformers are used because the underlying chosen infrastructure incorporates 380kV, 220kV and 150kV buses. In summary, three 380kV/220kV and ten 380kV/150kV transformers are used.

Network topology of the thirty regions

Figure 4.14 shows the network topology chosen for the energy regions.

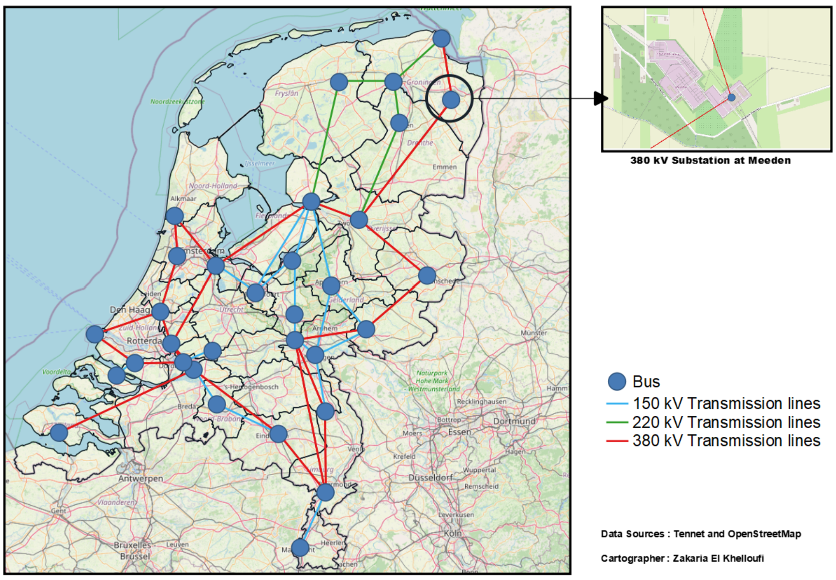

Figure 4.14: Network topology

4.2.2 Electricity demand

The calculation of the hourly electricity demand for the thirty regions is established in several steps:

- The hourly electricity data are exported from ETM model for the whole year divided into: agriculture, industry, households, buildings and transport.
- The total yearly electricity data are exported from Klimaatmonitor for the thirty regions divided into: the built environment (households, buildings), agriculture and industry.
- The annual total electricity demand of ETM model are compared to the annual total electricity demand of Klimaatmonitor.
- The national sectoral hourly electricity demand data are scaled down to the regional sectoral hourly electricity data.
- The regional sectoral hourly electricity data are aggregated.

ETM

The shape of the electricity demand as an hourly time-series is generated from ETM model [22] (figure 4.15). ETM provides the electricity demand data in MW divided into

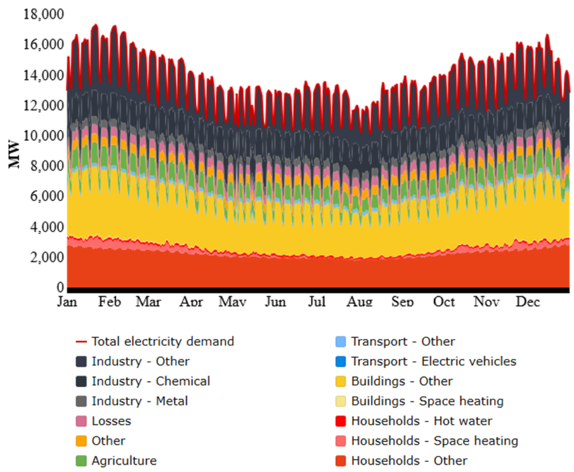

Figure 4.15: Hourly electricity demand for 2015 in the Netherlands [22]

sub-sectors of agriculture, industry, households, transport and buildings (see Appendix III). The electricity demand data of the sub-sectors within the same sector are summed to have a final distribution of electricity demand divided into the main sectors: agriculture, buildings, households, industry and transport (Figure 4.16).

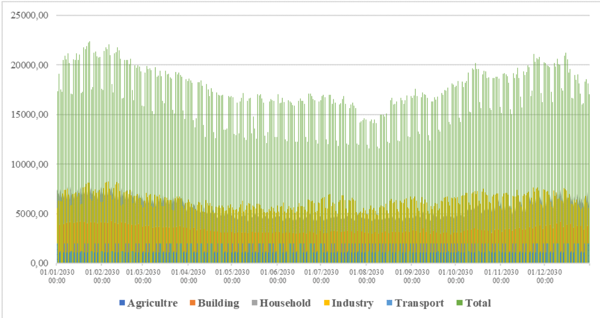

Figure 4.16: Hourly electricity demand per sector in MWh from ETM model

Klimaatmonitor database

Klimaatmonitor database [48] provides the yearly electricity demand in KWh per region divided into: the built environment, industry and agriculture (Table 4.9). The build environment is divided into: households, commercial and public services. To match with the data provided from ETM model, public and commercial services electricity are combined to represent electricity in building sector.

RES Regio	Households	Industry	Commercial Services	Public Services	Agriculture
Holland Rijnland	669.220.000	?	635.579.000	380.439.000	165.771.000
Achterhoek	381.570.000	415.356.000	305.471.000	133.388.000	127.561.000
Drechtsteden	341.380.000	?	314.100.000	153.216.000	12.771.000
Drenthe	623.940.000	449.610.000	505.689.000	284.976.000	136.960.000
Flevoland	478.360.000	219.029.000	640.332.000	215.197.000	221.339.000
Foodvalley	428.270.000	339.944.000	516.878.000	219.073.000	80.789.000
Friesland	727.620.000	688.576.000	638.821.000	324.441.000	182.227.000
Goeree-Overflakkee	60.640.000	9.301.000	70.416.000	27.658.000	19.544.000
Groningen	697.690.000	1.740.193.000	740.863.000	415.818.000	110.696.000
Hart-van Brabant	585.640.000	?	575.737.000	295.119.000	77.839.000
Hoeksche Waard	110.810.000	82.750.000	76.925.000	32.549.000	20.594.000
Metropoolregio Eindhoven	1.032.960.000	?	1.062.400.000	486.511.000	277.400.000

Rotterdam–Den Haag	2.753.820.000	4.581.159.000	3.915.724.000	1.693.780.000	1.611.378.000
Midden-Holland	274.350.000	151.373.000	286.078.000	105.267.000	247.877.000
Noord-Holland Noord	806.790.000	?	740.379.000	413.713.000	355.474.000
Noord-Holland Zuid	2.488.560.000	?	4.984.100.000	1.275.445.000	260.030.000
Noord Veluwe	214.310.000	?	209.913.000	96.889.000	29.409.000
Noord-en Midden Limburg	721.010.000	?	759.414.000	274.755.000	410.065.000
Noord-Oost Brabant	828.690.000	1.030.998.000	796.385.000	370.056.000	?
Alblasserwaard	94.130.000	?	75.618.000	42.474.000	14.826.000
Amersfoort	363.430.000	133.830.000	365.319.000	170.581.000	21.038.000
Arnhem Nijmegen U10/U16	877.700.000 1.121.600.000	? 429.421.000	835.136.000 1.313.993.000	513.934.000 615.886.000	? 91.079.000
Rivierenland	302.460.000	233.488.000	372.766.000	101.186.000	301.706.000
Cleantech regio	419.000.000	527.374.000	448.663.000	203.649.000	53.808.000
Twente	813.650.000	1.019.226.000	693.515.000	328.073.000	128.583.000
West-Brabant	928.470.000	?	1.074.520.000	422.154.000	?
West Overijssel	620.910.000	671.516.000	?	323.157.000	152.156.000
Zeeland	470.080.000	1.262.525.000	567.790.000	220.611.000	235.284.000
Zuid-Limburg	830.400.000	?	689.367.000	411.784.000	26.290.000

Table 4.9: Total electricity demand by sector in KWh from Klimaatmonitor [48]

As shown in Table 4.9 data is lacking for some regions, especially for the industry sector. Since the missing data is not available in another source, a forecasting approach is applied.

An example of the electricity demand forecast for the region Holland Rijnland is described below:
The historical data from 2010 to 2017 for the region Holland Rijnland is extracted from Klimaatmonitor [48] (Table 4.10).

Holland Rijnlad	2010	2011	2012	2013	2014	2015	2016	2017
Alphen aan den Rijn	46.706.000	49.823.000	43.238.000	45.342.000	45.936.000	41.410.000	40.083.000	42.432.000
Hillegom	12.660.000	13.731.000	14.512.000	15.029.000	15.392.000	14.558.000	15.024.000	14.470.000
Kaag en Braassem	7.365.000	7.985.000	8.843.000	9.505.000	9.413.000	9.007.000	8.570.000	8.284.000
Katwijk	50.135.000	49.948.000	?	51.099.000	52.491.000	32.911.000	31.764.000	?
Leiden	58.499.000	76.656.000	68.152.000	73.822.000	64.081.000	55.626.000	58.606.000	?
Leiderdorp	?	?	4.115.000	2.324.000	2.166.000	2.863.000	1.005.000	1.011.000
Lisse	9.369.000	9.788.000	9.816.000	10.212.000	9.590.000	9.083.000	?	9.132.000
Nieuwkoop	16.137.000	15.246.000	18.422.000	19.958.000	19.776.000	18.962.000	19.669.000	19.669.000
Noordwijk	11.887.000	12.119.000	13.322.000	13.216.000	12.724.000	12.236.000	12.247.000	12.842.000
Oegstgeest	2.802.000	3.046.000	2.413.000	1.174.000	1.378.000	1.258.000	1.130.000	2.165.000
Teylingen	32.886.000	32.988.000	30.920.000	31.862.000	?	31.000.000	34.345.000	32.510.000
Voorschoten	3.400.000	2.634.000	2.221.000	2.440.000	?	2.495.000	2.016.000	?
Zoeterwoude	25.829.000	23.149.000	24.654.000	26.244.000	?	28.132.000	41.122.000	33.307.000

Table 4.10: Total industry electricity demand fro the region Holland Rijnland between 2010-2017 in KWh [48]

A linear regression method (Figure 4.17) is applied for every missing demand data within the municipalities of Holland Rijnland region to find the electricity demand for the year 2017.

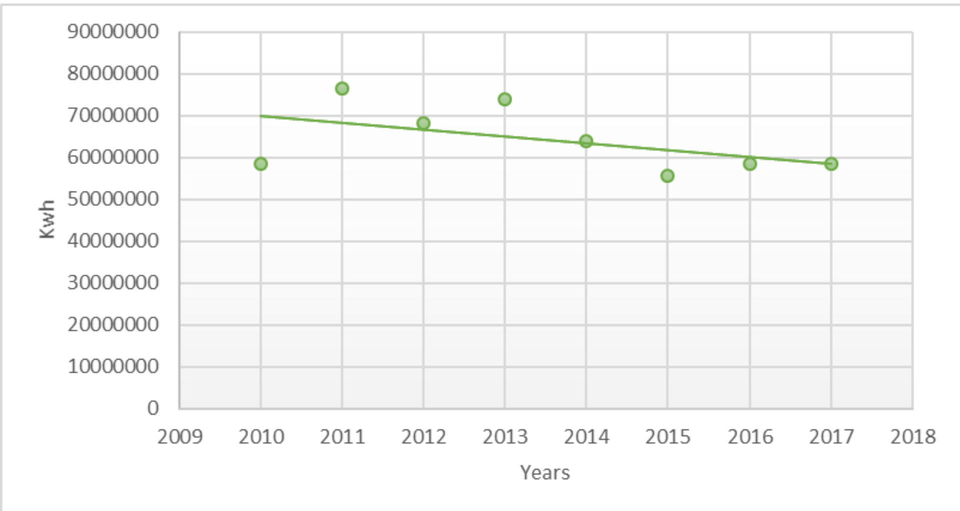

Figure 4.17: Linear regression for Leiden

The forecast method is then applied to all missing data for all energy regions. Therefore, the electricity distribution within the energy regions for the four sectors is found (Figure 4.18).

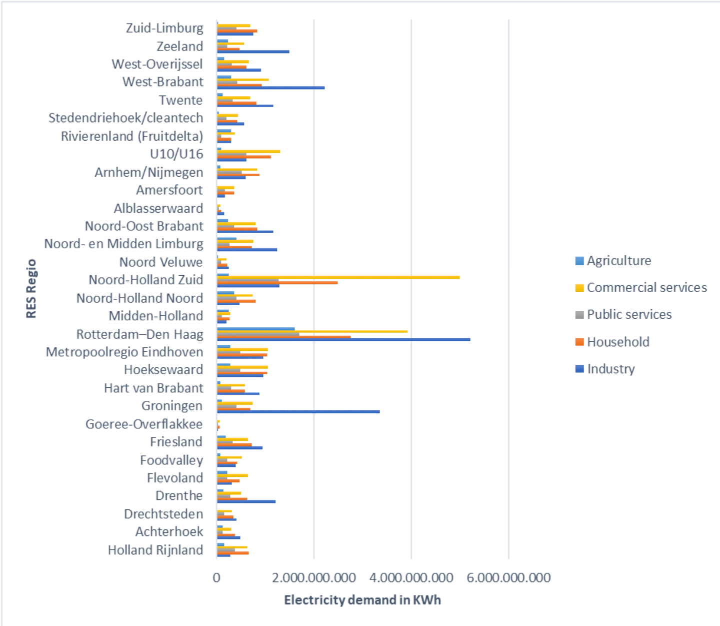

Figure 4.18: Annual electricity demand for RES regions in KWh

The electricity demand for transport sector within the energy regions is not provided in Klimaatmonitor. A scaling down of the annual hourly demand is done based on the number of electrical cars and buses per region (see Appendix V).

Comparison between Klimaatmonitor database and ETM

The annual electricity demand between the two sources is different, especially regarding agriculture sector, where in klimaatmonitor database is equal to 23 PJ and in ETM model is more than 34 PJ for the year 2017. Therefore, a reference data is needed. The data chosen is the electricity demand data provided by KEV 2019 [67], since it is the latest published data so far (Table 4.11).

Sector	Electricity demand in PJ
Industry	156
Households	81
Agriculture	34
Building	121
Transport	7

Table 4.11: Total electricity demand [67]

The electricity demand of agriculture sector in 2017 is 34 PJ. Therefore, the data provided by Klimaatmonitor was increased from 23 PJ to 34 PJ. The electricity demand in each energy region was increased in proportion to its share in the total annual demand.

Scaling down the electricity demand data

Now that the total electricity demand is matching between ETM and Klimaatmonitor database, the yearly electricity demand of every sector from ETM is distributed to the 30 buses in proportion to the total annual electricity demand, as determined by Klimaatmonitor database. An example for the region Holland Rijnland is displayed in Figure 4.19.

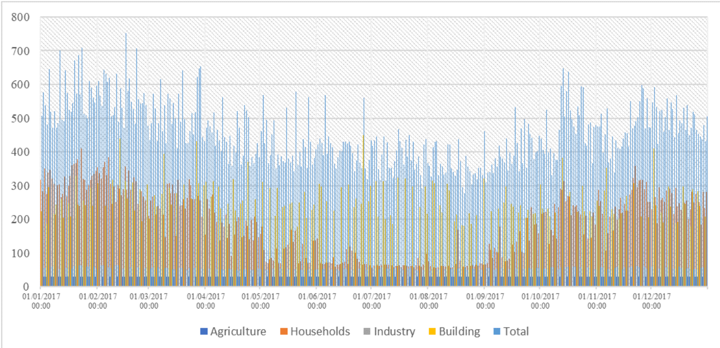

Figure 4.19: Holland Rijnland electricity demand by sector in MWh

The Load

In PyPSA model the hourly electricity demand profiles for each region can be represented by one data input only. Therefore, the electricity demand of all sectors are aggregated within the same region (Figure 4.20).

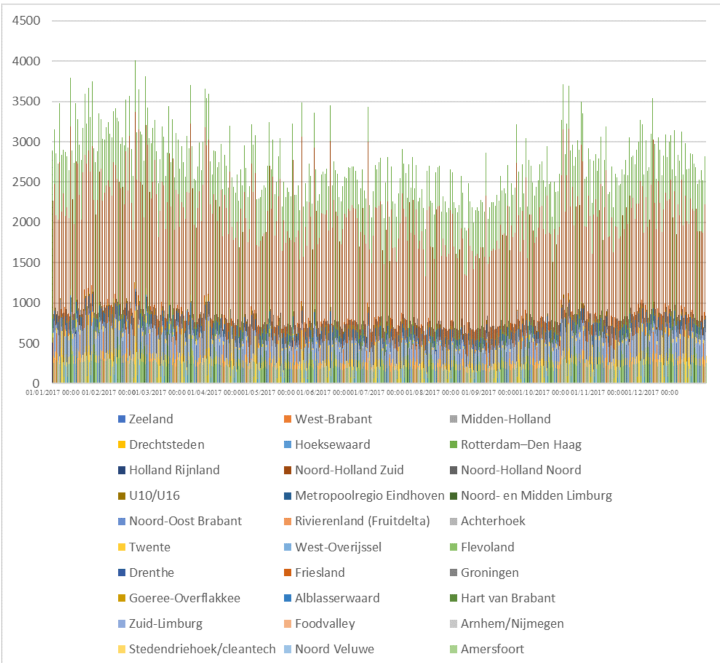

Figure 4.20: Hourly electricity demand by energy region in MWh

4.2.3 Power generation resources

In this paragraph the data regarding the installed capacity of both fossil fuel and renewable energy sources are gathered and divided within the thirty regions.
Installed capacity of power plants is different from one source to another. To avoid collecting wrong input data, a reference is used for the total installed capacity in the Netherlands based on the European Network of Transmission System Operators for Electricity (ENTSO-E) [20] for fossil fuel, nuclear and biomass generation (Figure 4.21) and the Centraal Bureau voor de Statistiek (CBS) [13] for vRES (Figure 4.22).

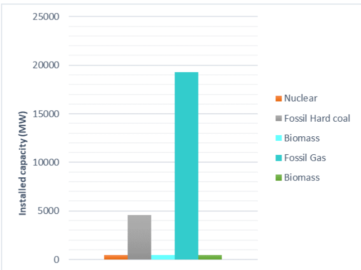

Figure 4.21: Installed capacity "ENTSO-E" in 2017 [20]

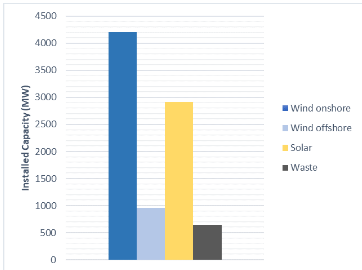

Figure 4.22: Installed capacity "CBS database" in 2017 [13]

4.2.3.1 Wind onshore

The installed capacity of wind onshore is retrieved from Klimaatmonitor, where it is divided over the thirty regions (Figure 4.23).

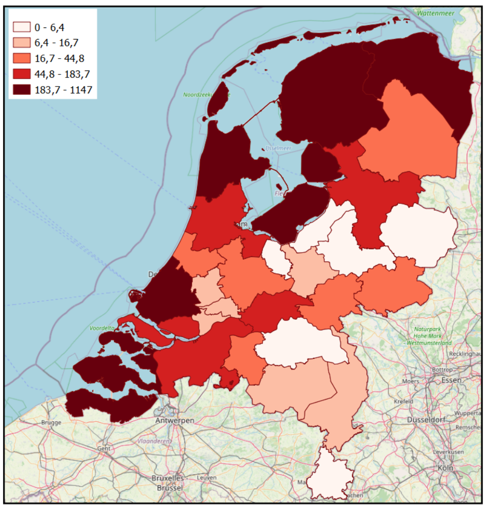

Figure 4.23: Wind onshore capacity distribution in MW (2017)

Flevoland, Groningen and Zeeland are the regions with the highest share of wind onshore power. However, Amersfoort and Twente regions had 0 MW installed capacity in 2017.

4.2.3.2 Solar

The solar installed capacity is divided into two main categories: small installed capacity (<15 kW) and big installed capacity (>15 kW), that incorporates roofs of home, solar parks of businesses and roofs of businesses. The solar capacity provided by Klimaatmonitor is summed and displayed in Figure 4.24. Friesland, Noord-Holland Zuid, Drenthe and Groningen are the regions with the most installed capacities.

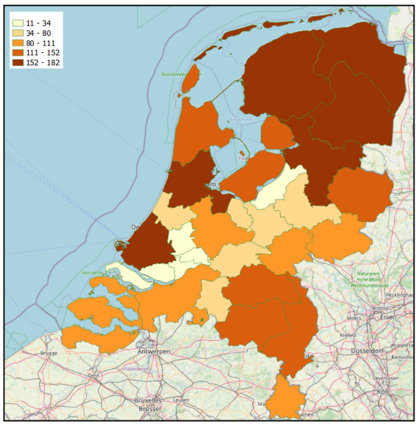

Figure 4.24: Solar capacity distribution in MW (2017)

4.2.3.3 Waste & biomass

The installed capacity of waste and biomass is provided by CBS divided into the eight provinces. The data is adapted to represent the energy regions (Figure 4.25).

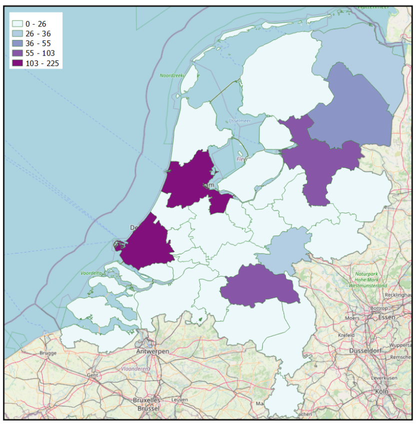

Figure 4.25: Waste power plants capacity distribution in MW (2017)

4.2.3.4 Wind offshore

Rijksdienst voor Ondernemend Nederland (RVO) provides the installed capacity for wind offshore projects (Figure 4.26). For the year 2017, 954 MW installed capacity of wind offshore energy was achieved in the Netherlands.

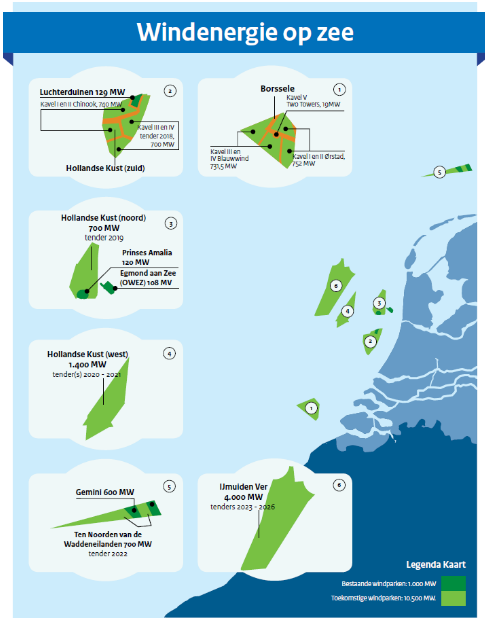

Figure 4.26: Actual and planned wind offshore projects [62]

The two first installed wind farms in the North Sea are "Egmond aan Zee (OWEZ) and the Prinses Amalia wind farm, with an installed capacity of 108 MW and 120 MW respectively" [77]. The two wind farms are connected to the electricity grid through NoordZeeWind/OWEZ 150kV substation which is located in Noord-Holland Zuid region. The third windfarm is Luchterduinen with a capacity of 129 MW [77], which is connected to Sassenheim 150kV located in Holland Rijnland region.
The last wind farms are the Buitengaats and Zee-Energie with a joint capacity of 600 MW [77]. Contrary to the other wind parks, they are connected through a 220kV transmission lines to Eemshaven-Gemini 220kV substation that is located in Groningen.

Each wind farm is connected to a bus in the HV grid through transmission lines. Both the transmission lines and the buses that connect the wind farm projects to the HV grid can be located using HoogspanningsNet. Therefore, each wind farm project was affiliated to an energy region based on the location of the buses they are connected to in the HV grid.

4.2.3.5 Gas power plants

TenneT provides the installed capacity of each production unit for every quarter of the year, where gas power plants can be filtered by choosing the fuel type equal to E06. For each production unit and fuel type the following data is given [84]:
"The name of the connected party, the capacity in MW, the location of the connection of the production unit, the name of the production unit".
The analysis of the data provided by TenneT shows that the gas installed capacity used for the year 2017 corresponds to 14302 MW, which is different than the total capacity given by Entso-E that is equal to 19297 MW. Therefore, another source is required to find the missing installed capacities.

Different sources are listed in literature to extract the installed capacity of gas power plants as Global Energy Observatory (GEO), Open Power System Data (OPSD), Carbon Monitoring for Action (CARMA) and Joint Research Centre Hydro-power plants database (JRC). To facilitate the extraction of the data and the comparison between the sources, the toolset “Powerplantsmatching” is used [28].
“Powerplantsmatching” can extract data regarding power plants from "ENTSO-E", "GEO","CARMA", "OPSD", "JRC" and in the same time compare the extracted data between the sources (Figure 4.27).

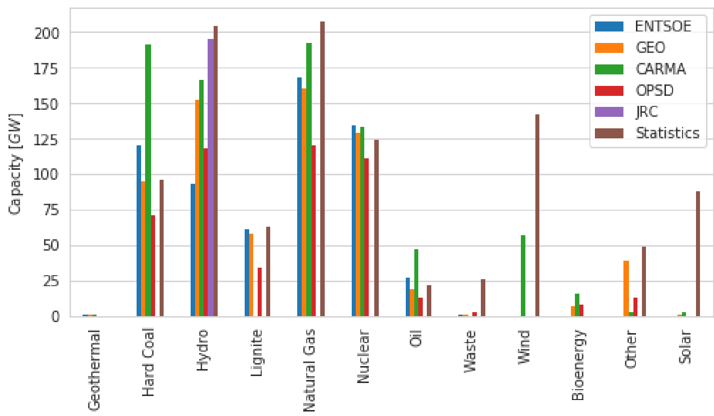

Figure 4.27: Installed capacities of fossil fuels, nuclear energy and vRES by source

The toolset is customized to include the Netherlands and gas power plants only. The data afterwards is merged within all the sources to avoid duplicated information and to have a global representation of the power plants. The result shows that the total installed capacity of gas power plants in the Netherlands is almost equal to 18000 MW. Moreover, all the power plants found in TenneT are provided in "powerplantsmatching" with their exact installed capacity. The gas power plants missing from TenneT data are shown in Table 4.12.

Power plant	**Installed capacity in MW**
Eem ec	1798
Ijmond	144
Maasstroom energie cv	427
Merwedekanaal	103
Sloecentrale	864

Table 4.12: Gas power plants installed capacity (MW)

To localize the power plants, TenneT provides the name of cities and "Powerplantsmatching" gives the coordinates (Figure 4.28).

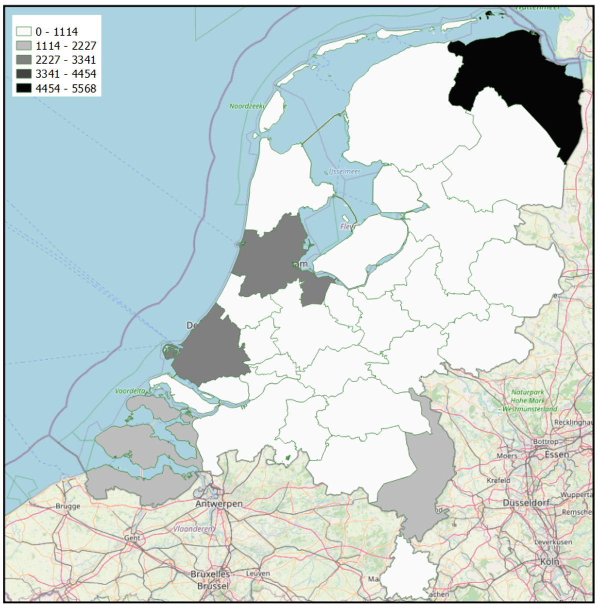

Figure 4.28: Gas installed capacity distribution

4.2.3.6 Coal power plants

The installed capacity of coal power plants is retrieved from the webpage of TenneT (Table 4.13) [84], where the fuel type is set to E05. Four quarters for the year 2017 are analysed. The location of the power plants within the thirty regions is presented in Figure 4.29.

connected-body	entity	city	fuel	capacity
ESSENT ENERGY TRADING B.V.	CUIJK	Katwijk (NB)	E05	25
NUON	Willem Alexander Centrale	Haelen	E05	249
EON BENELUX	Centrale Maasvlakte (MV1)	Rotterdam Maasvlakte	E05	555
ESSENT ENERGY TRADING B.V.	Amercentrale (A8)	Geertruidenberg	E05	645
ESSENT ENERGY TRADING B.V.	Amercentrale (A9)	Geertruidenberg	E05	640
EON BENELUX	Centrale Maasvlakte (MV3)	Maasvlakte Rotterdam	E05	1068
GDF SUEZ ENERGIE NEDERLAND NV	MVL380 Centrale Rotterdam 1	Maasvlakte Rotterdam	E05	731
NUON	Centrale Hemweg (HW-8)	Amsterdam	E05	650

Table 4.13: Coal power plants in the Netherlands

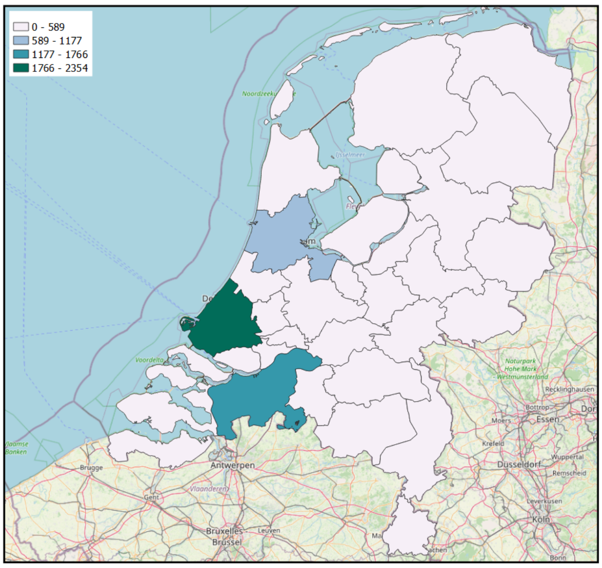

Figure 4.29: Coal installed capacity distribution in MW

The installed capacity of coal is mainly located in Rotterdam-Den Haag, West-Brabant and Noord-Holland Zuid regions.

4.2.3.7 Summary

The power generation resources: gas, coal, nuclear, biomass, waste, solar, wind onshore and wind offshore, are clustered within the different regions with their respective installed capacity (Figure 4.30), in which they are attached at the bus of their supply area.

In 2017, the installed capacity of the different power generation technologies in Groningen was 6830 MW, due mainly to gas generation. The regions Rotterdam/Den Haag and Noord-Holland Zuid had in average 3500 MW of installed capacity. The regions with the least installed capacities are Alblasserwaard, Drechtsteden and Hoeksche Waard with an average of 25 MW.

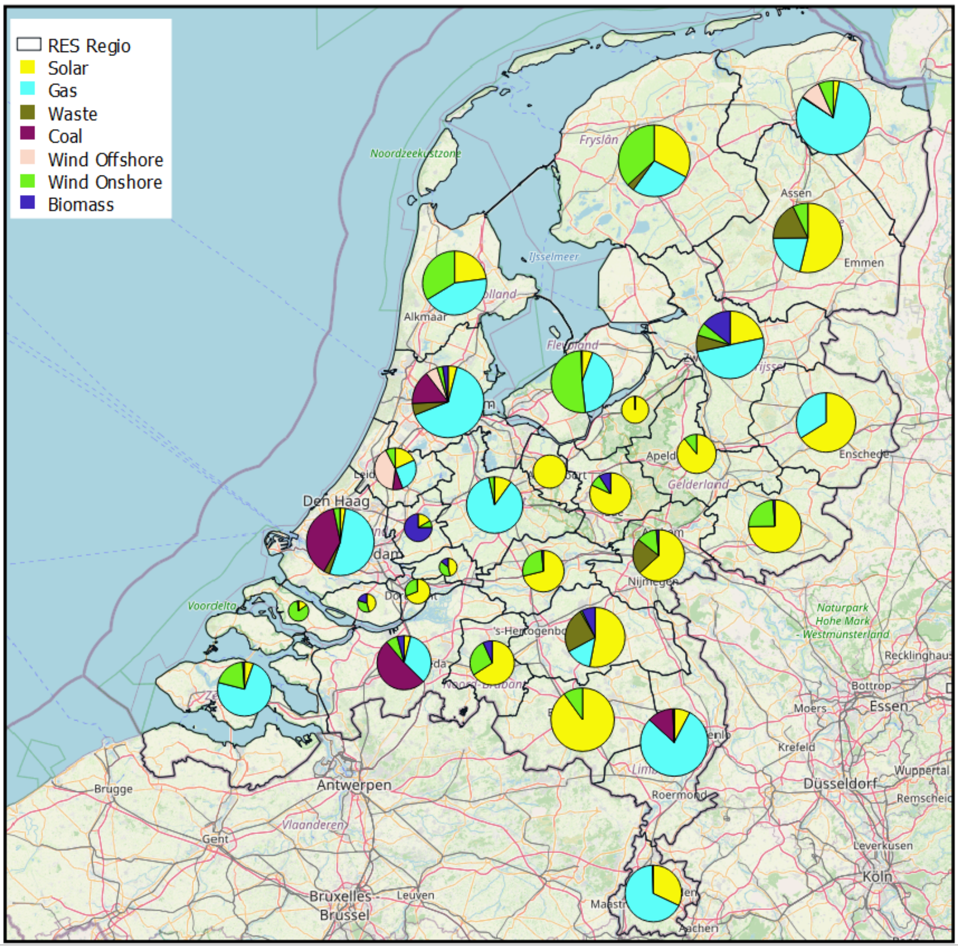

Figure 4.30: Installed capacity distribution within the thirty regions in 2017

4.2.4 Capacity factor

Meteorological data for renewable energy resources is essential to determine the capacity factor (also called per-unit availability time-series) of solar and wind generators.

The capacity factor (Figure 4.31) for both wind onshore and offshore is computed for each supply region in the year 2017 using the website www.renewables.ninja [83], in where the specifications of the wind turbines are set to 80 m for the turbine height and VestasV90 3000 for the turbine mode. The choice of these specifications is based on the study described in [96].

The installed capacity of the wind generators is then multiplied by the per-unit availability time-series $g_{n,s,t}$ for every hour of the year to find the available wind power feed-in in MW.

For solar power, the specifications of solar photovoltaics are 37 degrees for the tilt (which is considered as an optimal title angle for the Netherlands) and 180 degrees for the Azimuth

[79]. For every supply area, which is represented by a substation, the capacity factor is computed through the website www.renewables.ninja as well.

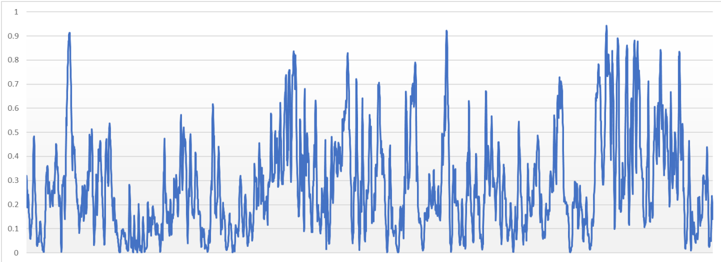

Figure 4.31: Wind capacity factor for the region Zeeland in 2017 [83]

5 Optimization model

Now that the Dutch power system is modelled, the tool PyPSA will be applied to run the linear optimal power flow using the Kirchhoff formulation and the commercial optimization solver Gurobi.

In order to guarantee the network security, n-1 criterion is applied to all power lines in the model, by allowing the loading up to 50% on their thermal capacity limit.
In this chapter, the modelling objectives for the different scenarios will be delineated along with the description of the optimization problem. The theories used are described in Appendix II.

5.1 Model objectives

The model is intended to solve three different optimization problems:

- Reference case: the optimal dispatch of generation and transmission lines.
- First objective: the optimal dispatch of generation, storage and investment in storage and transmission lines.
- Second objective: the optimal dispatch of generation, storage and investment in generation, storage and transmission lines.

The connections between the different objectives is displayed in Figure 5.1.

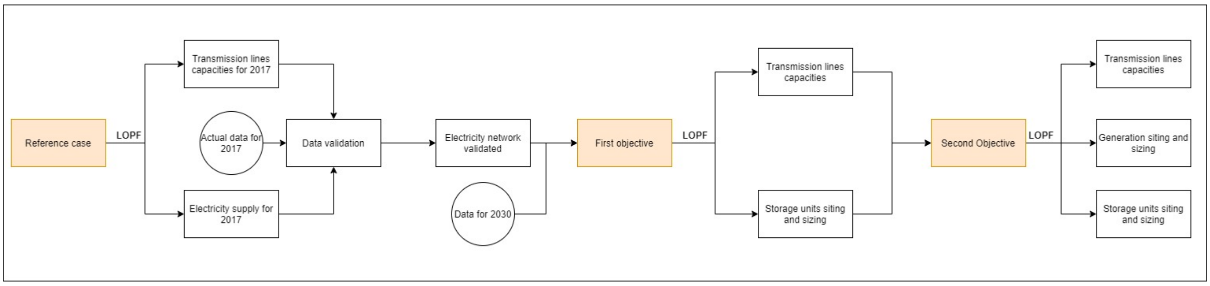

Figure 5.1: Objectives flowchart

5.1.1 Reference case

For the reference case, the objective of the model is the optimization of the generation dispatch based on the marginal costs of the different generators under consideration of grid constraints, while following the central criterion of meeting the load. The n-1 criterion will not be used in the reference case, meaning that the capacity of the transmission lines can be used fully. Allowing the transmission lines to reach their thermal capacity limit will help in:

- Identifying the most loaded transmission lines in the network.
- Adjusting transmission lines capacities in case the model can not converge to find an optimal solution.

Therefore, the model will provide two main outputs: the total electricity supply for the year 2017 and the transmission lines capacities needed between the regions. The results regarding the annual electricity supply from the various generation sources can be compared with the actual data for the year 2017 provided by NEV 2019.

5.1.2 First objective

The first objective of this thesis is finding the necessary energy storage systems and transmission lines capacities to incorporate the planned 26 TWh of electricity generation from large-scale solar PV and wind onshore. Therefore, the model is intended to find the optimal investment costs in storage units and transmission lines, and the dispatch in generation and storage units by performing the LOPF. The main outcome of the model are:

- The sitting and the sizing of the storage units.
- The necessary capacity of the transmission lines.
- The electricity supply by fuel type.

Additional results can be computed with the help of PyPSA model: the loading on the transmission lines along with the locational marginal price.
The necessary storage units and transmission lines to implement the planned 26 TWh of electricity generation will be used as input data in the following optimization problem.

5.1.3 Second objective

The second objective consists of finding the necessary installed capacity to meet the planned 35 TWh of large-scale solar PV and wind onshore based on the outcome of the first optimization problem. Therefore, the LOPF will be used to find the optimal investment in large-scale solar PV and wind onshore to generate the remaining 9 TWh along with the necessary storage units and transmission lines capacities. The main outcome of the model are:

- The sitting and the sizing of the electricity generation from large-scale solar PV and wind onshore.
- The sitting and the sizing of the storage units.
- The necessary capacity of the transmission lines.
- The electricity supply by fuel type.

Similar to the first objective, the loading on the transmission lines along with the locational marginal price can be computed as well.

5.2 Model Description

The Dutch power system is modelled as a thirty-region power system reflecting both the national energy strategy and the electricity grid. In this model, each energy region is represented by a single bus (except for Groningen), where electricity supply and demand of a specific region are affiliated to. The supply is characterised by different generation portfolio, that are constituted by the combination of eight generation technologies: gas, coal, biomass, waste, nuclear, wind onshore, wind offshore and solar. The analysis will be made only regarding gas, coal and vRES, because no data is available regarding the installed capacity of biomass, waste and nuclear by 2030.

Mathematical formulation

The optimization model is a linear optimal power flow model that minimizes the total annual system costs given technical and physical constraints. The costs include the variable and fixed costs of generation, storage and transmission.

5.2.1 Objective function

The objective function of the linear optimal power flow problem performed in this thesis is shown in Equation 5.1, where s refers to storage unit, m to buses, l to branches, r to generators and t to time. The optimization variables are the annualized lines fixed costs (F_l), storage investments ($H_{m,s}$), and the generation dispatch of both storage units ($h_{m,s,t}$) and generators ($p_{m,r,t}$), where the marginal costs of storage units and generators are respectively ($o_{m,s}$) and ($o_{m,r}$) which are important for the dispatch optimization and can be expressed in (EUR/MWh). The fixed capital costs for storage units s are defined by $c_{m,s}$ in (EUR/MW). The time steps (called snapshots) are weighted by the parameter w_t that can take values from 0 to 8760. The optimisation is run over all hours t for a specific year with fluctuated supply and load conditions. The variable and parameters are defined in the table below (Adapted from [44]).

Variables, coefficients and indices	
M	total number of buses
L	total number of transmission lines
S	total number of storage units
R	total number of generators
T	total hours of the time interval
m $\in \{1, .., M\}$	bus label
l $\in \{1, .., L\}$	line label
s $\in \{1, .., S\}$	storage unit label
r $\in \{1, .., R\}$	generator label
t $\in \{1, .., T\}$	time step
w_t	weight of the snapshot
$g_{m,r,t}$	generator dispatch (MW)
$G_{m,r}$	generator power capacity (MW)
$\tilde{G}_{m,r}$, $\bar{G}_{m,r}$	minimum and maximum install-able generator potential (MW)
$\tilde{g}_{m,r}$, $\bar{g}_{m,r}$	minimum and maximum power availablility $\in \{0, 1\}$
$o_{m,r}$	marginal cost of a generator (EUR/MWh)
K	M x L incidence matrix
pn,t	total active power injection at a bus m (MW)
$f_{l,t}$	power flow at a line l at time interval t (MW)
F_l	power rating at a line (MW)
B	diagonal L x L matrix of line susceptances
$\theta_{m,t}$	voltage angle at a bus m at time interval t (rad)
$y_{m,t}$	inleastic load (MW)
$h_{m,s,t}$	dispatch of a storage unit (MW)
$H_{m,s}$	power capacity of a storage unit (MW)
$\tilde{h}_{m,s,t}$, $\bar{h}_{m,s,t}$	power availability per unit of storage capacity
$\tilde{H}_{m,s}$, $\bar{h}_{m,s}$	installable potential of a storage unit (MW)
$u_{m,s,t}$	state of charge of a storage unit (MWh)
$q_{m,s}$	hours at nominal power to fill up a storage unit
$\eta_{m,s,-}$, $\eta_{m,s,+}$	charging and discharging efficiency
$o_{m,s}$	marginal cost of storage units (EUR/MWh)
$c_{m,s}$	capital cost of storage units (EUR/MW)
c_l	fixed cost of a transmission line l (EUR/MW$_{km}$)

$$\min_{H_{m,s},g_{m,r,t},o_{m,s},F_l}[\sum_t(w_t(\sum_{m,r,t} o_{m,r}g_{m,r,t} + \sum_{m,r,t} o_{m,s}h_{m,s,t})) + \sum_{m,s} c_{m,s}H_{m,s} + \sum_l c_lF_l] \quad (5.1)$$

where, w_t is equal to 1 and $\sum_t w_t$ is equal to 8760.

This objective function is subject to a number of constraints [11] described in the following subsections.

5.2.2 Power balance and transmission lines constraints

$$\sum_l K_{m,l}f_{l,t} = \sum_r p_{m,r,t} + \sum_s h_{m,s,t} - y_{m,t} \qquad \forall m,t \quad (5.2)$$

where, $y_{n,t}$ is the inelastic load that needs to be met either by generator, the capacity flow $f_{l,t}$ of a transmission line l or storage units each time t.

The Kirchhoff current laws; Current Law and Voltage Law; take the following form:

$$p_{m,t} = \sum_l K_{m,l}f_{l,t} \qquad \forall m,t \quad (5.3)$$

$$f_{l,t} = \sum_n (BK^T)_{lm}\theta_{m,t} \qquad \forall m,t \quad (5.4)$$

$$\theta_{0,t} = 0 \qquad \forall t \quad (5.5)$$

The power flow constraint is:

$$|f_{l,t}| \leq F_l \qquad \forall t,l \quad (5.6)$$

where, all branches $f_{l,t}$ are constrained by their capacities F_l.

5.2.3 Generator constraints

For conventional generators, their dispatch ($p_{m,r,t}$) is constrained by their capacity $P_{m,r}$

$$\tilde{P}_{m,r} \leq p_{m,r,t} \leq \bar{P}_{m,r} \qquad \forall m, r, t \tag{5.7}$$

The dispatch of renewable energy generators on the other hand depends on weather conditions. As a consequence, this dispatch is translated to an availability $\bar{p}_{m,r,t}$ per units of its capacity:

$$\tilde{p}_{m,r,t} P_{n,r} \leq p_{m,r,t} \leq \bar{p}_{m,r,t} P_{m,r} \qquad \forall m, r, t \tag{5.8}$$

Generators power capacity is also constrained by the maximum install-able potential capacity.

$$\tilde{P}_{m,r} \leq P_{m,r} \leq \bar{P}_{m,r} \qquad \forall m, r \tag{5.9}$$

5.2.4 Storage operation

The storage dispatch and power generation are constrained by their maximum capacity [44],

$$\tilde{h}_{m,s,t} H_{m,s} \leq h_{m,s,t} \leq \bar{h}_{m,s,t} H_{m,s} \qquad \forall m, s, t \tag{5.10}$$

$$\tilde{H}_{m,s} \leq H_{m,s} \leq \bar{H}_{m,s} \qquad \forall n, s \tag{5.11}$$

The state of charge of storage units is subject to two constraints [44]:

$$0 \leq e_{m,s,t} \leq q_{m,s} Hm, s \qquad \forall m, s, t \tag{5.12}$$

and time linking constraint [44],

$$u_{m,s,t} = \eta_{m,s,0} u_{m,s,t-1} + \eta_{m,s,+}[g_{m,s,t}]^{+} - \eta^{-}_{m,s,-}1[g_{m,s,t}]^{-} \qquad \forall m, r, t \tag{5.13}$$

"The Positive and negative components of the equation are expressed by $[.]^{+} = max(;0)$, $[.]^{-} = min(.;0)$" [44]. The storage units have a charging and discharging efficiency denoted respectively by $\eta_{m,s,+}$ and $\eta_{m,s,-}$.

6 Simulation setups

In this chapter the different scenarios will be defined along with the assumptions made in each scenario for 2030. Two main scenarios are considered: Scenario ES and Scenario RES. Within each scenario, two sub-scenarios are identified regarding the installed capacity of the planned large-scale solar PV projects: achievement of 50%/100% of the planned projects.

6.1 Scenarios definition

In order to capture the uncertainty in electricity demand and generation in the Dutch power system for 2030, different scenarios are incorporated in PyPSA model (Figure 6.1).

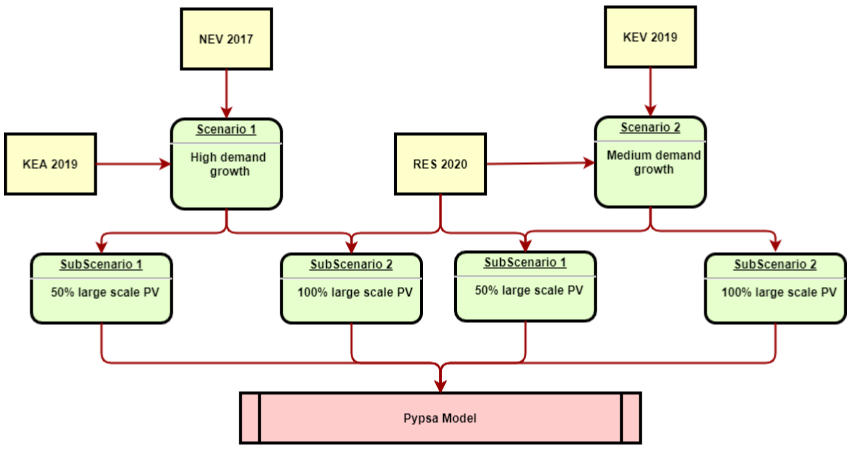

Figure 6.1: Scenario chart

Two main scenarios demonstrates the uncertainty in electricity demand:

- The energy system 2030: reflects the vision of the National Energieverkenning 2017 [18] and the plans of the draft Climate and Energy Agreement (KEA) 2019 [76], where the electricity demand growth is expected to be 455 PJ.
- The regional energy strategy 2030: translates the plans of the Klimaat- en Energieverkenning 2019 [67] and the Regional Energy Strategy (RES) 2020 [75], where the electricity demand growth is expected to be 427 PJ.

Two sub-scenarios are based on the RES 2020 forecast and capture the uncertainty in electricity supply:

- 50% of large-scale planned solar PV projects are achieved.
- 100% of large-scale planned solar PV projects are achieved.

The sub-scenarios are incorporated in each main scenario to capture the uncertainty in both electricity supply and demand. Then, implemented in PyPSA model.

6.1.1 Reference case

The reference case represents the year 2017, in which the latest data of electricity demand of the energy regions is published. The electricity installed capacity and demand are described in details in Chapter 5. Figure 6.2 gives a summary of the results (the electricity demand in each region in KWh and the installed capacity of the various generation sources in MW).

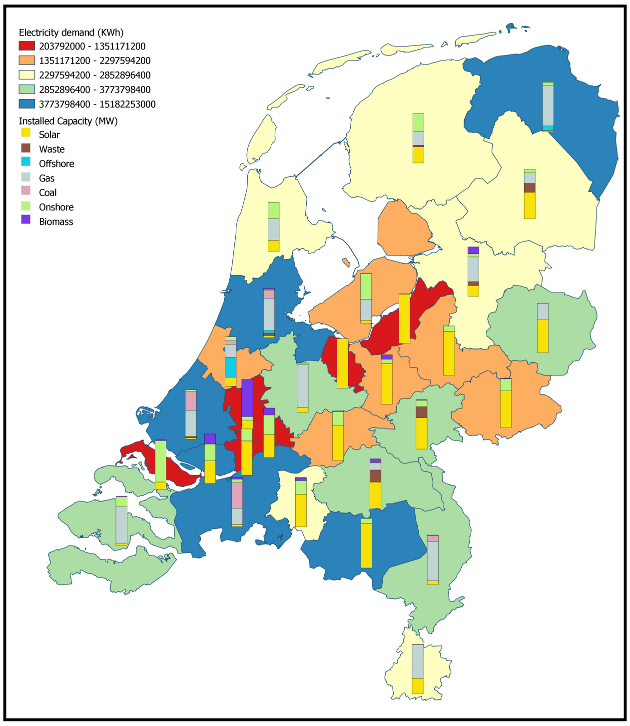

Figure 6.2: Installed capacity (MW) and total electricity demand (kWh) within the energy regions in 2017

The regions with the high electricity demand (blue colour) are:

- Rotterdam-Den Haag and Noord-Holland Zuid regions due to industry, households, and commercial services sectors.
- Noord-Holland Zuid, U10/16 and Eindhoven regions due to households and

commercial services sectors.

- West-Brabant region due to industry and commercial services sectors.
- Zeeland, Groningen, Noord-Oost Brabant and Drenthe regions due to industry sector.

6.1.2 Main scenarios 2030

In this section, the two main scenarios will be presented: Energy System (ES) 2030 scenario (where the electricity demand growth is high) and Regional Energy Strategy (RES) 2030 scenario (where the electricity demand growth is medium).

6.1.2.1 Energy system 2030

Climate Neutral Strategies (Kalavasta) [45] together with the Energy Transition Model [22] created a scenario [21] based on existing policies: the National Energieverkenning 2017 and the plans of the draft Climate and Energy Agreement 2019. The scenario is incorporated in the ETM interface, in which the forecast electricity demand and supply are described in details. In this thesis only the data regarding the electricity demand is used.

6.1.2.1.1 Energy-saving

energy-saving used in the NEV 2017 follows the Energy Saving Monitoring Protocol (PME). In the PME, energy-saving results from "concrete actions by citizens and companies, such as investments in building insulation, more efficient equipment, lighting and vehicles" [18]. The energy-saving in the different sectors is presented in Table 6.1.

Sector	**Efficiency 2017-2030**
Households	1.7
Building	1.5
Transport	1.5
Industry	0.8
Agriculture	-0.8

Table 6.1: Energy-saving by sector NEV 2017 [18]

6.1.2.1.2 Electricity demand growth

ETM gives the hourly electricity demand for 2030 for all sectors. A linear growth of electricity demand of the energy regions between 2017 and 2030 is assumed. The annual electricity demand for the year 2030 is presented in Table 6.2.

Sector	Electricity demand (PJ)
Households	86.12
Building	113.88
Transport	25.33
Industry	184.55
Agriculture	35.27
Other	0.36

Table 6.2: Energy demand by sector 2030 in ETM [22]

The electricity demand growth of the different sectors as described by the NEV 2017 is displayed in Appendix VII.

6.1.2.2 Regional Energy Strategy 2030

In this scenario the Klimaat- en Energieverkenning 2019 and the Regional Energy Strategies 2020 [75] are used, where the total electricity demand for the year 2030 per region for buildings, households is forecast following the method described in [16]. The total electricity demand for industry, transport and agriculture is taken from the KEV 2019, where a linear growth of the electricity demand is assumed.

6.1.2.2.1 Energy-saving

The electricity saving as described in KEV 2019 is displayed in Table 6.3.

Sector	2000-2010	2013-2020	2020-2030
Households	1.3	2.1	1.0
Building	0.7	1.9	1.5
Transport	0.1	1.2	1.2
Industry	1.0	0.7	0.5
Agriculture	3.8	0.6	0.3

Table 6.3: Energy-saving by sector (%) [67]

6.1.2.2.2 Electricity demand growth Households

Electricity demand for households in 2030 is computed on the basis of three components as described in [16]:

1. Households electricity demand for 2017.

   The households electricity demand for 2017 is described in Chapter 5.

2. The growth in the number of households for 2030.

   The number of households in 2030 can be extracted from PRIMOS website [69], where the data is given by municipality. However, the list of municipalities provided by PRIMOS follows the old division of the Netherlands before 2019. Therefore, the list is updated, in where some municipalities are merged with others. Then, the growth of the number of households between 2017 and 2030 is calculated (Figure 6.3).

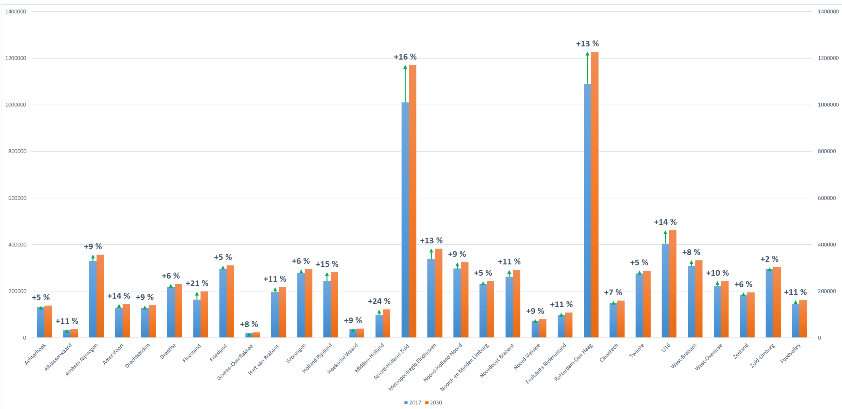

Figure 6.3: Number of households for 2017 and 2030

3. Expected average efficiency improvement from 2017 to 2030

   The expected energy efficiency (Table 6.3) in households between 2017 and 2030 can be computed as follow:

$$\eta_{2017,2030} = (1 - \eta_{2017,2020})^3 (1 - \eta_{2020,2030})^{10} = 0.848 \tag{6.1}$$

   Where, $\eta_{2017,2020} = 0.021$ and $\eta_{2020,2030} = 0.01$.

As a result the electricity forecast for 2030 per region is computed as follow:

$$d_{2030} = d_{2017} * G_{2017,2030} * \eta_{2017,2030} \tag{6.2}$$

Where, d_{2030} and d_{2017} are respectively the electricity demand for 2030 and 2017, and $G_{2017,2030}$ is the expected growth in the number of households between 2017 and 2030.

The final electricity demand of households for 2030 is shown in Figure 6.4, where the total electricity demand is equal to 71 PJ.

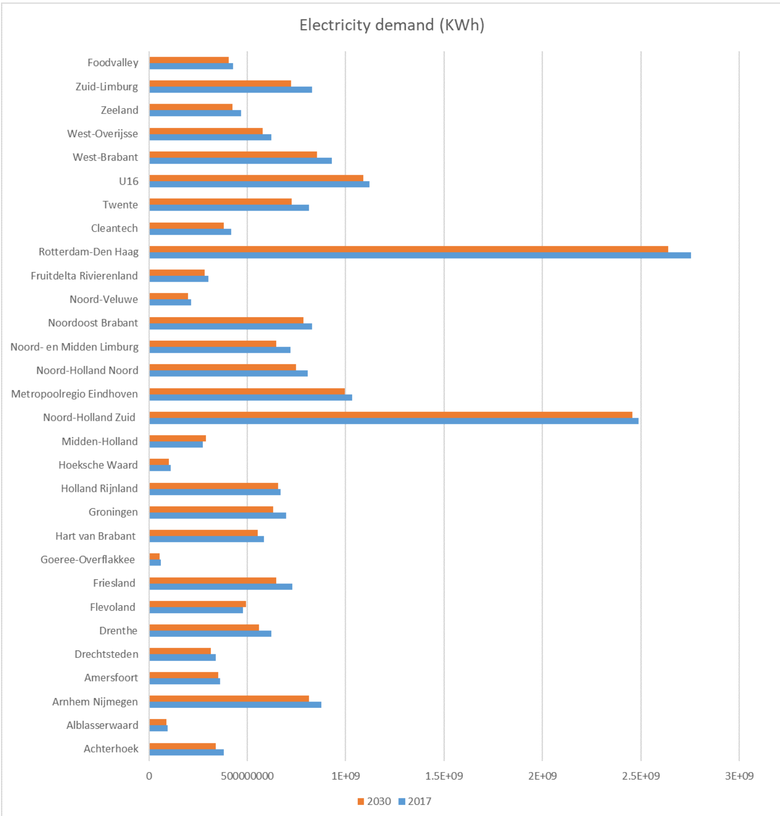

Figure 6.4: Households electricity demand for 2017 and 2030 in KWh

Buildings

Similar to households electricity demand, electricity buildings demand for 2030 is based on three elements: the electricity demand in buildings for 2017, the energy efficiency in buildings and the growth in the number of buildings for 2030. The method described in [16] assumes that the energy demand of the service sector scales linearly with the number of jobs in the service sector, which is extracted from Welvaart en Leefomgeving (WLO) 2015 [66].

First, WLO 2015 gives two growth scenarios for 2030: Low and high. The average between the two scenarios will be used.

Second, WLO 2015 data is divided following the Coördinatiecommissie Regionaal Onderzoeksprogramma (COROP) regions. COROP regions consists of three different regions: randstad (Holland, Utrecht and Flevoland), intermediaire zone (Overijssel, Gelderland and Noord-Brabant) and the rest of the Netherlands. Therefore, the data within each COROP regions will be assigned to the appropriate energy region.

Last, the reference year in WLO 2015 is 2012. An assumption of a linear growth is made, to change the reference year to 2017.

As a result, the building growth between 2017 and 2030 is computed and displayed in Figure 6.5.

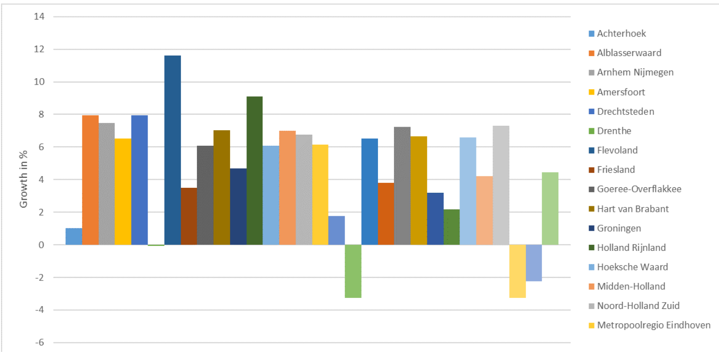

Figure 6.5: The growth in number of jobs in the energy regions for 2030

The energy efficiency in buildings is computed similarly to the households energy efficiency:

$$\eta_{2017,2030} = (1 - \eta_{2017,2020})^3 (1 - \eta_{2020,2030})^{10} = 0.850400427 \tag{6.3}$$

Therefore, the building electricity demand by 2030 is computed (Figure 6.6).

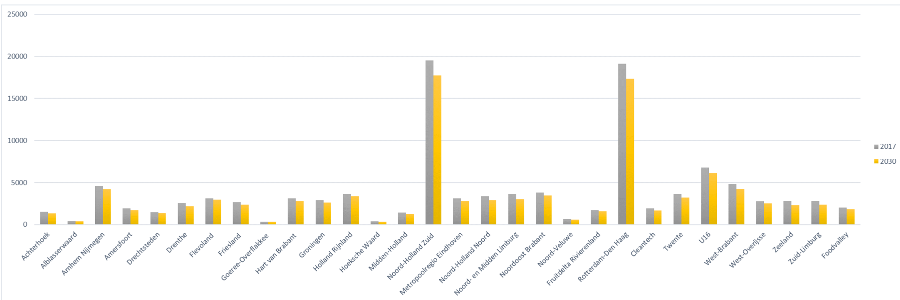

Figure 6.6: Electricity demand in building (TJ) for 2017 and 2030

Other sectors

The total electricity demand for transport, agriculture and industry is taken from KEV 2019 (Table 6.4).

Sector	Electricity demand (PJ)
Transport	14
Industry	155
Agriculture	48

Table 6.4: Energy demand by sector 2030 in KEV 2019

The input data in the ETM model are adapted to meet the total electricity demand in RES Scenario. Therefore hourly electricity demand is generated for every sector.

6.1.3 Sub-scenarios 2030

Now that the electricity demand is defined for the main scenarios, the electricity generation for 2030 will be set in this section.
As discussed in Chapter 1, a national target is set for both onshore and offshore renewable generation (Table 6.5), in where 35 TWh of renewable energy electricity generation is expected from both large-scale solar PV ($>$ 15 kWp) and onshore wind energy, and 49 TWh from offshore wind energy.

Type	Generation (TWh)
Wind Offshore	49
Wind Onshore and large-scale solar PV	35
Other renewable options	n.d.
Total	84

Table 6.5: KEA renewable energy generation target for 2030 [76]

6.1.3.1 Onshore renewable generation

In coordination with several ministries and government agencies, the National Regional Energy Strategies Program (NPRES) published the target of electricity generation from onshore renewable resources (Table 6.6)

Because of uncertainty in the grid capacity and other factors: only 50% of the target regarding large-scale solar energy is expected to be met by 2030 and 95 % of wind onshore

Type	Installed Capacity (MW)	Generation (TWh)
Large-scale PV	9450	8.5
Wind onshore	7000	17.7

Table 6.6: Electricity generation from onshore renewable energy sources 2030 [73]

target [73]. In addition, 7 TWh of electricity generation from small-scale solar PV is expected by 2030. Since only 5% of wind onshore projects are expected to not be achieved by 2030, the electricity supply uncertainty will be based only on the projects related to large-scale solar PV.

The expected onshore renewable generation from 2018 to 2030 is given divided into the energy regions (Table 6.7). The table shows: 50% of the expected electricity supply from large-scale solar PV and 100% of the expected electricity supply from wind onshore and small-scale solar PV.

RES regions	Large-scale PV (2030 (50%))	Wind onshore (2030)	Small-scale PV (2030)
Achterhoek	0.07	0.08	0.16
Alblasserwaard	0.04	0.01	0.02
Amersfoort	0.04	0.03	0.11
Arnhem / Nijmegen	0.13	0.14	0.26
Cleantech regio	0.1	0.02	0.13
Drechtsteden	0.08	0.05	0.05
Drenthe	0.39	0.77	0.32
Flevoland	0.19	1.71	0.18
Foodvalley	0.11	0	0.14
Friesland	0.25	1.61	0.37
Goeree-Overflakkee	0.02	0.48	0.03
Groningen	0.37	1.67	0.23
Hart van Brabant	0.15	0.16	0.13
Hoeksche Waard	0.04	0.08	0.02
Holland Rijnland	0.06	0.06	0.15
Metropoolregio Eindhoven	0.2	0.12	0.32
Midden-Holland	0.06	0.01	0.07
Noord- en Midden-Limburg	0.18	0.22	0.29
Noord-Holland Noord	0.13	1.22	0.27
Noord-Holland Zuid	0.24	0.13	0.37
Noord Veluwe	0.02	0.05	0.07
Noord-Oost Brabant	0.13	0.09	0.25
Rivierenland	0.09	0.18	0.11
Rotterdam-Den Haag	0.14	1.14	0.35
Twente	0.2	0	0.19
U10/U16	0.06	0.07	0.25
West Overijssel	0.2	0.13	0.21
West-Brabant	0.18	0.61	0.2
Zeeland	0.15	0.22	0.2
Zuid-Limburg	0.14	0.02	0.33
Total	4.16	11.08	5.78

Table 6.7: Onshore power generation RES target in TWh for 2030 (Adapted from ([73])

This electricity generation in TWh is converted to the installed capacity in MW based on:

- The weather condition of the reference year 2017.

- Solar PV with 35 degrees tilt and 180 degrees Azimuth.
- Wind turbine of 80 m hub height and turbine model Vestas V90 3000.

For wind onshore generation, the use of new turbine models and height is expected ([73]). However, in PyPSA model it is possible to model each renewable generation with only one weather data. Therefore, the expected wind onshore generation is used based on the old specifications. The installed capacity for the Sub-scenario1 is illustrated in Table 6.8, where only the half of the installed capacity of large-scale solar PV is computed. In Sub-scenario2, 100% of the installed capacity from the expected large-scale solar PV will be used.

RES regions	Large-scale PV (2030 (50%))	Small-scale PV (2030)	Wind onshore (2030)
Achterhoek	93	195	78
Alblasserwaard	45	18	15
Amersfoort	55	129	16
Arnhem / Nijmegen	148	305	102
Cleantech regio	112	149	17
Drechtsteden	81	63	35
Drenthe	445	398	311
Flevoland	252	215	2015
Foodvalley	129	157	5.7
Friesland	338	432	846
Goeree-Overflakkee	44	26	286
Groningen	466	304	1186
Hart van Brabant	172	154	123
Hoeksche Waard	44	26	86
Holland Rijnland	72	171	46
Metropoolregio Eindhoven	264	373	90
Midden-Holland	631	72	14
Noord- en Midden-Limburg	224	340	147
Noord-Holland Noord	190	326	628
Noord-Holland Zuid	281	425	126
Noord Veluwe	28	84	27
Noord-Oost Brabant	184	295	56
Rivierenland	111	138	121
Rotterdam-Den Haag	166	382	487
Twente	245	245	0
U10/U16	101	302	61
West Overijssel	264	264	103
West-Brabant	208	235	460
Zeeland	193	237	501
Zuid-Limburg	142	374	12
Total	5170	6846	8012

Table 6.8: Onshore renewable energy installed capacity in MW for Sub-scenario1 for 2030

The total installed capacity of large-scale solar PV (10.340 MW) and wind onshore (8012 MW) is almost similar to RES 2020 expectations (Table 6.6).

Regarding large-scale solar PV, a big amount of installed capacity in Groningen, Drenthe and Friesland is expected with respectively 466 MW, 445 MW and 338 MW due to the space available in these regions. For small-scale solar PV, Noord-Holland Zuid, Drenthe, Friesland, Eindhoven and Rotterdam-Den Haag are the regions with the highest installed capacity either on roof top of households or businesses. Regarding wind onshore, 2015 MW is expected to be installed in Feloveland and 1186 MW in Groningen. The only region with no wind onshore energy is Tweente. In Flevoeland the capacity will increase from 0 MW in 2017 to 5.7 MW in 2030.

6.1.3.2 Conventional generation

According to NEV 2017, all coal power plants will be closed by 2030. Therefore, the installed capacity for both sub-scenarios is set to zero.
Regarding gas power plants, NEV 2017 expects that the installed capacity in Gronignen will be decreased to the half by 2030. However, KEV 2019 draws a roadmap to entirely phaseout gas from Groningen fields. Since the model is running for a scenario where the electricity demand is expected to be high and there is uncertainty regarding the expected installed capacity from vRES, the NEV 2017 target regarding gas will be used. This, will ensure that the electricity peak demand is met. Therefore, the capacity in Groningen fields is reduced by the half for the year 2030.

6.1.3.3 Offshore renewable generation

KEA sets a target of 49 TWh of wind offshore generation by 2030. To achieve this target, TenneT have developed the 2030 Road-map [89] (Figure 6.7), where the installed capacity of the wind park is set along with their connections to the HV grid.

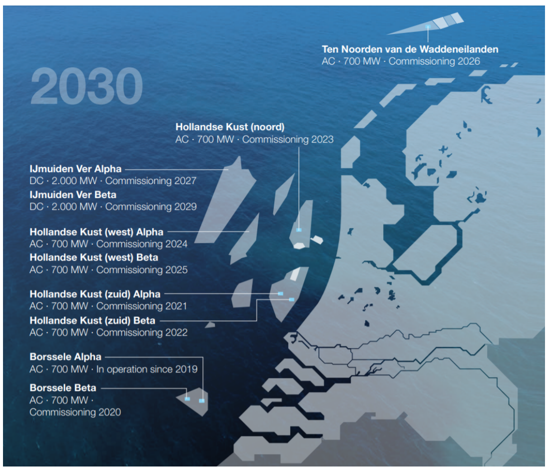

Figure 6.7: 2030 TenneT road-map for offshore wind power [89]

Different steps are needed to model the offshore wind energy:

- Find the substations to which the wind parks are connected through the transmission lines.
- Affiliate the installed capacity respectively to the energy region where the wind park is connected to.
- The capacity factor of wind offshore is computed based on the location of the wind parks in the sea.
- Adjust the wind turbine model and height to meet the 49 TWh (Following the specifications set in [16] regarding turbines for the new projects).

6.1.3.4 Storage units

Now that the electricity supply is defined for the sub-scenarios, the storage units technologies will be set in this subsection.
Two types of storage units will be installed in each energy region: battery and hydrogen storage. In order to assess the performance of the storage units, two cases will be analyzed in each sub-scenario:

- Case1: the installation of battery storage at each energy region.
- Case2: the installation of battery and hydrogen storage at each energy region.

The case where only hydrogen storage is considered was not taken into account. By 2030, the total number of Electrical Vehicles (EV) in the Netherlands is expected to reach two millions. The best representation of the storage units in EV is batteries. Moreover, battery storage can be used for solar system energy. Therefore, the use of only hydrogen storage in the Netherlands by 2030 is not considered.

6.2 Scenarios analysis

An analysis regrading the expected electricity demand and supply in the different scenarios/sub-scenarios is performed in this section along with the cost assumptions.

6.2.1 Electricity demand

The share of electricity demand by sector is shown respectively in Figure 6.8, 6.9 and 6.10.

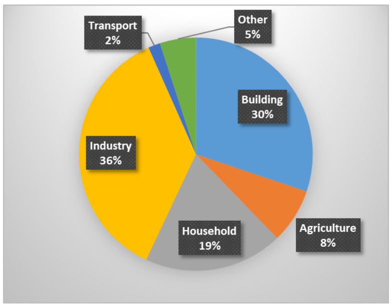

Figure 6.8: 2017

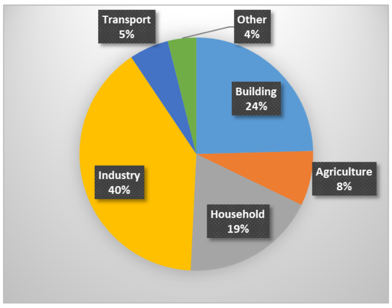

Figure 6.9: ES 2030

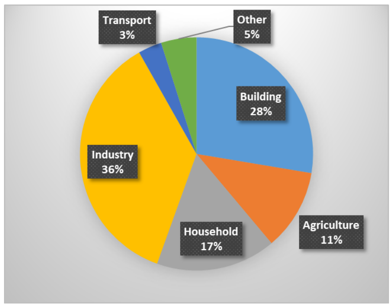

Figure 6.10: RES 2030

Electricity demand from industry sector constitutes the highest share in the three scenarios with an average of 38%. The share of transport electricity demand increases from 2% to 5% in Scenario RE 2030 due to the expected growth in the number of electric vehicles (around 2 millions by 2030) according to NEV 2017. In both households and buildings sectors the share of electricity demand decreases because of the expected energy efficiency, which is almost 0.85%. In agriculture sector, the electricity demand increases in both scenarios, which reflects the negative efficiency in Table 6.1. In addition, the high growth in RE 2030 scenario is mainly due to the increase of electricity demand in transport and industry sectors, in contrast to a moderate increase in Scenario RES 2030 (Figure 6.11).

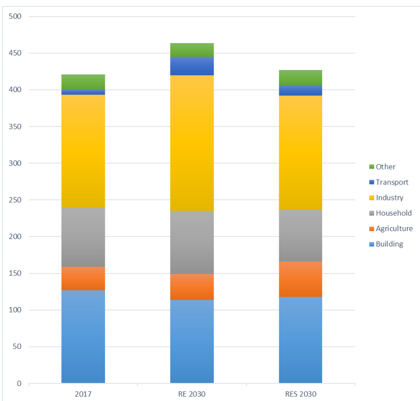

Figure 6.11: Final electricity demand for the different scenarios and the reference case (PJ)

6.2.2 Electricity supply

To accelerate the energy transition and to meet the CO_2 reduction target, coal is phased out by 2030. However, to ensure security of supply, Groningen gas is reduced to the half. The uncertainty regarding generation is demonstrated in solar power supply (Figure 6.12).

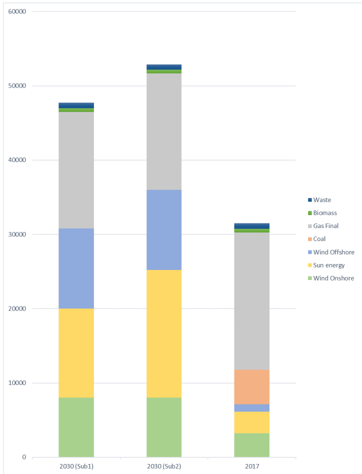

Figure 6.12: Installed capacity in each sub-scenario and the reference case (MW)

Since the 35 TWh target set by KEA 2019 incorporates only wind onshore and large-scale solar PV, no vision is set yet for waste and biomass. Therefore, last known installed capacity for both waste and biomass of the year 2020 are preserved. The main differences between the scenarios is the increase in renewable energy resources capacity, mainly wind offshore energy, where 49 TWh electricity supply is expected by 2030.

The three main categories of energy for electricity generation in the Netherlands are fossil fuels (gas and coal), nuclear and renewable energy sources (solar, wind onshore and offshore, biomass and waste), where 58% of installed capacity in 2017 is from gas and 15% from coal, in contrast to 10% from wind onshore energy and 9% from solar energy (Figure 6.13).

The share of conventional and renewable energy source capacity in Sub-scenario1 is: 33% from gas, 22% from wind offshore, 17% from wind onshore and solar power (Figure 6.14). In Sub-scenario2, the solar power will be leading by 32% followed by gas 30 % of the total installed capacity.

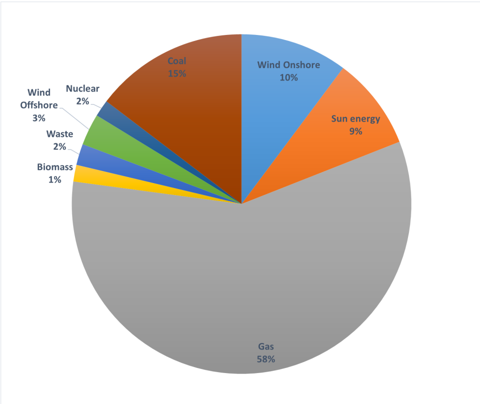

Figure 6.13: Share of installed capacity in 2017 (MW)

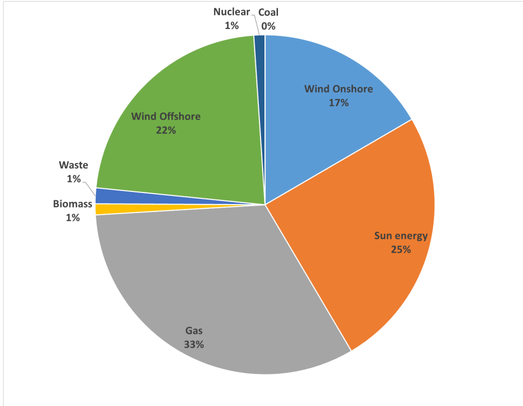

Figure 6.14: Share of installed capacity for Sub-scenario1 2030 (MW)

The distribution of the installed capacity over the energy regions for the reference case 2017 and the Sub-scenario1 is respectively shown in Figure 6.15 and Figure 6.16.

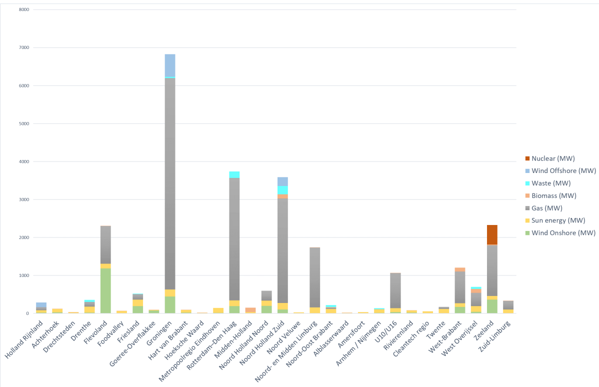

Figure 6.15: Installed capacity by region 2017 (MW)

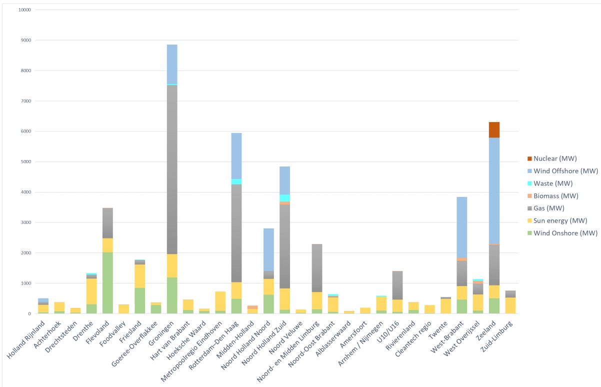

Figure 6.16: Installed capacity by region Sub-scenario1 2030 (MW)

As shown in Figure 5.16, all regions expect a growth in renewable energy generation. However, this growth is proportional within the energy regions due to the location, weather condition and electricity demand.

In Zeeland a big amount of offshore wind energy is expected because of Borssele sub-station, in which many new wind parks will be connected to. Regions like Groningen, Friesland and Noord-Holland Noord expect a big increase in wind onshore installations, due to their location (at the coast). Rotterdam-Den Haag and Noord-Holand Zuid expect a high share of renewable energy in the future because of their high electricity demand.

6.2.3 Assumptions

To achieve the 26 TWh electricity generation by 2030, investments in transmission lines and storage units are required. In this subsection, the different capital costs of the modelled storage units and transmission lines are described. Moreover, the capital costs used for the power generation expansion (from 26 TWh to 35 TWh) in wind onshore energy and solar PV are set as well.

6.2.3.1 Battery storage

The flexibility in each bus is represented by short-term and long-term storage units. Since no data is available regarding storage capacity in the Netherlands, the extension of the capacity of storage units at a certain capital cost in each bus within the linear optimal power flow is allowed.

Short-term storage units can be presented by different technologies. Battery storage are chosen in this thesis to balance the instability of the grid caused by the integration of renewable energy sources since they are feasible at all locations and do not prerequisite any technical local characteristics [97]. These batteries are modeled in a way they operate on an hourly basis and provide 6h of electricity with an efficiency of charging and discharging equal to 93.27% (Table 6.9). Long-term storage units can be represented by compressed hydrogen storage. Similarly to batteries, hydrogen storage is modelled in a way it operates on an hourly basis and provides 168h of electricity, with an efficiency of charging/discharging respectively equal to 72.5%/42.5% (Table 6.9).

Capital Costs	**Efficiency of charging**	**Efficiency of discharging**	**energy to power ration**
65822 EUR/MW	0.9327	0.9327	6 h
65402 EUR/MW	0.725	0.425	168 h

Table 6.9: Battery storage assumptions for 2030 [72]

6.2.3.2 Transmission lines

The costs of the extension of transmission lines are given in Table 6.10

Line Type	**Capital Cost in** $EUR/MVA * km$
380 KV	85
220 kV	290
150 kV	230

Table 6.10: Investment costs of transmission lines by 2030 [60]

6.2.3.3 Power generation

Both large-scale solar PV and wind onshore are extended in the model based on their capital costs (EUR/MW) (Table 6.11) to generate an extra 9 TWh.

RES	**Capital Cost in** EUR/kW_{el}
Wind onshore	1182
Solar PV	600

Table 6.11: Overnight cost of wind onshore and solar PV by 2030 [44]

6.2.4 Summary

Now that all the different scenarios/sub-scenarios are defined along with the necessary electricity supply and demand as well as cost assumptions, the LOPF will be used to optimize the expansion in both storage units and transmission lines to meet the regional target by 2030. The results will be displayed in the next chapter.
the LOPF will be used as well to optimize the expansion in generation to meet the national target based on the results of the regional target. The results will be displayed in Chapter 8.

7 Regional results

In this chapter, the results of the different scenarios along with the reference case will be presented. Regarding the reference case, the results will be validated with real data. For the scenarios, the electricity generation, storage units, line loading, locational marginal price and the state of charge will be discussed for each sub-scenario.

7.1 Reference case

The reference case is used to validate the accuracy of the input data utilized to model the Dutch electricity grid. For this case, the objective of PyPSA model is the hourly optimization of the dispatch of electricity generation for the year 2017 based on the marginal costs without any further investments. The transmission lines in the Dutch electricity network are used only at half capacity as described in Chapter 4. However, in some cases (e.g. at peak electricity demand consumption) the capacity used can exceed the half. Therefore, the modelled transmission lines for the year 2017 are allowed to extend till their maximum thermal capacity limit. This expansion will give insights regarding possible bottlenecks in the network and ensures the convergence of the model in case the thermal capacity of the transmission lines is not sufficient.

7.1.1 Electricity grid

The optimization results show that different transmission lines at different voltage levels operate with more than 50% of their thermal capacity. In PyPSA model the transmission lines that exceed their thermal capacity can be represented as an over-loaded transmission line. Therefore, the loading of all the transmission lines in the model has been calculated and graphically displayed by the use of PyPSA model (Figure 7.1). The transmission lines are graphically represented by their capacity (width of the line) and loading (colours).

As shown in Figure 7.1, the transmission lines that needed more than 50% of their thermal capacity are mostly located in the north and in the center of the country. The extra capacity is needed at different voltage levels (380kV, 220kV and 150kV).

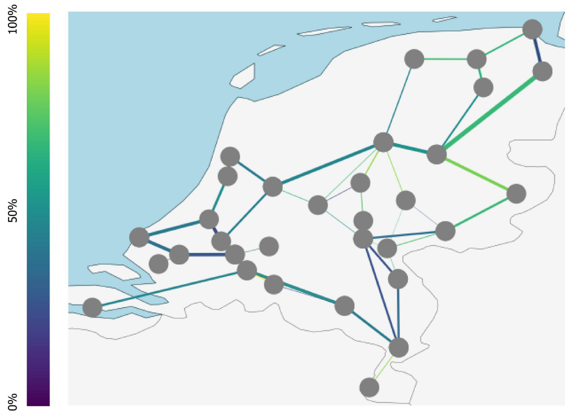

Figure 7.1: The capacity and the loading of the transmission lines in 2017

The convergence of the model shows that the modelled transmission lines did not exceed the maximum limit (100% of their thermal capacity). Therefore, the transmission lines used in the scenarios for the year 2030 will be modelled using the capacities of the year 2017.

7.1.2 Electricity generation

The optimal dispatch of electricity generation resources based on their marginal costs provides the hourly electricity supply in MWh (Figure 7.2).

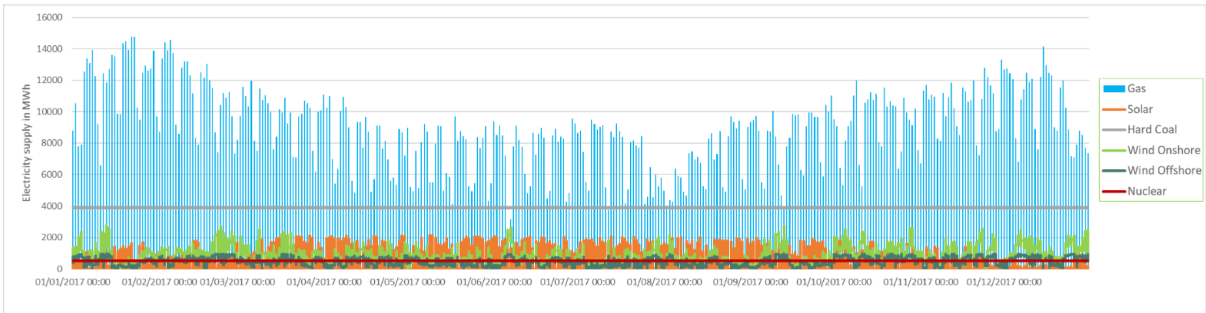

Figure 7.2: Hourly electricity supply in 2017 (MWh)

The electricity demand in 2017 was mainly satisfied by the electricity supply from gas due to the high share of gas installed capacity (almost 60% of the total installed capacity). Therefore, the patterns of electricity supply from gas follows the same distribution of the electricity demand: high in winter and low in summer. The total electricity supply from gas in 2017 according to the outcome of the model is 53710558.5 MWh, which corresponds to 193.35 PJ.

Hard coal constituted the second source of electricity generation in the Netherlands in 2017 with almost 4700 MW installed capacity. The electricity supply from hard coal is constant all over the year in 2017 (Figure 7.2) due mainly to its marginal cost which is lower than gas. Moreover, the supply from vRES is very low. Therefore, coal power plants need to run all over the year with their maximum output capacity. The total electricity supply from hard coal in 2017 according to the outcome of the model is 3988800 MWh, which corresponds to 122.35 PJ.

The installed capacity of solar energy in 2017 was 2911 MW. Since the solar capacity factor is very low in the Netherlands, the electricity supply is very low as well. As shown in Figure 7.3, at it's maximum capacity solar energy can supply approximately 2000 MW only. The electricity supply from solar energy in 2017 based on PyPSA model is 3062191 MWh (11 PJ).

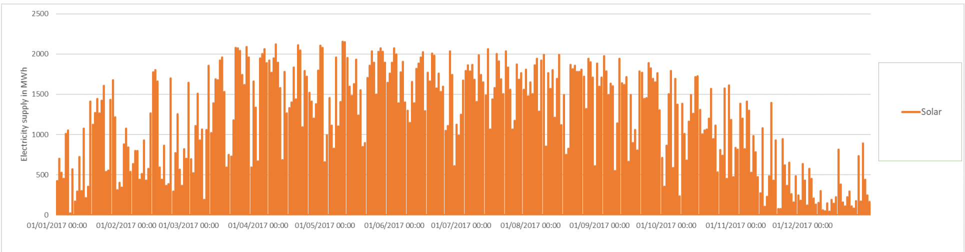

Figure 7.3: Electricity supply from solar energy in 2017 (MWh)

Even though wind offshore capacity factor is higher than wind onshore capacity factor, the supply of electricity from wind offshore is low in 2017 as shown in Figure 7.4. This is due to the fact that the installed capacity of wind offshore (957 MW) is lower than the installed capacity of wind onshore (3245.93 MW). The electricity supply of wind onshore and offshore according to the results of the model is approximately 7092492 MWh (25.53 PJ) and 3943322 MWh (14.19 PJ).

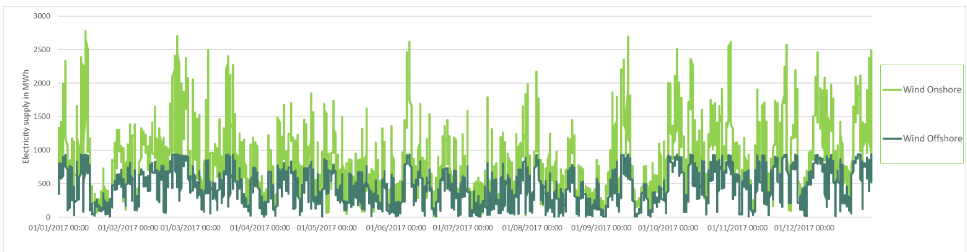

Figure 7.4: Electricity supply from wind energy in 2017 (MWh)

7.1.3 Validation

The results of the optimization model regarding the electricity supply by the different electricity generation resources for the year 2017 are compared to the data provided by KEV 2019 report (Table 7.1).

Electricity generation sources	**Electricity supply in PJ (PyPSA Model)**	**Electricity supply in PJ (NEV 2019)**
Wind onshore and offshore	39.72	39
Solar	10	8
Gas	193.35	208
Hard Coal	122.35	113
Total	366.42	368

Table 7.1: Electricity supply in the Netherlands in 2017

As shown in the Table 7.1, the main differences in electricity supply for the year 2017 are regarding hard coal and gas. These differences are caused by different aspects. First, the different technologies (e.g. OCGT, CCGT) within each generation resources are clustered. Therefore, the efficiencies were not taken into account. Second, the optimization model considers only the marginal cost of the generation resources, without taking into account additional costs (e.g. start up costs). However, these difference won't affect the results of the scenarios, because hard coal will be phased-out and gas installed capacity will be reduced (see Chapter 6). The difference in electricity supply from solar energy is mainly due to the way solar PV has been modelled. Even though the solar irradiances have been computed separately for each region, the tilt and azimuth are considered the same in each region. Moreover, solar PV technologies have been clustered. Contrary to the reference case, where vRES modelling consists of defining the installed capacity in each energy region. The modelling of the vRES in the scenarios consists of defining the installed capacity to meet the expected electricity generation by the energy regions in TWh. Therefore, the electricity supply of the vRES in the scenarios cannot exceed the energy regions electricity generation plans (the electricity generation is already set). As a result, the way vRES were modelled won't affect the final results.

7.2 Scenario RES 2030

In this scenario, PyPSA model is used to optimize the dispatch in generation and storage units and the investment costs in storage units and transmission lines under a medium growth of electricity demand by 2030. Therefore, the main results are the sitting and the sizing of the energy storage units as well as the required transmission lines expansion. Two sub-scenarios are considered: Sub-scenario1 (where 50% of solar PV installed capacity is achieved) and Sub-scenario2 (where 100% of solar PV installed capacity is achieved).

In each sub-scenario two cases will be analyzed:

- Case1: the installation of battery storage at each energy region.
- Case2: the installation of battery and hydrogen storage at each energy region.

7.2.1 Sub-scenario1

7.2.1.1 Transmission lines

The optimization results show that a transmission expansion is needed to incorporate the vRES electricity supply integration into the grid. The extended transmission lines in both cases are the connections between: Zeeland- West-Brabant, West-Brabant - Hart van Brabant, FoodValley - Noord Veluwe, U10/U16 - Amersfoort, Amersfoort - Noord Veluwe. The capacities of the transmission lines and the average loading are almost similar in both cases (Figure 7.5).

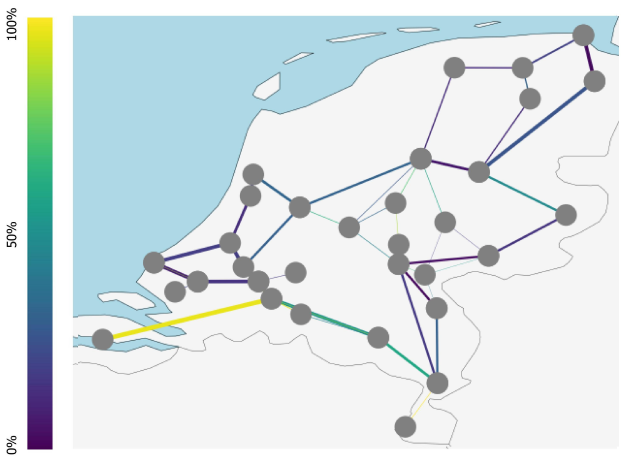

Figure 7.5: Transmission lines capacity and average loading in Sub-scenario1

7.2.1.2 Storage units

The distribution of storage units within the energy regions is displayed in Figure 7.6 for Case1 and Figure 7.7 for Case2. The total installed capacity for battery storage is 1856.8 MW in Case1, where FoodValley, Arnhem/Nijmegen, U10/U16 and Zeeland are the regions that require large battery capacities. Regarding Case2, 1537.3 MW of battery storage and 319.5 MW of hydrogen storage are needed, where 242 MW and 214 MW battery capacities are installed respectively in FoodValley and Arnhem/Nijmegen regions. The use of hydrogen storage in Zeeland region decreased the required installed capacity of battery storage in Rotterdam-Den Haag, U10/16 and Eindhoven to almost the half.

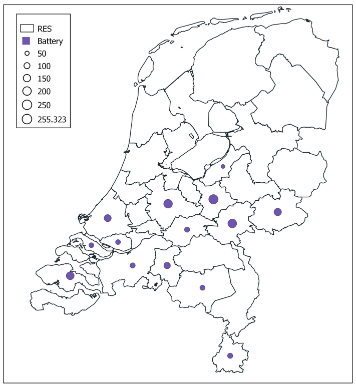

Figure 7.6: Storage units distribution within the energy regions in Case1

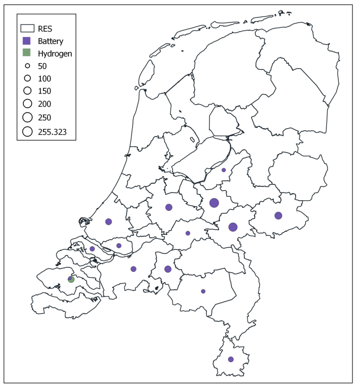

Figure 7.7: Storage units distribution within the energy regions in Case2

The optimal cost for the investment in storage units, transmission lines and the dispatch of electricity generation for Case1 is 1.68 billion euro and for Case2 is 1.86 billion euro.

7.2.1.3 Electricity generation

According to the optimal dispatch of electricity generation, 109 PJ of electricity supply from gas is needed in 2030, where gas power plants operate mainly in periods where vRES generation is low and electricity demand is high. In this scenario the installed capacity of large-scale solar PV is reduced to the half. Therefore, more electricity supply from gas is needed in summer. The peak electricity supply from gas is approximately 15994 MW. Regarding vRES, the annual electricity supply from solar and wind onshore/offshore energy is respectively 44.9 PJ, 57.8 PJ and 172.6 PJ. The electricity supply from the different generation sources is presented in Figure 7.8.

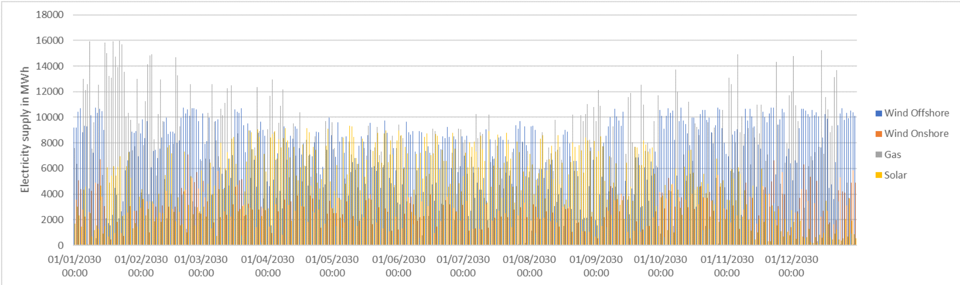

Figure 7.8: Electricity supply in Case1 (battery storage) in MWh

The electricity supply in Case2 is displayed in Figure 7.9. The implementation of hydrogen storage in the power system increases the electricity supply from wind offshore energy to 173.048. The supply of electricity from solar, wind onshore and gas is respectively 45.05 PJ, 58.48 PJ and 109 PJ.

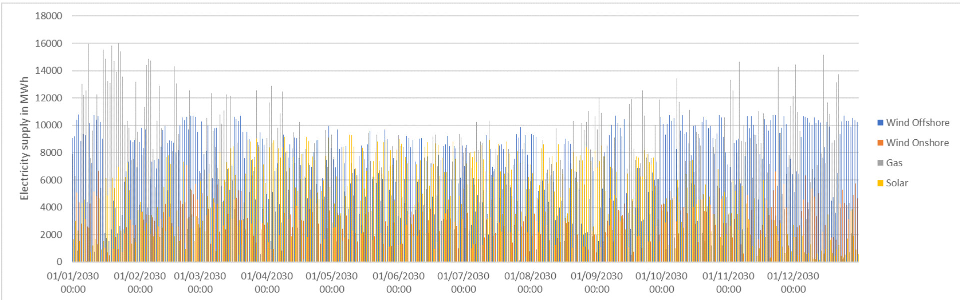

Figure 7.9: Electricity supply in Case2 (battery and hydrogen storage)in MWh

7.2.1.4 Line loading and LMP

The transmission lines loading is calculated after performing the non linear PF as discussed in Chapter 3. The PF can be calculated only for a specific hour. Therefore, the hours chosen represent three main cases: High vRES/High demand, Low vRES/High demand and High vRES/Low demand. For the same hours, the locational marginal price will be computed. The results for Case1 and Case2 are similar. Therefore, only the results for Case1 are shown in this section.

In Figure 7.10 and Figure 7.11, the transmission lines loading and LMP are computed in the case that both electricity demand and vRES electricity supply are high. The loading of the transmission lines occurs at different voltage levels, mainly in the 380kV transmission lines located in the south and the 150kV transmission lines in the center.

The overloaded 380kV between Zeeland and West-Brabant block the flow of the cheap electricity supplied by wind offshore energy located in Zeeland. At the voltage level

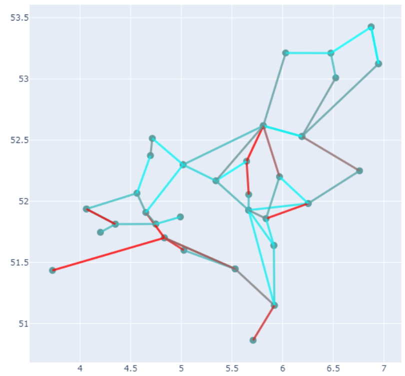

Figure 7.10: Transmission lines loading: High vRES supply/High demand

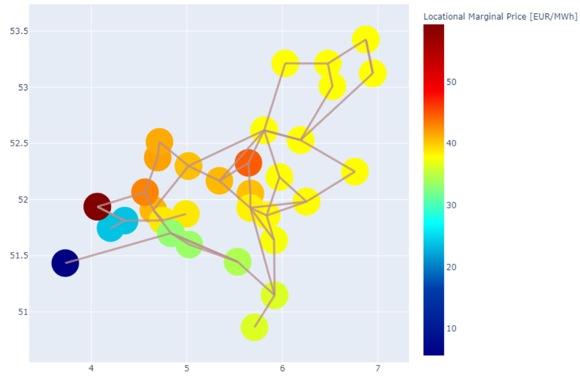

Figure 7.11: LMP: High vRES supply/High demand

150kV, the overloaded transmission lines in the center obstruct the flow of electricity from wind onshore energy installed in Foodvalley to Noord Veluwe. The main source of electricity supply in Noord Veluwe is solar energy. In this scenario, the installed capacity of large-scale solar PV is reduced. Therefore, the LMP in Noord Veluwe is high.

In the second case, the electricity supply from gas is necessary to meet the electricity demand in each region. Therefore, the LMP is equal to 50 MWh/euro in all regions (Figure 7.13). Similarly to Case1, the high loaded transmission lines are located in the center (mainly the 150kV infrastructure) and in the south (around Zeeland, West-Brabant and Rotterdam-Den Haag regions) (Figure 7.12).

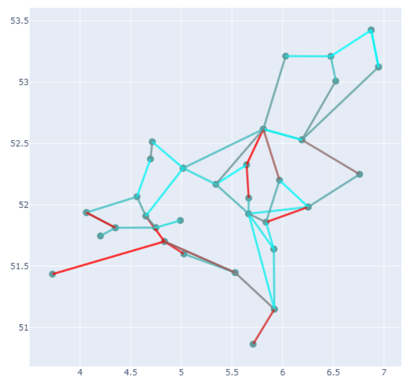

Figure 7.12: Transmission lines loading: Low vRES/High demand

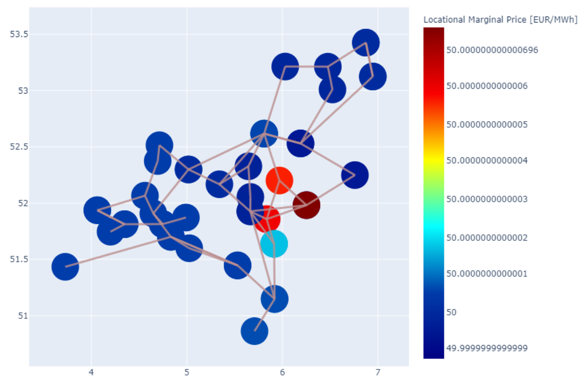

Figure 7.13: LMP: Low vRES/High demand

The last case shows a high electricity supply from vRES and a low electricity demand. Even though the transmission lines are over loaded between certain regions (Figure 7.14), the electricity demand is met by vRES generation. Therefore, the LMP is equal to 0 MWh/euro in all regions Figure 7.15).

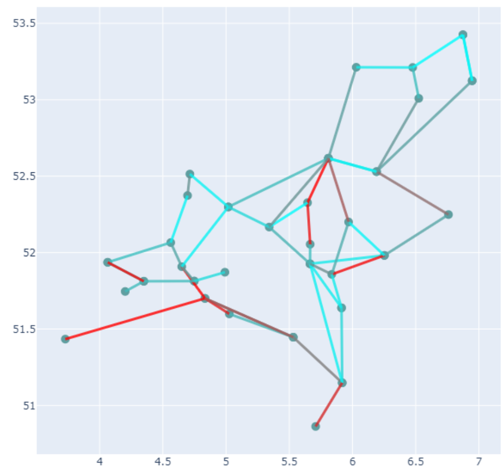

Figure 7.14: Transmission lines loading: High vRES/Low demand

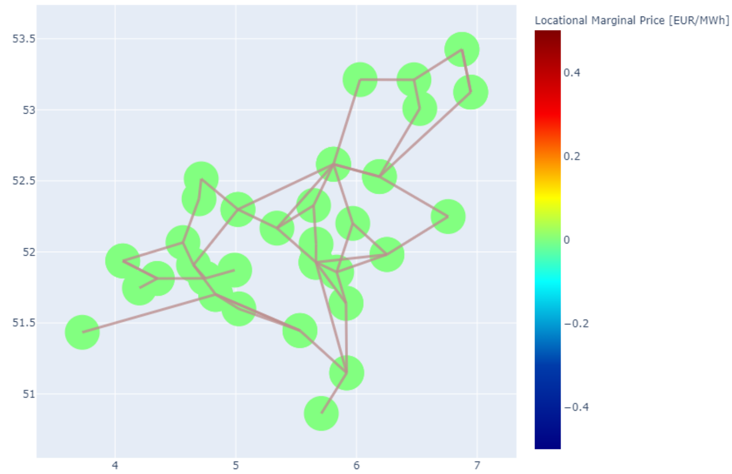

Figure 7.15: LMP: High vRES/Low demand

7.2.1.5 State of charge

The annual trend of storage units state of charge for Zeeland region is displayed in Figure 7.16 for battery storage and in Figure 7.17 for hydrogen storage. The short-term battery storage indicates a high frequency to level out hourly and daily generation fluctuations from vRES (mainly from solar energy). The state of charge in long-term hydrogen storage shows a balancing of longer-term synoptic and seasonal variability coming from a high wind offshore feed-in.

Figure 7.16: Annual trend of battery storage unit state of charge in Zeeland region

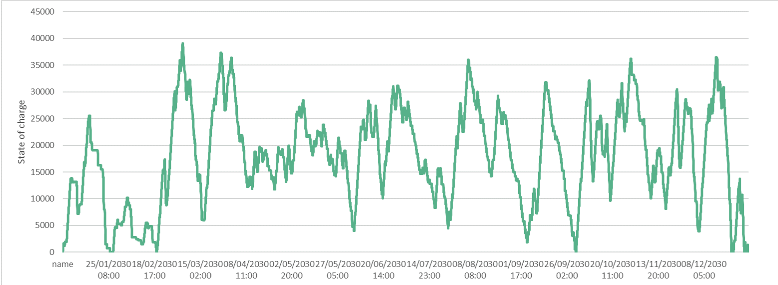

Figure 7.17: Annual trend of hydrogen storage unit state of charge in Zeeland region

The annual duration curve is sorted for the operation modes by storage technology for Zeeland region (Figure 7.18). The negative values show storage charging and the positive values indicate storage discharging. Charging mode is the dominant mode for hydrogen storage due to the low efficiency of charging, while the discharging mode is significantly low. Charging and discharging modes operate equally in battery storage because the efficiencies for charging/discharging are equal. The operation changes in battery storage have high frequency. However, the long-term hydrogen storage have a low frequency especially in discharging mode.

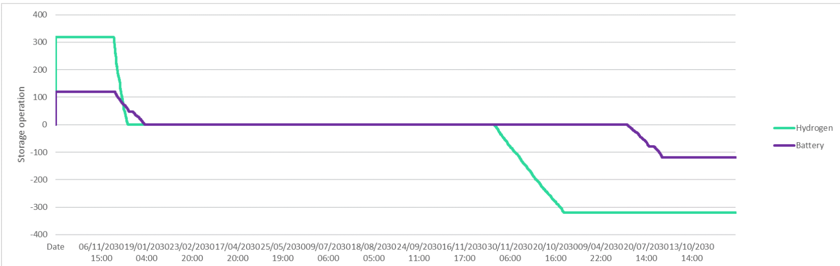

Figure 7.18: Annual duration curve sorted for the operation modes by storage technology in Zeeland

7.2.2 Sub-scenario2

7.2.2.1 Transmission lines

The capacity of the transmission lines and their average loading are displayed in Figure 7.19 and Figure 7.20. The results show that different transmission lines need to be extended at the 380kV and 150kV voltage level in both cases. In Case1, the model extended the following connections: Zeeland - West-Brabant, West-Brabant - Hart van Brabant, FoodValley - Noord Veluwe, Amersfoort - U10/16 and Noord Veluwe - Amersfoort. In Case2, an additional extension was needed between Hoekse Waard and Rotterdam-Den

Haag regions.

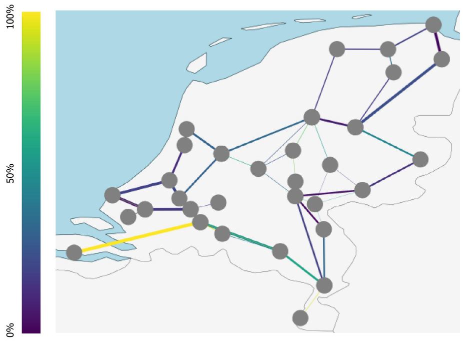

Figure 7.19: Transmission lines capacity and average loading in Case1

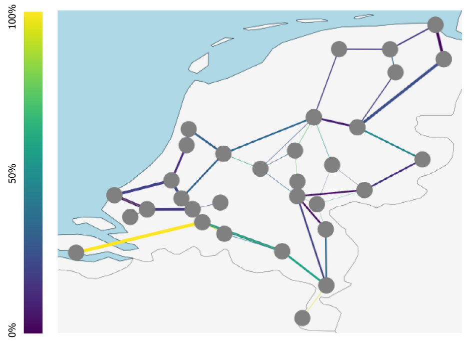

Figure 7.20: Transmission lines capacity and average loading in Case2

In both cases, the overloaded transmission lines are: the 380kV transmission line between Zeeland and West-Brabant region and the 150kV transmission lines between Zuid-Limubrg - Noord en Midden Limburg and West-Brabant - Hart van Brabant represented by a yellow colour. The 380kV transmission line connecting West-Brabant to Noord en Midden Limburg is overloaded as well.

7.2.2.2 Storage units

Based on the investment costs in storage units and transmission lines, the model found the optimal storage units expansion. Under this scenario, a high share of vRES is expected. Therefore, a high capacity of storage units is needed to handle the vRES fluctuations. In Case1, 1734 MW of battery storage is needed. In Case2, 1509 MW of battery storage and 225 MW of hydrogen storage are required. The distribution of storage units in Case1 and Case2 are displayed respectively in Figure 7.21 and Figure 7.22.

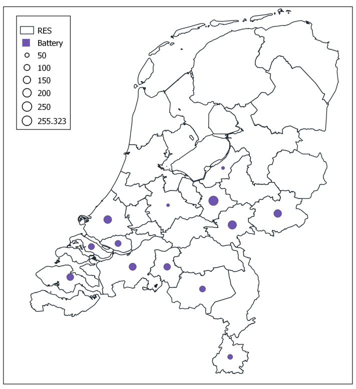

Figure 7.21: Storage units distribution within the energy regions in Case1

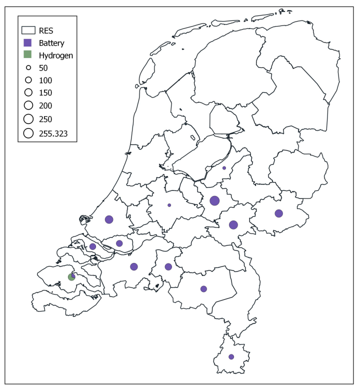

Figure 7.22: Storage units distribution within the energy regions in Case2

In both cases, the distribution of battery storage within the energy regions is similar. However, the installed capacity in each energy region in the two cases is different. In Case1, 143.8 MW battery storage is needed in Zeeland. However, in Case2 the capacity needed from storage units is divided between battery storage (96.6 MW) and hydrogen storage (224.9 MW). Moreover, the installed capacity needed from battery storage in Rotterdam-Den Haag region decreased from 183.1 MW in Case1 to 117.376 MW in Case2. Regarding hydrogen storage, the model built capacity only in Zeeland region.
The optimal cost for the investment in storage units, transmission lines and the dispatch of electricity generation in both cases is approximately 1.67 billion euro.

7.2.2.3 Electricity generation

The supply of electricity form gas, solar, wind onshore and offshore for Case1 and Case2 are respectively shown in figure 7.23 and figure 7.24.

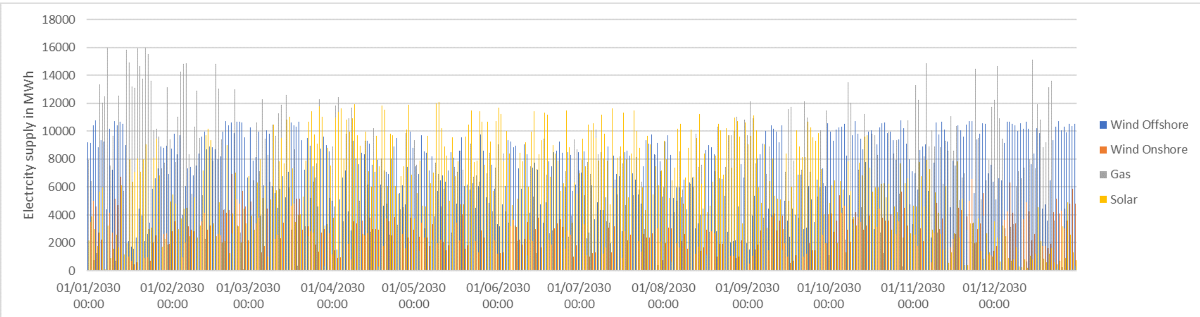

Figure 7.23: Electricity supply in Sub-scenario2 (Case1) by 2030

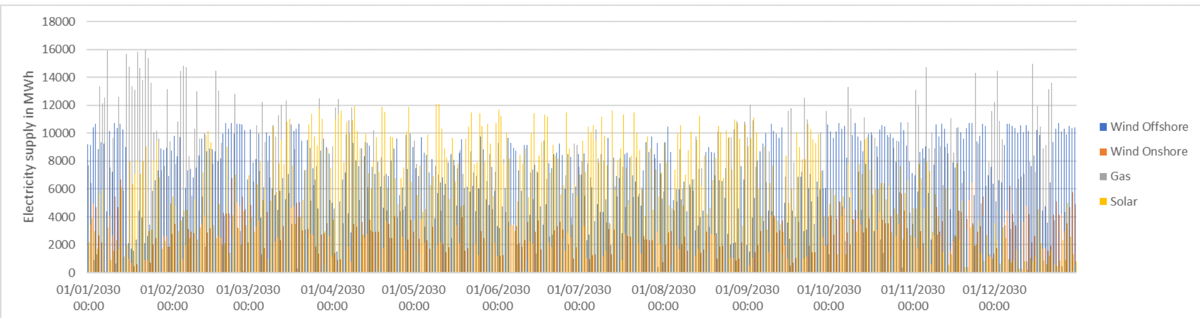

Figure 7.24: Electricity supply in Sub-scenario2 (Case2) by 2030

The optimization results for Case1 show that 102.4 PJ of electricity supply from gas is needed in 2030. Gas power plants operate mainly in periods where vRES generation is low and electricity demand is high. The peak electricity supply from gas is approximately 15762 MW. Regarding vRES, the annual electricity supply from solar and wind onshore/offshore energy is respectively 59 PJ, 57.2 PJ and 172.7 PJ.

In Case2, the electricity supply from solar energy decreased to 57.6 PJ and the electricity supply from gas stayed almost the same. However, the electricity supply from wind onshore and offshore increased respectively to 56.6 PJ to 173.7 PJ.

7.2.2.4 Line loading and LMP

The line loading and LMP results for Case1 and Case2 are almost similar. Therefore, the results will be discussed only for one case.

The transmission lines loading and the LMP in the case where both vRES supply and demand are high are shown in Figure 7.25 and Figure 7.26. The LMP takes the values in the rang of 0 euro/MWh to 50 euro/MWh. The high electricity demand requires a high generation from vRES, which causes a high loading on the transmission lines. Therefore, the high electricity supply of vRES in some regions cannot flow to regions with low vRES supply (e.g. the regions located in the center). As a result, regions with low vRES electricity supply use other sources of electricity generation (e.g. gas, biomass). Regions located in the south have enough vRES generation. Therefore, the overloaded transmission lines does not affect the LMP in these regions.

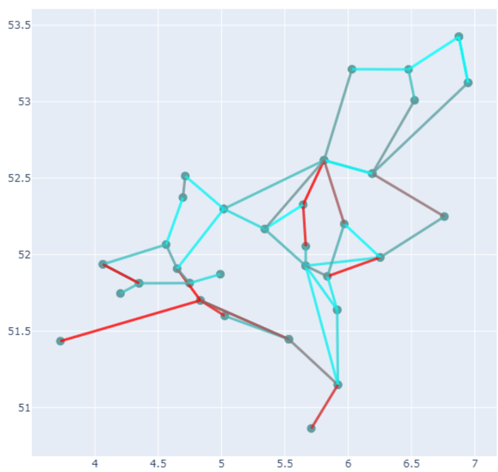

Figure 7.25: Transmission lines loading: High vRES/High demand

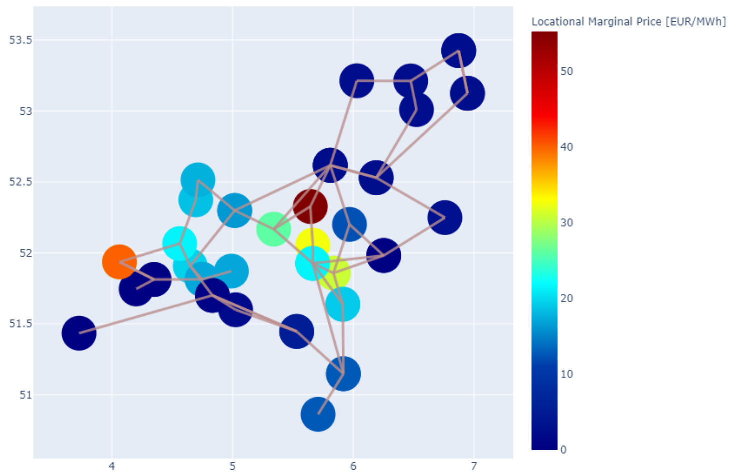

Figure 7.26: LMP: High vRES/High demand

The second case represents a high electricity demand and a low vRES electricity supply.

In this case, electricity demand is met mainly by gas generation. As shown in Figure 7.28, the minimum value of the LMP is 41.9 euro/MWh. Similar to the first case, the over loaded lines (Figure 7.27) does not allow the flow of cheap electricity. Therefore, in the regions located in the middle, the LMP is 50 euro/MWh.

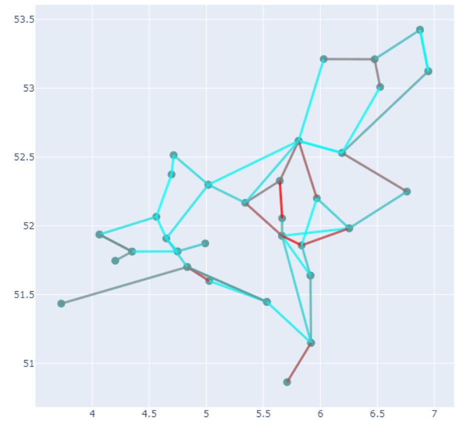

Figure 7.27: Transmission lines loading: Low vRES/High demand

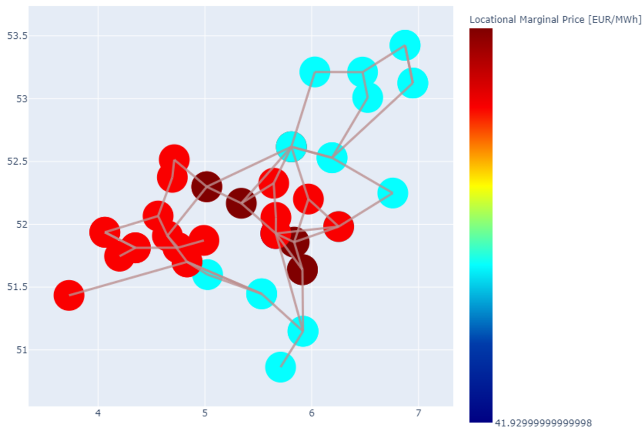

Figure 7.28: LMP: Low vRES/High demand

In the last case, the vRES electricity supply is higher than the electricity demand. Therefore, the LMP is 0 MWh/euro within all the energy regions (Figure 7.30). The overloading of some transmission lines in the south (Figure 7.29) does not affect the prices, because the demand can be met within each energy region by the vRES generation.

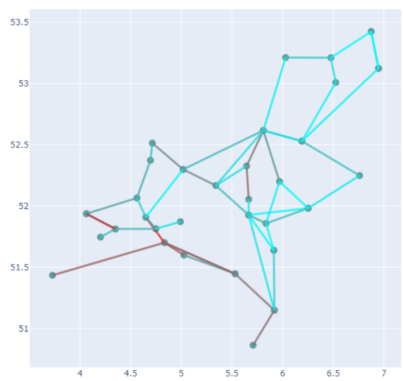

Figure 7.29: Transmission lines loading: High vRES/Low demand

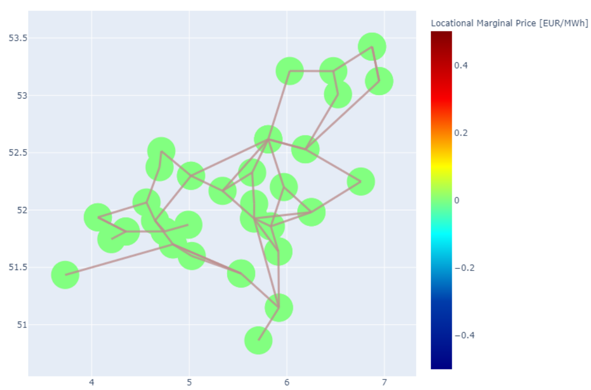

Figure 7.30: LMP: High vRES/Low demand

7.2.2.5 State of charge

In Case2, the model had to build two different types of storage units. The two storage technologies used (battery and hydrogen) have different technical properties in terms of efficiency and capacity. Therefore, both technologies show distinct operation modes. The trend of states of charge for both hydrogen and battery storage shows a much higher frequency for the battery storage units (Figure 7.31) and a lower frequency for hydrogen storage (Figure 7.32). The storage level for hydrogen changes only gradually. Moreover, the peak in hydrogen storage occurs during periods of high wind offshore feed-in.

Figure 7.31: Annual trend of battery storage unit state of charge in Zeeland

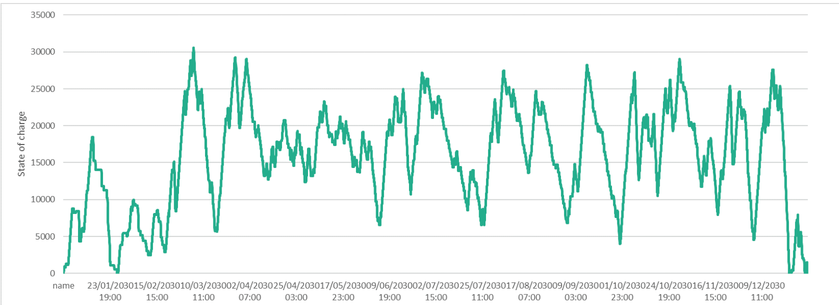

Figure 7.32: Annual trend of hydrogen storage unit state of charge in Zeeland

In Figure 7.33, the annual duration curve is sorted for the operation modes by storage technologies. The negative values show storage charging and the positive values indicate storage discharging. Charging mode is the dominant mode for hydrogen storage due to the low efficiency of charging, while the discharging mode is significantly low. Charging and discharging modes operate equally in battery storage because the efficiencies of charging/discharging are equal. The operation changes in battery storage have high frequency. However, the long-term hydrogen storage have a low frequency, especially in discharging mode.

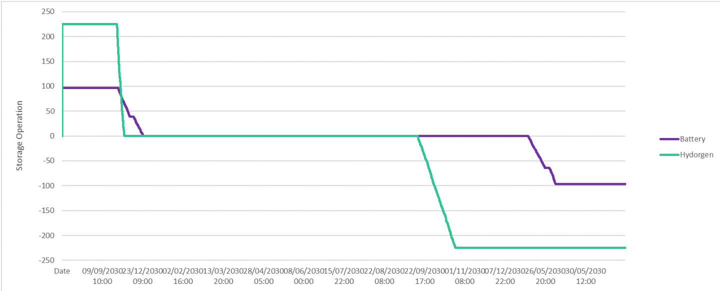

Figure 7.33: Annual duration curve sorted for the operation modes by storage technology in Zeeland

7.3 Scenario ES 2030

In this scenario, the electricity demand is expected to be high. The results will be presented for each sub-scenario: Sub-scenario1 (where 50% of solar PV installed capacity is achieved) and Sub-scenario2 (where 100% of solar PV installed capacity is achieved).

7.3.1 Sub-scenario1

7.3.1.1 Transmission lines

The capacities of the transmission lines and the average loading for both cases are almost similar (Figure 7.34). The optimization results show that a transmission expansion is needed to incorporate the vRES electricity supply into the grid, especially at the 150kV voltage level. The extended transmission lines in Case1 are the connections between: Zeeland- West-Brabant, West-Brabant - Hart van Brabant, Rivierenland - Arnhem/Nijmegen, FoodValley - Noord Veluwe, Amersfoort - Rivierenland, U10/U16 - Amersfoort, Flevoland - Noord Veluwe and Amersfoort - Noord Veluwe.

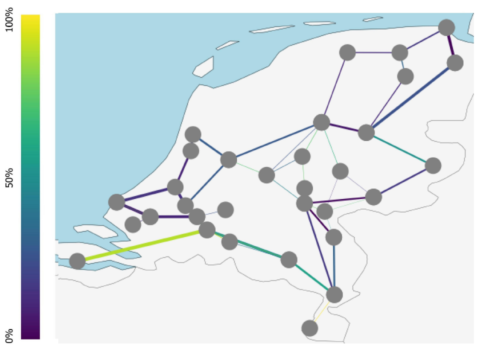

Figure 7.34: Transmission lines capacity and average loading in Sub-scenario1 for Case1/2

7.3.1.2 Storage units

The optimization results show that 3383 MW installed capacity from battery storage is required in Case1. The locations of the batteries along with their capacities are displayed in Figure 7.35. The energy regions that need the most of battery storage are: Zeeland (506 MW), U10/U16 (460 MW), Achterhoek (402 MW), Arnhem/Nijmegen (381 MW) and Flevoland (360MW). In Case2, the required storage units installed capacity is 792.42 MW from hydrogen storage and 2372.35 MW installed capacity from battery storage (Figure 7.36). The model built hydrogen storage in two regions: Zeeland and West-Brabant. Regarding battery storage, U10/16, Achterhoek, Arnhem/Nijmegen and Zeeland are the regions that needed the most of battery storage capacities.

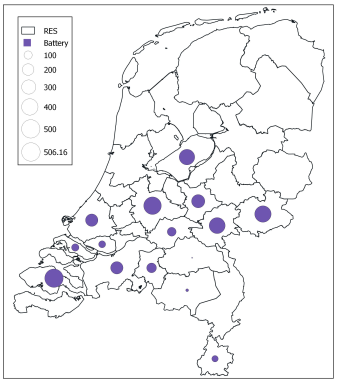

Figure 7.35: Storage units distribution within the energy regions in Case1 (MW)

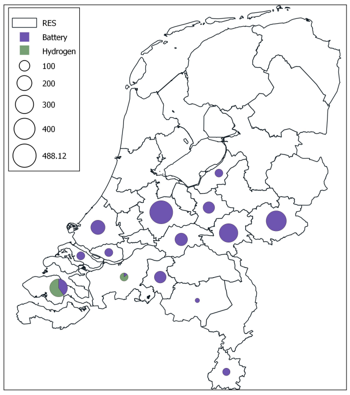

Figure 7.36: Storage units distribution within the energy regions in Case2 (MW)

7.3.1.3 Electricity generation

The supply of electricity form gas, solar, wind onshore and offshore for Case1 and Case2 is presented respectively in Figure 7.37 and Figure 7.38.

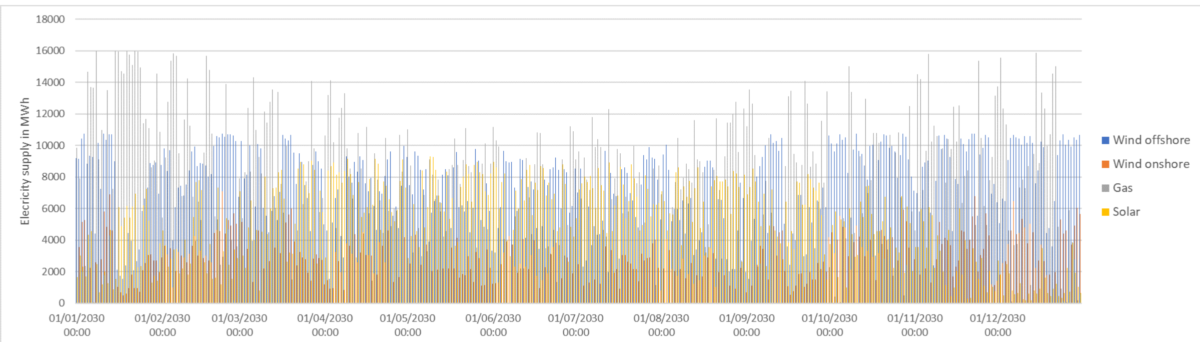

Figure 7.37: Electricity supply in Case1 by 2030

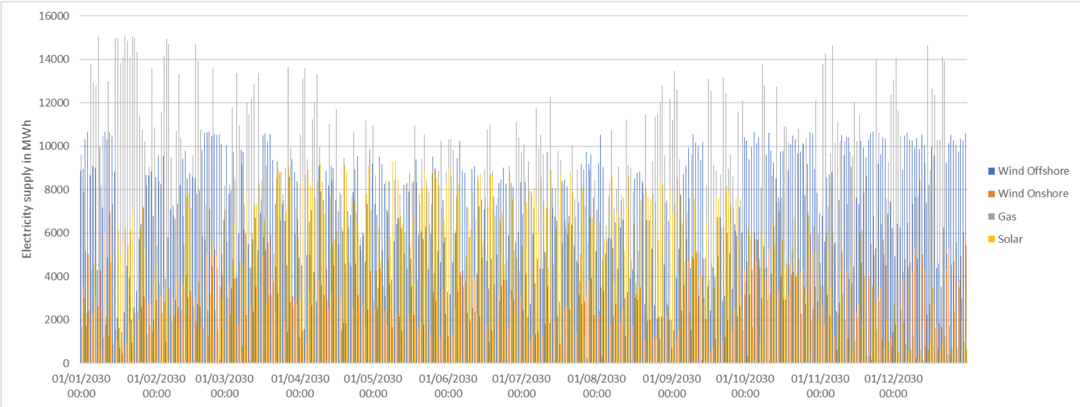

Figure 7.38: Electricity supply in Case2 by 2030

In this scenario the electricity demand is excepted to be very high. Therefore, the required electricity supply from gas in Case1 is 135 PJ, where the electricity peak supply is 15994 MW. Gas power plants operate mainly in periods where electricity supply from solar and wind is low and electricity demand is high (e.g. January and February). The electricity supply from wind offshore/onshore is 173.943 PJ/61.93 PJ and from solar energy is 46.41 PJ. Regarding Case2, 137.48 PJ electricity supply from gas is needed, where the electricity peak supply is 16000 MW. The electricity supply from wind onshore/offshore and solar is respectively 62.06 PJ/171.86 PJ and 46.61 PJ.

The optimal cost for the investment in storage units, transmission lines and the dispatch of electricity generation is 2.08 billions euro in both cases.

7.3.1.4 Line loading and LMP

The line loading and LMP results for both cases are almost similar. Therefore, the results will be discussed for Case1 only.

The transmission lines loading and the LMP in the case where both vRES supply and demand are high are shown in Figure 7.39 and Figure 7.40. The LMP takes the values in the rang of 0 euro/MWh to 50 euro/MWh. Even though the electricity supply from vRES is high, the average LMP is 40 euro/MWh. This is mainly due to the fact that most of the regions cannot satisfy their electricity demand by the vRES. The LMP is low only in three regions: Zeeland (where the electricity supply from vRES is very high), Hoeksche waard and Goeree-overflakkee (where the electricity demand is relatively low). The loading of the transmission lines have relatively a small effect on the flow of cheap electricity.

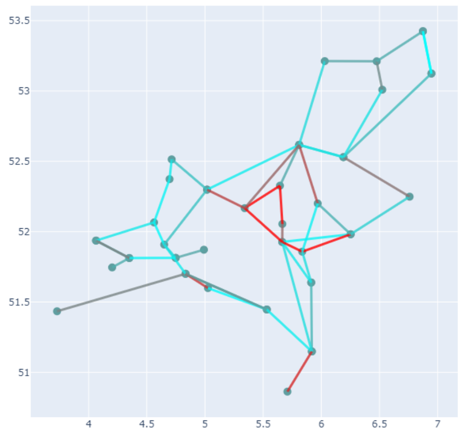

Figure 7.39: Transmission lines loading: High vRES/High demand

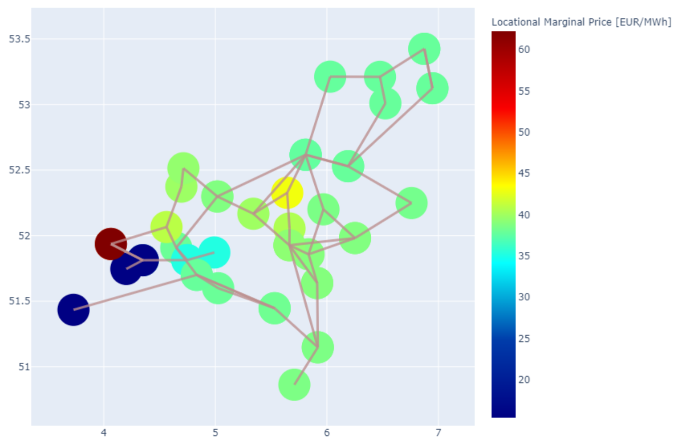

Figure 7.40: LMP: High vRES/High demand

The second case represents a high electricity demand and a low vRES electricity supply. The LMP takes the values in the rang of 40 euro/MWh to 50 euro/MWh (Figure 7.42). The electricity demand is cheap mainly in the regions located in the south. The LMP in Rotterdam-Den Haag region is the highest (mainly due to the high electricity demand) (Figure 7.41).

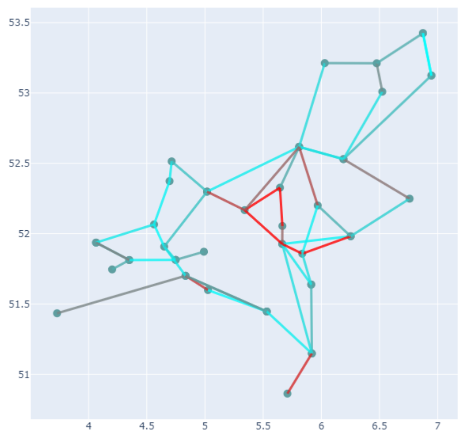

Figure 7.41: Transmission lines loading: Low vRES/High demand

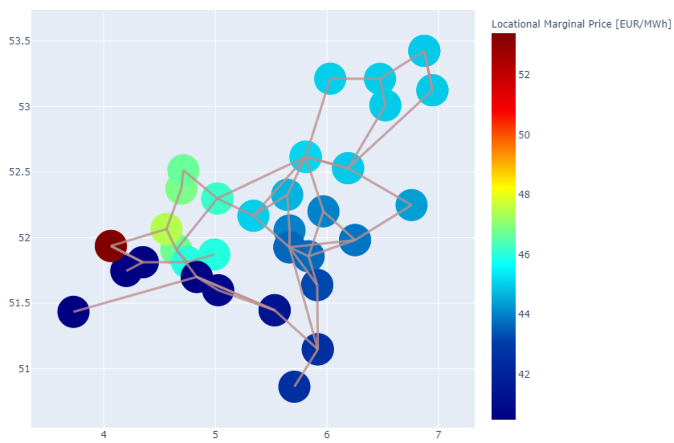

Figure 7.42: LMP: Low vRES/High demand

In the last case, the vRES electricity supply is higher than the electricity demand.

Therefore, the LMP is 0 MWh/euro within all the energy regions (Figure 7.44). The loading of the lines does not affect the transfer of cheap electricity between the regions (Figure 7.43).

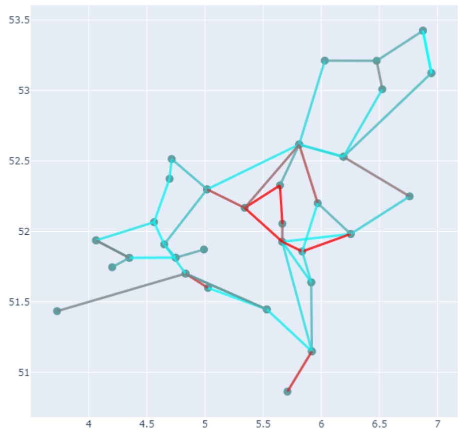

Figure 7.43: Transmission lines loading: High vRES/Low demand

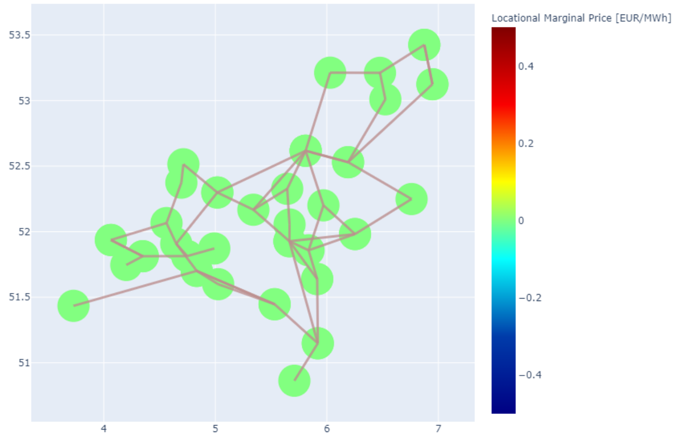

Figure 7.44: LMP: High vRES/Low demand

7.3.2 Sub-scenario2

7.3.2.1 Transmission lines

The capacities of the transmission lines and the average loading for both cases are almost similar (Figure 7.45).

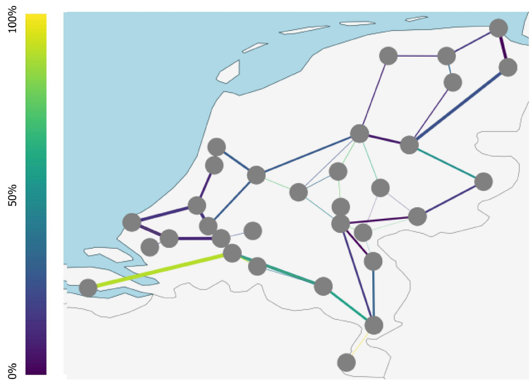

Figure 7.45: Transmission lines capacity and average loading in Sub-scenario2 for Case1/2

Similarly to Sub-scenario1, the connections that needed more capacities in both cases are: Zeeland - West-Brabant, West-Brabant - Hart van Brabant, Rivierenland - Arnhem/Nijmegen, FoodValley - Noord Veluwe, Amersfoort - Rivierenland, U10/U16 - Amersfoort, Flevoland - Noord Veluwe and Amersfoort - Noord Veluwe.

7.3.2.2 storage units

The optimization results show that 2495 MW of battery storage and 588 MW of hydrogen storage are needed to incorporate the vRES planned projects in Case2 (Figure 7.46). The model built hydrogen capacity in two regions: Zeeland and West-Brabant. Regarding battery storage, the model built 445 MW in Achterhoek, 395 MW in Zeeland and 306 MW in Arnhem/Nijmegen. In Case1, the model built battery storage in different region: Zeeland, West-Brabant, Achterhoek, Zeeland and Arnhem/Nijmegen regions (Figure 7.47). The required battery storage needed in case1 is 2867 MW.

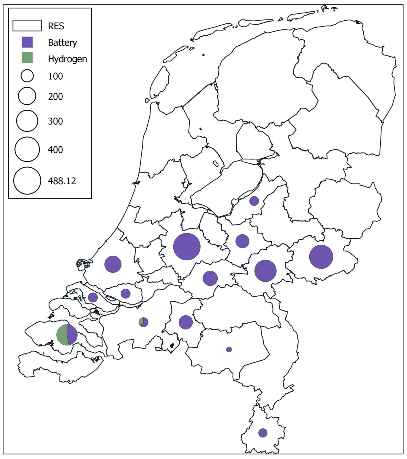

Figure 7.46: Storage units distribution within the energy regions in Case2 in MW

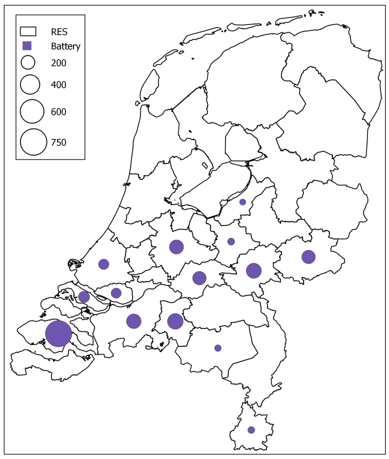

Figure 7.47: Storage units distribution within the energy regions in Case1 in MW

7.3.2.3 Electricity generation

The supply of electricity form gas, solar, wind onshore and offshore for Case2 is presented in Figure 7.48. The electricity supply from gas is 129.37 PJ, where the gas peak supply is 15985 MW. The electricity supply from solar energy is 60.4 PJ and from wind offshore/onshore is respectively 171.6 PJ and 60.85 PJ. In case1, the electricity supply from gas is 127 PJ. Moreover, the electricity supply from solar wind onshore/offshore is respectively 60.2 PJ, 173.7 PJ and 60 PJ. The optimal cost for the investment in storage units, transmission lines and the dispatch of electricity generation is 2.08 billions euro in both cases.

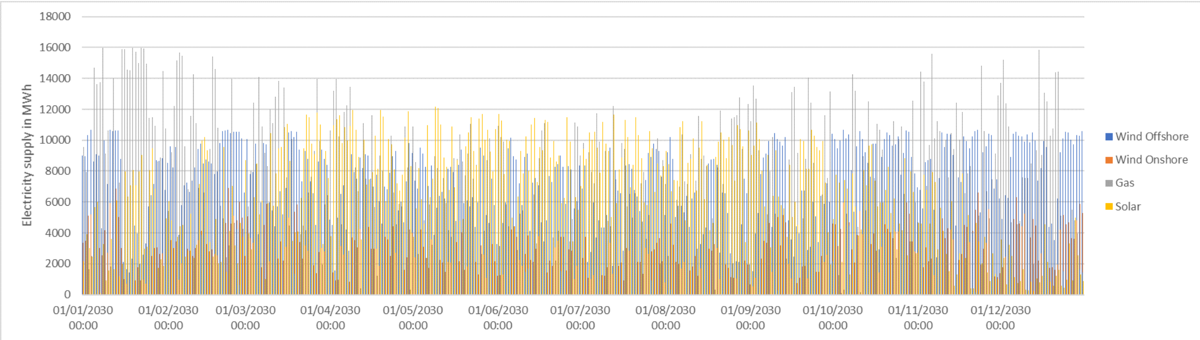

Figure 7.48: Electricity supply in Case2 by 2030

7.3.2.4 Line loading and LMP

The line loading and LMP results for both cases are almost similar. Therefore, the results will be discussed only for Case1 only.

The transmission lines loading and the LMP in the case where both vRES supply and demand are high are shown in Figure 7.49 and Figure 7.50. The LMP takes the values in the rang of 12 euro/MWh to 50 euro/MWh. Even though the electricity supply from vRES is high, the LMP is high in most regions. Rotterdam-Den Haag is the region with the highest LMP, mainly due to the high electricity demand. Zeeland in contrast is the region with the lowest LMP, mainly due to the high feed-in of wind offshore energy. The electricity demand is mainly satisfied by electricity supply from gas. Moreover, the loading of the electricity lines does not have a high impact on the LMP.

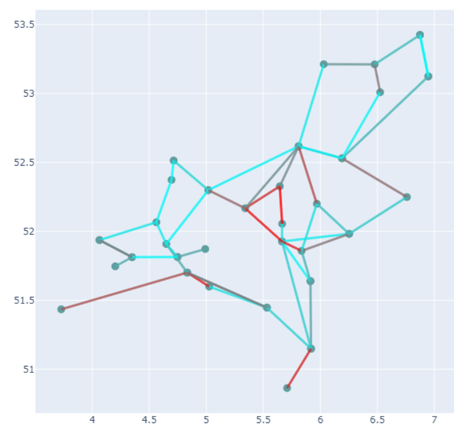

Figure 7.49: Transmission lines loading: High vRES/High demand

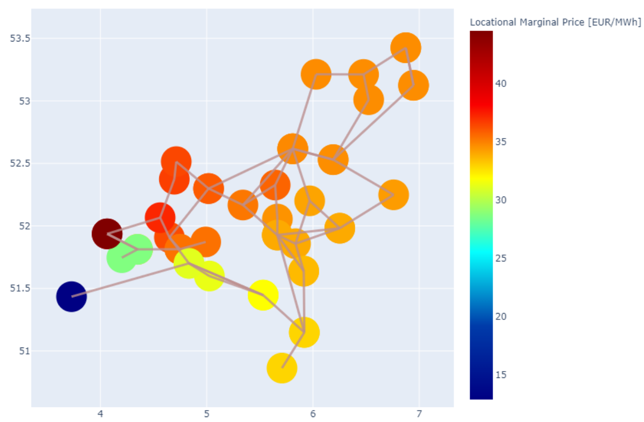

Figure 7.50: LMP: High vRES/High demand

The second case represents a high electricity demand and a low vRES electricity supply. The LMP takes the values in the rang of 42 euro/MWh to 50 euro/MWh (Figure 7.51). The high loading of the line between West-Brabant and Hart an Brabant block the flow of the relatively cheap electricity to Hart Brabant (Figure 7.52). Therefore, the LMP is 50 euro/MWh.

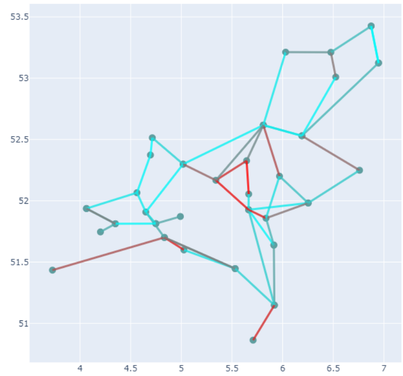

Figure 7.51: Transmission lines loading: Low vRES/High demand

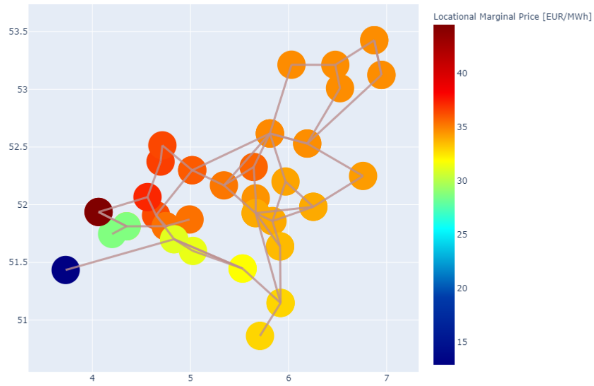

Figure 7.52: LMP: Low vRES/High demand

In the last case, the vRES electricity supply is higher than the electricity demand. Therefore, the LMP is 0 MWh/euro within all the energy regions (Figure 7.54). The loading of the lines does not impact the transfer of cheap electricity between the energy regions (Figure 7.53).

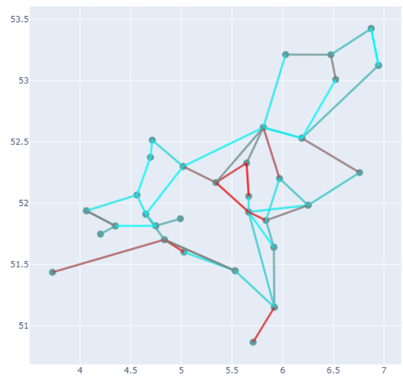

Figure 7.53: Transmission lines loading: High vRES/Low demand

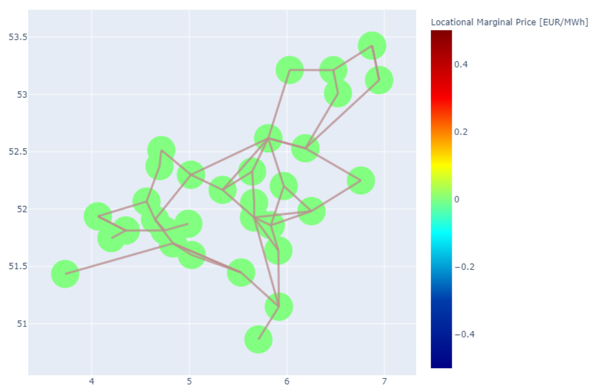

Figure 7.54: LMP: High vRES/Low demand

8 National results

The national target consists of 35 TWh of electricity generation from wind onshore and large-scale solar PV energy. However, only 26 TWh is planned by the energy regions.
To find the best location of the remaining 9 TWh within the energy regions along with the necessary storage and transmission lines capacity, the LOPF was performed to optimize the expansion costs of large-scale solar PV and wind onshore, storage units and transmission lines. This expansion is based on the results of the first optimization problem. Therefore, the necessary storage and transmission lines capacities of Scenario ES and Scenario RES are implemented as inputs in the second optimization problem. Only Sub-scenario1 (100% of solar PV installed capacity is achieved) in each scenario (RES and ES) will be considered to perform the expansion.

8.1 Scenario RES: Sub-scenario2

In this section, the results of the electricity generation will be presented under Scenario RES along with the necessary storage units and transmission lines capacities.

8.1.1 Electricity generation

The optimization results show that the remaining 9TWh of electricity generation is needed from wind onshore energy. Moreover, the best location to install the generation capacities from wind onshore is Rotterdam-Den Haag region. The model expended the installed capacity of wind onshore energy in Rotterdam-Den Haag region from 487.7 MW to 2807 MW in both cases.

The annual electricity supply from wind onshore before (Sub-scenario2: Case1 and Case2) and after the expansion in Rotterdam-Den Haag region is shown in Figure 8.1. The electricity supply increased dramatically and reaches 2500 MWh in peak periods. The electricity supply from gas decreased from 26.8 PJ (before the expansion) to 13.1 PJ (after the expansion).

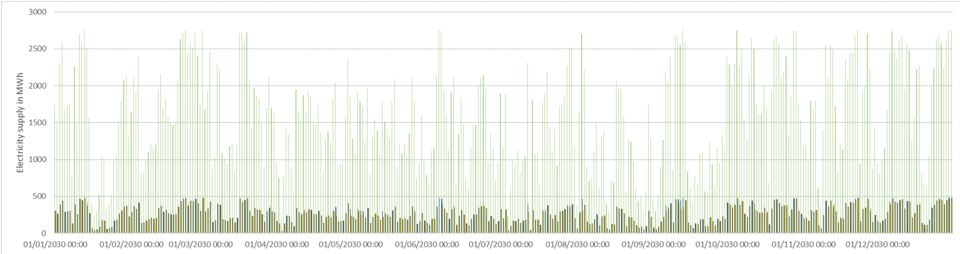

Figure 8.1: Electricity supply of wind onshore energy before and after the expansion in Rotterdam-Den Haag region in MWh

The annual electricity supply in Case1 is 89.96 PJ from gas, 61.9 PJ from solar and 151.79 PJ/91.06 PJ from wind offshore/onshore (Figure 8.2). In Case2, the electricity supply from wind offshore is 154.83 PJ, wind onshore 91 PJ, gas 89.32 PJ, solar 61.92 PJ (Figure 8.3).

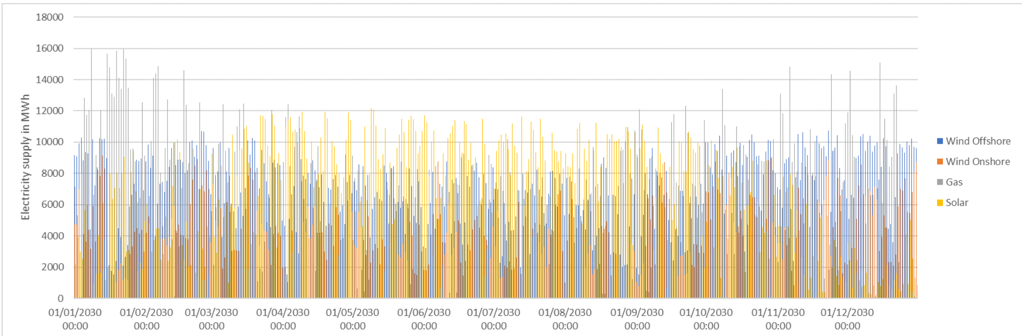

Figure 8.2: Electricity supply in case only battery storage units are installed and the electricity demand is relatively high by 2030 (MWh)

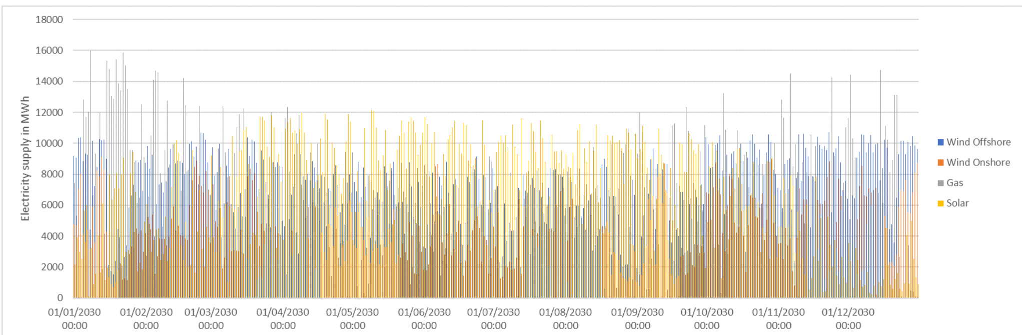

Figure 8.3: Electricity supply in case battery and hydrogen storage units are installed and the electricity demand is relatively high by 2030 (MWh)

8.1.2 Transmission lines

No transmission lines expansion was needed to incorporate the 9 TWh electricity generation from wind onshore energy in both cases. The transmission lines capacities and average loading for both cases are similar (Figure 8.4).

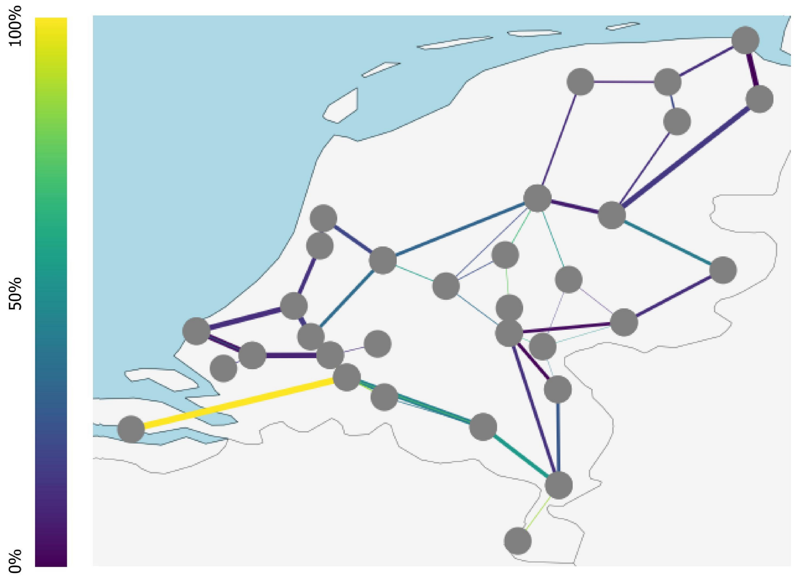

Figure 8.4: Transmission lines capacity and average loading in case electricity demand is relatively high for Case1 and Case2 by 2030

As shown in Table 8.1, the transmission lines with the high loading are mainly located at the 150 kV voltage level. Only two 380 kV transmission lines have high loading.

Voltage level	Connections	Loading
380 kV	Zeeland - West Brabant	72.5%
150 kV	West Brabant - Hart van Brabant	71.2%
150 kV	Hoekse Waard - Rotterdam-Den Haag	64.1%
150 kV	Noord en Midden Limburg - Zuid Limburg	74.1%
150 kV	FoodValley - Noord Veluwe	63.7%
380 kV	West Brabant - Midden Holland	61.8%

Table 8.1: Transmission lines loading at different voltage levels (%)

8.1.3 Storage units

The necessary storage capacity to incorporate the 35 TWh in Case1 is 1881.46 MW of battery storage (Figure 8.5). The optimization model built an extra capacity of 146 MW of battery storage in Flevoeland region. In Case2, the necessary storage capacity is 509 MW of hydrogen storage and 1509 MW of battery storage (Figure 8.6). The model built new hydrogen storage capacities in West-Brabant (12 MW), Flevoland (219 MW) regions and expended the capacity in Zeeland region from 225 MW to 278 MW. Regarding battery storage, no new capacity was built.

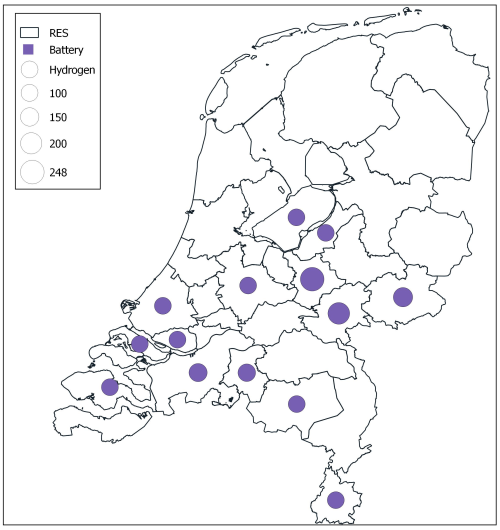

Figure 8.5: Storage units distribution within the energy regions in Case1 in MW

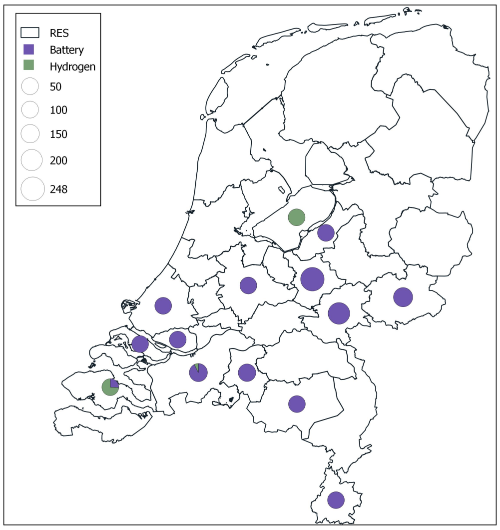

Figure 8.6: Storage units distribution within the energy regions in Case2 in MW

8.1.4 State of charge

The state of charge and the capacity dispatch for the storage units in all energy regions have been summed by technology.

The short-term battery storage (Figure 8.7) exhibit the same fluctuations, that indicates a high frequency. The dispatch of capacities reaches the maximum and minimum values in most hours of the year. In periods where the electricity generation is low (mainly from solar energy), the dispatch of battery storage reaches lower levels.

Figure 8.7: Annual trend of battery storage unit state of charge in the energy regions

With the expansion of wind onshore generation, more capacity of hydrogen storage have been installed. Therefore, the dispatch of capacity is higher and the peak is reached more frequently (Figure 8.8). The seasonal fluctuations in the capacity dispatch of hydrogen is mainly due to the high feed-in from wind energy.

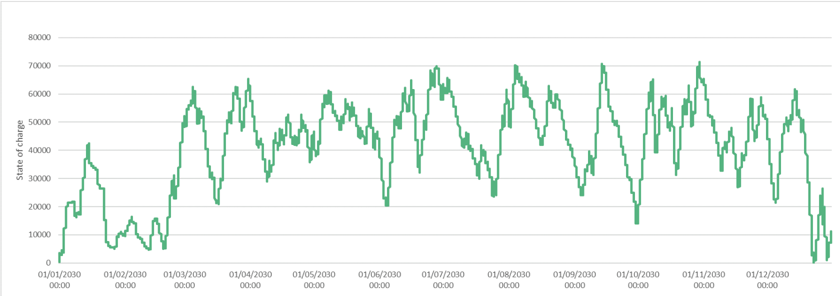

Figure 8.8: Annual duration curve sorted for the operations mode by storage technology in the energy regions

Figure 8.9 shows that the most dominant operation mode in battery storage is the discharging mode due to the high feed-in from solar PV. However, for hydrogen storage, charging mode is more dominant due mainly to the low charging efficiency.

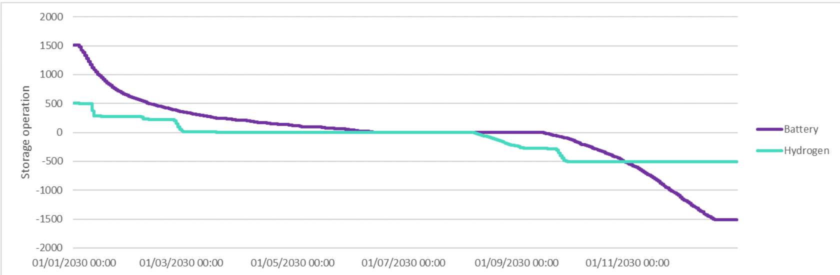

Figure 8.9: Annual duration curve sorted for the operation modes by storage technology in the energy regions

8.2 Scenario ES: Sub-scenario2

In this section, the results of the electricity generation will be presented under Scenario ES along with the necessary storage units and transmission lines capacities.

8.2.1 Electricity generation

Similarly to Scenario RES, The optimization results show that the remaining 9 TWh of electricity generation is needed from wind onshore energy in Rotterdam-Den Haag region (Figure 8.10). Moreover, the best location to install the generation capacities from wind onshore is Rotterdam-Den Haag region. The model expended the installed capacity of wind onshore energy in Rotterdam-Den Haag region from 487.7 MW to 2785.8 MW.

The annual electricity supply in Case2 is 112.29 PJ from gas, 62.13 PJ from solar and 147.5 PJ/ 90.83 PJ from wind offshore/onshore (Figure 8.11). Regarding Case1, the

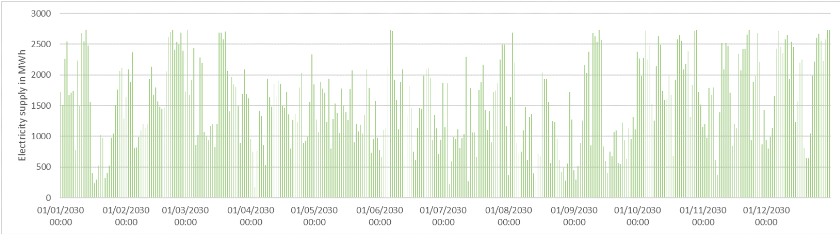

Figure 8.10: Electricity supply of wind onshore energy after the expansion in Rotterdam-Den Haag region in MWh

electricity required from wind onshore energy and solar PV is similar to Case2. However, less wind offshore energy was generated (152 PJ).

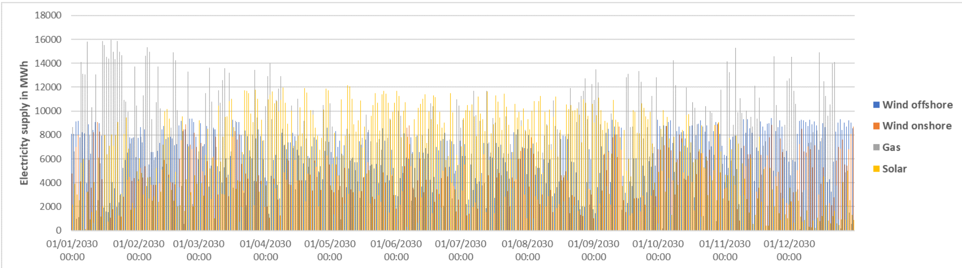

Figure 8.11: Electricity supply in case battery and hydrogen storage units are installed and the electricity demand is very high by 2030 (MWh)

8.2.2 Transmission lines

No transmission lines expansion was needed to incorporate the 9 TWh electricity generation from wind onshore energy in both cases. The transmission lines capacities and average loading for both cases are similar Figure 8.12.

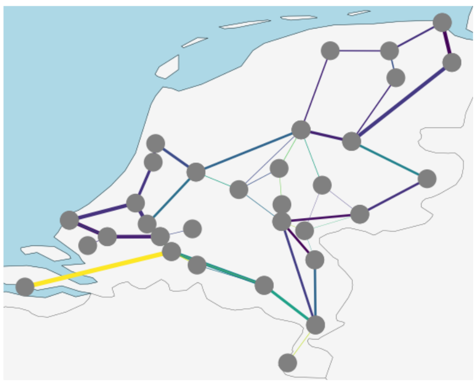

Figure 8.12: Transmission lines capacity and average loading in case the electricity demand is very high for Case1 and Case2 by 2030

As shown in Table 8.2, the transmission lines with the high loading are mainly located at the 150 kV voltage level. Only one 380 kV transmission line have high loading.

Voltage level	Connections	Loading
380 kV	Zeeland - West Brabant	83.6%
150 kV	West Brabant - Hart van Brabant	76.4%
150 kV	WestBrabant - Metropoolregio Eindhoven	64.4%
150 kV	Noord en Midden Limburg - Zuid Limburg	75.9%
150 kV	Rivierenland - Arnhem / Nijmegen	74.1%
150 kV	FoodValley - Noord Veluwe	66.7%
150 kV	Flevoland - Noord Veluwe	64%
150 kV	West-Brabant - Midden-Holland	63.6%

Table 8.2: Transmission lines loading at different voltage levels (%)

8.2.3 Storage units

The necessary storage capacity to incorporate the 35 TWh in Case2 is 2779.7 MW of battery storage and 587.7 of hydrogen storage (Figure 8.13). Regarding battery storage, the optimization model expended the capacity in different regions: Hart van Brabant region from 132 MW to 269 MW, FoodValley region from 51.31 MW to 55 MW and Arnhem/Nijmegen region from 305.8 MW to 450.7 MW. No extra capacity was needed in hydrogen storage. In Case1, 3160 MW battery storage capacity was required. The model built extra capacity of battery storage in Hart van Brabant and Arnhem/Nijmegen regions (Figure 8.14)

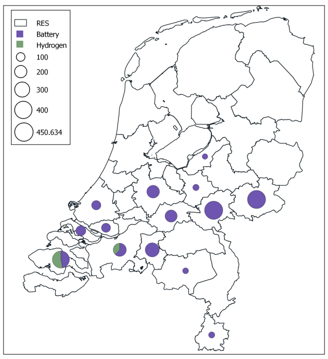

Figure 8.13: Storage units distribution within the energy regions in Case2 in MW

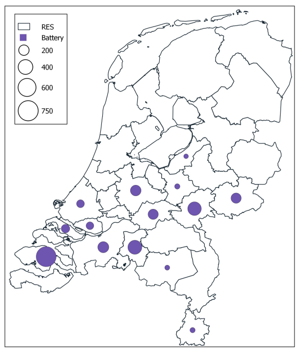

Figure 8.14: Storage units distribution within the energy regions in Case1 in MW

8.2.4 State of charge

Both battery and hydrogen storage in this sub-scenario show the same behavior illustrated in Sub-scenario1.

9 Discussion

9.1 Scenarios discussion

In this chapter RES and RE scenarios will be discussed before and after the electricity generation expansion. Figure 9.1 and Figure 9.2 give a summary of the installed capacity respectively in Sub-scenario1 and Sub-scenario2.

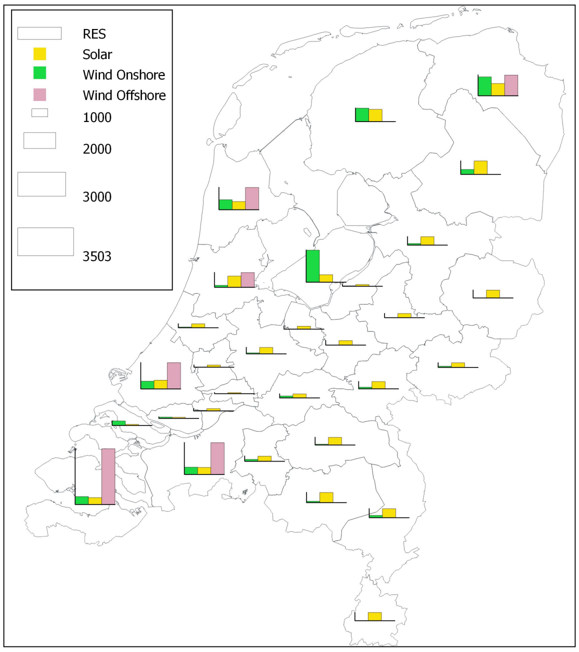

Figure 9.1: Installed capacity of solar, wind onshore/offshore in Sub-scenario1 in MW

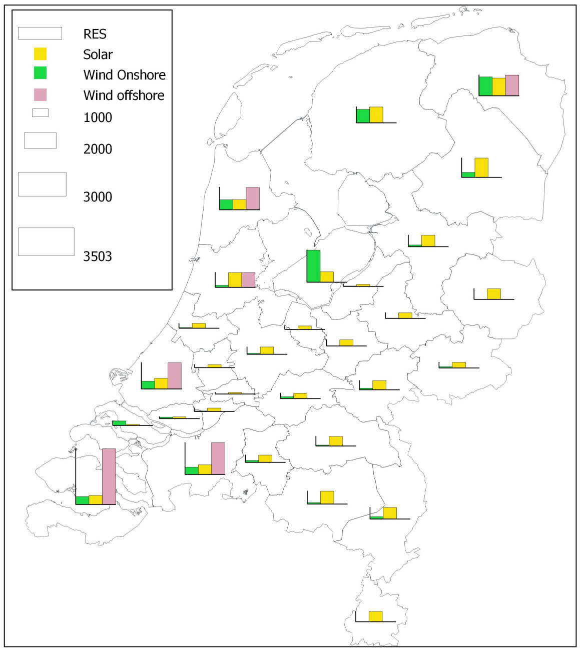

Figure 9.2: Installed capacity of solar, wind onshore/offshore in Sub-scenario2 in MW

9.1.1 Scenario RES 2030

Under this scenario, the assessment of the vRES plans of the energy regions was performed for a medium growth of electricity supply. In both sub-scenarios, where 100% and 50% of large-scale solar PV projects were achieved, the electricity supply from gas does not exceed 109 PJ. According to KEV 2019, to achieve a reduction of 49% of CO_2 by 2030 compared to 1990, a generation of approximately 120 PJ of electricity is needed from gas and 0 PJ from hard coal. However, the peak electricity supply from gas reaches 15994 MW in both cases, where only battery storage units are installed and where both battery and hydrogen storage units are installed.

In both sub-scenarios, the 380 kV electricity grid shows a robust performance, where only the 380 kV transmission line connecting Zeeland to West-Brabant needed to be expanded. However, different 150 kV transmission lines connecting the energy regions in the center (e.g. Amersfort, Noord Veluwe) require more capacity. Regarding, the 220 kV electricity grid, no extra capacity is needed.

The capacity needed from battery storage in Sub-scenario1 and Sub-scenario2 is respectively 1856 MW and 1509 MW. In Sub-scenario1 a high electricity supply from solar is expected (Figure 9.1). Therefore, most of the electricity generated is supplied to meet the electricity demand. However, in case the electricity generated from solar is low (Figure 9.1), more battery storage capacity was needed to store the electricity generated. In both sub-scenarios, hydrogen storage was installed in Zeeland region, where a high feed-in of wind offshore energy is located. FoodValley and Nijmegen/Arnhem are the regions with the highest installed capacity of battery storage. In Sub-scenario2 the installed capacity of hydrogen increased because of the high wind offshore electricity generation in Zeeland.

In all cases, the short-term battery storage shows a high frequency to level out hourly generation fluctuations from solar energy. However, the long-term hydrogen storage shows a seasonal variability coming from a high wind offshore feed-in. The annual duration curve for the operation modes in both battery and hydrogen storage shows that the most dominant operation mode in hydrogen storage is the discharging mode due to the low discharging efficiency. However, in battery storage, both operation modes (charging and discharging) operate equally.

The LMP depends strongly on the loading of the transmission lines and the electricity generated at each bus in both sub-scenarios. In case the electricity supply from vRES and the electricity demand is high, the LMP takes the values in the range of 0 euro/MWh to 50 euro/MWh. The overloaded transmission lines in the 150 kV electricity grid block the flow of the cheap electricity coming from regions with electricity generation surplus. However, in regions where electricity generation from vRES is sufficient to meet the electricity demand, the line loading does not affect the LMP. In case the electricity supply from vRES is low and the electricity demand is high, the electricity demand is mainly met by the supply from gas. Therefore, the LMP at all buses takes higher values. In the last case, where the electricity supply from vRES is higher than the electricity demand, the LMP is equal to 0 in all buses.

The expansion of the electricity generation from large-scale solar PV and wind onshore to 35 TWh shows that more investment costs are needed at the level of storage units. However, no capacity was required in the transmission lines. The best technology to generate the remaining 9 TWh of electricity according to the optimization model is wind onshore. Moreover, the best location is Rotterdam-Den Haag. In this scenario more hydrogen storage capacity was needed. The model built different hydrogen capacities in West-Brabant, Flevoland and Zeeland regions. Installing more hydrogen capacity increased the electricity supply from wind offshore and decreased the electricity supply from solar energy. The electricity supply needed from gas is only 90 PJ. Therefore, the national target in reducing CO_2 by 49% by 2030 is met.

9.1.2 Scenario ES 2030

Under this scenario, the assessment of the vRES plans of the energy regions was performed for a high growth of electricity supply. In both sub-scenarios, where 100% and 50% of large-scale solar PV projects were achieved, the electricity supply from gas exceed 130 PJ. As discussed in Subsection 9.1, to achieve a reduction of 49% of CO_2 by 2030 compared to 1990 according to KEV 2019, a generation of approximately 120 PJ is needed from gas and 0 PJ from hard coal. Therefore, under the actual energy region's vRES planned project, the target in reducing CO_2 can not be achieved.

In both sub-scenarios, the only transmission line that needed an expansion at the 380kV voltage level is the transmission line connecting Zeeland to West-Brabant. However, different 150kV transmission lines required more capacities: Zeeland - West-Brabant, West Brabant - Hart van Brabant, Rivierenland -Arnhem/Nijmegen, FoodValley - Noord Veluwe, Regio Amersfoort - Rivierenland, U10/U16- Amersfoort, Flevoland - Noord

Veluwe and Amersfoort - Noord Veluwe. Regarding the 220kV electricity grid, no transmission expansion was needed.

Regarding hydrogen storage, 792 MW and 587.78 MW were needed respectively in Sub-scenario1 and Sub-scenario2. The model built hydrogen storage at two different locations: Zeeland and West-Brabant. Regarding battery storage, an average of 2400 MW is required in both sub-scenarios, where the regions with the highest battery installed capacities are: Zeeland, U10/U16, Achterhoek, Arnhem/Nijmegen and Flevoland.

The expansion of the electricity generation from 26 TWh to 35 TWh using large-scale solar PV and wind onshore shows that more investment costs are needed at the level of storage units. However, no capacity was needed in the transmission lines. Similarly to Scenario RES, the model expended the installed capacity from wind onshore energy in Rotterdam-Den Haag region from 487 MW to 2785.84 MW. In this scenario no hydrogen storage was built. Regarding battery storage the model expended as well the capacities in Hart van Brabant and Arnhem/Nijmegen regions from 132.14 MW to 269.14 MW and from 305.84 MW to 450.71 MW respectively. The electricity generation from gas is 112.29 PJ. Therefore, the national target in reducing CO_2 by 49% can be achieved.

9.2 Limitations

The results illustrated in Chapter 7 and Chapter 8 need to be recognized with the apprehension of certain limitations at the modelling level. The modelling of the Dutch electricity grid considering the energy regions, requires different assumptions regarding the substations representing the different energy regions as well as the transmission lines connecting those regions. Even though the grid data used is very detailed and highly accurate, other assumptions might lead to different results regarding the transmission lines analysis. Moreover, only a part of the HV grid was added to connect the remaining energy regions and a large part of the HV grid was disregarded as well as the LV and MV grids. Even if most of the power system models, include only the 380 kV and 220 kV, the lack of a large share of the electricity network need to be recognized while assessing the outcome of the model.

The modelling of the vRES depends on weather data. In this thesis 2017 weather data were used. Therefore, the results regarding the installed capacity within the energy regions in the different scenarios may change. Moreover, the sizing of the storage units might change as well since it is directly related to the electricity generation from the vRES. However, it won't have a high effect on the spatial allocation of the storage units. The results might be affected as well by the modelling of the different power plants, where minimal up or down times of power plants and storage units are not considered. Moreover, the generation sources were clustered by fuel type, where each fuel type was represented by one marginal cost.

The electricity demand scenarios were modelled based on the established and intended policies. The non-achievement of certain policies in the different sectors might lead to different electricity demand.

The optimal power flow used to optimize the investment costs is the LOPF. The LOPF does not take into considerations the non-linear effects of the power transmission in AC networks (e.g. reactive power flows or voltage stability). Additional aspects, such as the transmission lines between other countries, reserve power, transmission losses, demand side management and sector-coupling were not considered.

10 Conclusion and Recommendations

10.1 Conclusion

This thesis presents a conceptual framework to assess the regional energy strategy in achieving the national energy transition goals. The methodology consists of optimizing the investment costs in the Dutch power system expansion while taking into account uncertainty in electricity demand and supply. The optimization problem was formulated as a linear optimal power flow. Moreover, scenario analysis was performed to capture uncertainty in electricity supply and demand by building different sets of scenarios. Therefore, this thesis aimed to answer the following research question: Given multiple scenarios in the Dutch electricity supply and demand, what is the cost-optimal power system expansion considering energy storage systems to incorporate the regional plans by 2030?

The energy regions need to deliver a plan for their transition, where the necessary renewable energy and storage installed capacity along with the transmission lines capacities are identified. So far 26 TWh of electricity generation from large-scale solar PV and wind onshore is planned within the energy regions. However, the needed infrastructure and energy storage systems to ensure an efficient incorporation of these onshore vRES are not set yet. Moreover, 9 TWh of electricity generation from onshore vRES need to be divided within the energy regions. Therefore, the goal of this thesis is:

- Finding out the necessary installed capacity and location of storage units along with the necessary transmission expansion to adequately accommodate the 26 TWh of electricity generation from large-scale solar PV and wind onshore under uncertainty in electricity supply and demand in a cost optimal way.
- Determining the least cost investment in large-scale solar PV and wind onshore to meet the 35 TWh electricity generation under uncertainty in electricity supply and demand.

To answer the research question, several sub-questions were formulated:

1. Which components are important to model the current power system?

   As discussed in Chapter 2, the most realistic way to model the power system is using AC models, where different components need to be identified, among others, buses, transformers, transmission lines, electricity demand and supply.

   The input data needed to model the buses, transformers and transmission lines is called grid data. This data is mostly not publicly available. Therefore, different sources are needed to extract these data. According to the literature review performed in Chapter 2, the sources that contain grid data are divided into two categories: open source data and open grid data. Both sources have advantages and disadvantages. Therefore, in this thesis grid data for the Netherlands were extracted from both sources and then pre-processed in order to identify the most reliable data sources to model the Dutch electricity grid.

2. How to model the Dutch electricity power system?

   In order to evaluate the energy region's vRES planned projects, each energy region need to be represented by one bus. Therefore, the Dutch electricity grid was modelled in a way that the energy regions were presented with the actual substations in the electricity grid. Moreover, the transmission lines of the Dutch grid were added in series and in parallel to form one main transmission line that connects two energy regions. The underlying topology of the grid used to model the Dutch electricity grid incorporates the 380kV, 220kV and 150kV transmission lines, buses and transformers, where the data used were based on the results of the first sub-question. Two main components remain: electricity demand and supply. Both electricity supply and demand were modelled using a spatio-temporal approach. The electricity demand profiles were developed by dividing the electricity demand into different sectors: households, buildings, agriculture, industry and transport. Moreover, the hourly electricity demand of each sector was divided within the energy regions. The electricity supply profiles were developed by clustering the electricity generation sources by fuel type and affiliate the different types to the appropriate energy region.

3. How to model different scenarios in the electricity supply and demand?

   The scenarios were developed to capture the uncertainty in electricity supply and demand. The uncertainty in electricity supply is present in the actual plans of the energy regions regarding the electricity generation from large-scale solar PV. However, the uncertainty in electricity demand is regarding the expected electricity demand in the different sectors. Therefore, a two-phase scenario planning was developed, where generation type and capacity uncertainty (achievement of 50% and 100% of large-scale solar PV planned projects by the energy regions) are presented in the first phase and the allocation of the installed capacity to segments of two different electricity load shapes (medium growth and high growth) as a second phase decision.

In the scenarios, both electricity demand and supply were developed using a high temporal demand and supply profiles. The electricity demand profiles were developed using ETM model. Regarding the electricity supply profiles, the vRES plans of the energy regions in TWh were translated into installed capacity in MW using an accurate parametrization.

4. What types of energy storage systems can be used and how can they be modelled?

   Two different types of energy storage technologies were chosen: short-term storage battery and long-term hydrogen storage. Battery storage units have a high charging and discharging efficiencies. Moreover, they can provide and store energy for 6h. Hydrogen storage units have a very low charging efficiency. However, they can provide and store energy for 168h. The storage units were modelled based on their technical characteristics (charging/discharging efficiencies and energy to power ration).

5. What is the cost-optimal investment in energy storage and transmission lines to accommodate the 26 TWh regional plans by 2030 under uncertainty ?

   The DC linear optimal power flow is used to find the cost-optimal investment in both energy storage and transmission lines to incorporate the planned vRES in the energy regions under the modelled scenarios. Different DC grid models are available to perform the DCLOPF. In this study, PyPSA model is used, where the investment costs in both transmission and storage, and dispatch costs of generation and storage are minimized.

   The DCLOPF is run for two different scenarios, where the growth of electricity demand is medium and high. Within each scenario, two different sub-scenarios are considered, where large-scale solar PV planned projects are achieved at 50% (Sub-scenario1) and 100% (Sub-scenario2) level. Within each sub-scenario, two cases are identified, where only battery storage is considered (Case1) and both battery and hydrogen storage are considered (Case2).

Regarding the scenario where the growth of electricity demand is medium, an average of 1700 MW storage units are required to be installed within the energy regions, mostly in FoodValley, Nijmegen/Arnhem and Zeeland regions. Hydrogen storage was built only in Zeeland region, where a high feed-in of wind offshore electricity is generated. More capacity is needed in the 380 kV transmission line connecting Zeeland to West-Brabant in both sub-scenarios. However, at the 150kV voltage level, different transmission lines require more capacity, mainly the 150 kV transmission lines connecting: West-Brabant - Hart van Brabant, FoodValley - Noord Veluwe, U10/U16 - Amersfoort, Amersfoort -Noord Veluwe.

In the scenario where the electricity demand is high, an average of 3300 MW battery storage capacities are needed in Case1. Regarding Case2, 800 MW of hydrogen and 2372.35 MW of battery storage installed capacity are required. In both sub-scenarios, hydrogen storage was built in Zeeland and West-Brabant regions. The regions with the highest storage installed capacity are Zeeland, West-Brabant, U10/U16, Achterhoek and Arnhem/Nijmegen regions. Regarding the transmission lines, at the 380kV voltage level, only the connection between Zeeland and West-Brabant needed more capacity. Regarding the 150 kV electricity grid, the following connections needed more capacities: Zeeland - West-Brabant, West-Brabant - Hart van Brabant, Rivierenland -Arnhem/Nijmegen, FoodValley - Noord Veluwe, Amersfoort - Rivierenland, U10/U16- Amersfoort, Flevoland - Noord Veluwe and Amersfoort - Noord Veluwe.

6. What is the cost-optimal power system expansion to meet the extra 9 TWh electricity generation from large-scale solar PV and wind onshore?

   Based on the results of the last sub-question, an expansion in electricity generation (from 26 TWh to 35 TWh), transmission and storage units is performed using PyPSA

model. In addition to the optimization variables defined in the last sub-question, the investment costs in large-scale solar PV and wind onshore were added. Therefore, the investment costs in generation, transmission and storage, and dispatch costs of generation and storage are minimized.
The optimization results show that the remaining 9 TWh need to be generated exclusively from wind onshore energy. Moreover, the best location for the generation expansion is Rotterdam-Den Haag region, where the installed capacity increased from 487 MW to 2785.84 MW in both scenarios. No expansion was required at the level of the transmission lines in both scenarios as well. However, the model built new hydrogen capacities in West-Brabant and Flevoland regions, and expended the capacity in Zeeland in Sub-scenario1. Moreover, no extra capacities of battery storage were built. In Sub-scenario2, no hydrogen capacities were built and extra capacities of battery storage were expended in Hart van Brabant and Arnhem/Nijmegen regions. The electricity supply from gas is 90 PJ in Scenarios RES and 112.29 in Scenario RE. Therefore, installing the remaining 9 TWh would help achieving the national target in Scenario ES.

10.2 Recommendations

The pre-processing data performed in Chapter 4 allowed the gathering of an accurate data set of the Dutch electricity grid. The data can be used to perform an ACOPF, where the reactive power is taken into account. Therefore, less transmission capacities might be needed. Moreover, transmission expansion planning can be performed, where the model can choose new nodes to connect the regions. However, the use of an ACOPF will result in longer simulation times. Therefore, time series aggregation methods can be adopted to deal with the problem of simulation time.
Based on the same methodology of gathering grid data for the Netherlands, the electricity demand of the different sectors together with the power generation capacities can be allocated to multiple voltage levels (high voltage, medium voltage and low voltage). Therefore, an in depth analysis can be made to analyze the growth of electricity demand in the different sectors in regard to the transmission lines at different voltage levels. One of the main problems is the mapping of the electricity demand sectors in order to allocate them to the appropriate substation. OpenStreetMap can be used to map the electricity

sectors.

Another recommendation, is coupling the electricity grid developed in this thesis with the gas infrastructure. This will allow ta assess flexibility in the network. One of the major problems is data regarding gas consumption by the energy regions. Similarly to this work, the annual gas demand data can be retrieved from Klimaatmonitor and the hourly national gas demand data can be retrieved from ETM.

The model is built by combining different open sources data that are freely available. Therefore, the model is suitable for improvement. Moreover, this work can be extended to explore other directions such as the variations in both CO_2 cap and price, coupling to other sectors and the interconnection between surrounding countries.

10.3 Reflection

10.3.1 Data availability

The most striking observation I had while writing this thesis was the lack of official data sources for the power system in the Netherlands. This lack of sources have a high impact on both the number and the quality of research that have been carried out for the expansion of the Dutch power system. On one side, the majority of research are done at low granularity resolution, where the data is aggregated at the national level. On the other side, the research performed with high spatio-temporal resolution mainly by government entities or consultancies does not describe in details how the data have been gathered and from which sources. Therefore, reproduction of the used methods or models is impossible. The only choice I had was either carry out the research with many assumptions and simplifications or look for unofficial data sources. Surprisingly, different sources such as ETM and HoogspanningsNet offer a large set of data, which can be considered reliable.

10.3.2 Spatio-temporal resolution

The main focus of this thesis is the assessment of the regional plans (regarding renewable energy projects) and to which extent the integration of these plans in the power system will help the country meeting its target in reducing CO_2 emissions. Therefore, the electricity demand and supply profiles, where fluctuations of electricity consumption and renewable energy supply in a specific region are essential for this assessment. Even though the results show that electricity supply from gas will be decreased by 2030 in both scenarios, the peak supply is high, Therefore, the fluctuations in electricity consumption in a specific region can give insights where demand-side management need to be introduced. Moreover, the results show as well that the storage units built in a region heavily depend on the type of installed renewable energy sources. Therefore, the fluctuations of solar, wind onshore and wind offshore will give insights regarding the more adequate type of storage needed in each region.

10.3.3 High electrification scenario

The scenario with the high electricity demand (ES) is based on the established and proposed policies incorporated in NEV 2017 for the different sectors (households, buildings, industry, transport and agriculture) and the national targets described in KEA 2019.

Households

The emissions in households sector are almost entirely caused by "the use of natural gas for: space heating, hot water production and cooking" [67]. To reduce CO_2 emissions in households sectors by 2030, the government set two main policies [18]: natural gas-free new construction and making 1.5 millions of existing buildings sustainable.

- Natural gas-free new construction:

  The natural gas-free developments consist of the abolition of gas from the new buildings. In the established and intended policies scenario in NEV 2017, more than 60% of the new buildings were assumed to be equipped by heat pumps and the rest connected to the heat network [18]. Moreover, an increasingly important part of the electricity demand of households is assumed to be covered by the electricity generated by households themselves (small-scale solar PV) [18]. The same assumptions were used in the Scenario ES.

- Disconnection of 1.5 millions of existing homes from gas supply:
  It has been agreed in the Climate and Energy Agreement that a transition vision for heat will be drawn by the municipalities, in which each municipality need to state in which neighborhood the homes and buildings will be disconnected from gas and made more sustainable by 2030. Since no established or concrete policies have been set yet about the distribution of the 1.5 million homes and other buildings among the municipalities and which technologies will be used instead of gas, this agreement was not taken into account in the NEV 2017. Therefore, gas supply remained the dominant fuel for households sector and the electricity demand by 2030 was assumed to be 79 PJ [18]. In the Scenario ES, this agreement has been taken into account and the following assumptions were made regarding the 1.5 millions existing homes [21]: 50% will be connected to the heat network, 25% will be equipped by hybrid heat-pumps, 25% will be equipped by electric heat-pumps. As a result, the electricity demand in the Scenario ES reached 86.12 PJ.

The high electrification scenario used in this thesis have a good approximation of the expected electricity demand in households sector by 2030. However, the increase in the use of electric heat-pumps in the 1.5 millions homes agreement would increase the electricity demand. Therefore, the outcome of the model especially regarding the storage units capacities would change.

10.3.4 Cost assumptions

In the first optimization problem, different cost assumptions regarding the transmission lines and the storage units were made. In order to incorporate the energy region's vRES into the electricity grid optimally, the model needed to extend both the transmission lines and storage units based on their investment costs. In literature, the technical specifications (efficiency and energy to power ration) used for battery and hydrogen in power system expansion are different:

- Battery: energy to power ration of q = 6 and the round-trip efficiency is 93%.
- Hydrogen: energy to power ration of q = 168, a charging efficiency of 0.725 and a discharging efficiency of 0.425.

The results of the model show that the technical specifications of battery storage units

make them suitable to regions with a high share of solar energy. However, hydrogen storage units are more suitable in regions with a high share of wind onshore/offshore energy. Therefore, the increase or decrease in the investment costs of battery storage in regards to hydrogen storage investment cost won't affect the type of storage in the region. However, the total investment cost will be affected.
In most literature regarding power system expansion, the investment cost of the transmission lines (regardless their voltage level) is expected to be 450 EUR/MVA*km by 2030. In this thesis, the investment costs for the different transmission lines (380kV, 220kV and 110kV) are considered different, which is more realistic. The increase or decrease of the 380kV transmission lines investment costs would have a small effect on the results since the model extended only one 380kV transmission line. However, the increase or decrease of the 150kV transmission lines would have higher effects, because the model extended several 150kV transmission lines.

In the second optimization problem, assumptions regarding the investment costs of solar PV and wind onshore were made. Even though investment costs of solar PV are lower than investment costs of wind onshore, the model chose building more wind onshore capacity. Therefore, even though the investment costs of solar PV decreases, it will be more cost-efficient to build wind onshore since the capacity factor of solar PV (solar irradiance) in the Netherlands is very low compared to wind onshore capacity factor (wind speed).

10.3.5 Inter-national capacities

The Netherlands have interconnection with Norway and UK through DC connections, and with Belgium and Germany through AC connections [87]. TenneT already set different plans to increase cross-border capacities following the expected high share of vRES in the generation mix and market decarbonization. Following the technical specifications used for storage units and the modelled electricity demand, curtailment of vRES occurs when there is excess of generated electricity during low demand periods. Therefore, by exporting electricity the Netherlands can avoid curtailment of vRES surplus electricity generation.
In the different scenarios, flexible gas supply is mandatory to meet the electricity demand especially in periods of peak electricity demand and low supply from vRES. Importing

electricity would decrease the use of electricity supply from gas. Moreover, customers can benefit from cheap prices of the electricity imported. The LMP shows a high volatility of prices within the energy regions, especially when the electricity demand is high and the supply from vRES is low. By importing cheap electricity, the interconnection might lead to more stable and less volatile prices.

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Appendix

A Appendix I: Extracting OSM data

The method in this section is described in [50].

The OSM raw data is loaded into PostGIS "which is a spatial database extender for PostgreSQL object-relational database" [52].

First a database is created through PgAdmin4 which is the official client for PostgreSQL [68]. Second, this database is enabled with PostGIS extension using SQL. Last, PostGIS is accessed through QGIS; “free and open-source cross-platform desktop geographic information system application that supports viewing, editing, and analysis of geospatial data” [70]; using the same identification of the database created in PgAdmin4. As a result, a connection is established between PostGIS and QGIS through the database.

Using Osm2pgsql; "a command-line based program that converts OpenStreetMap data" [57]; allows loading the OSM data into POSTGIS. As a consequence, the data is accessed immediately through QGIS (Figure A.1).

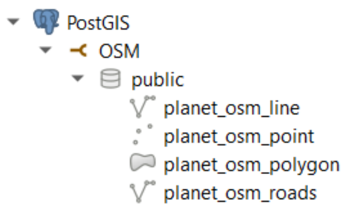

Figure A.1: PostGIS databse incorporated into QGIS [70]

B Appendix II: Theory

In this chapter, the theories used in this thesis are described along with the process of extracting grid data (mainly substations and transmission lines) for the Netherlands.

B.1 Optimal power flow

The purpose of the optimal power flow is the optimization of the steady-state power system performance subject to several constraints with respect to an objective H[59].

$$minH(a;y) \tag{B.1}$$

subject to

$$J(a;y) \tag{B.2}$$

$$h(a;y) \leqslant 0 \tag{B.3}$$

Where $H(a;y)$ is the objective function to be optimized, $J(a;y)$ and $h(a;y)$ represent respectively the non-linear equality constraints of the nodal equations and the non-linear inequality constraints of the defined variables (dependent and independent) [59]. y refers to the vector of control variables, it includes generator's characteristics, transformer tap setting and voltage magnitudes of buses [91]. Whereas a constitutes the vector of dependent variables as generator reactive power, demand (PQ) node voltages [91].

The linear optimal power flow can be utilized for different purposes, depending on the chosen objective function and defined constraints. The list below [59] presents different objectives and constraints that are frequently found in the optimal power flow formulation, in which the objectives are constructed mathematically with potential solutions and the constraints are designed appropriately to satisfy both upper and lower bounds to find practical solutions.

1. Objectives
    - Active power objectives are divided into two main categories
        - Economical and environmental dispatch (including losses)
        - The maximum power dispatch
    - Reactive power objectives
        - In term of active and reactive power and loss minimization
    - Other objectives

- "Minimum deviation from target schedule and Minimum control shifts to alleviate violations"

2. Constraints

- Limits on generators and transformers (control variables)
  - Generated power
  - Transformer output voltage limits
- Operating limits on both line and transformerss
  - MVA, A, MW and $MVAr$
  - $MW/MVAr$ interchange/reserves margins
  - Voltage, angle
- Control parameters
  - "Control to handle violation, control effectiveness, control rate change

In general, OPF aim to optimize (minimization) the total generator fuel costs for both conventional and renewable energy sources subject to generators power output and transmission line capacity and power balance [14]. The constraints in this case are expressed based on the current (direct or alternating), then either AC power flow or DC power flow equations. In the next section ACOPF will be presented.

Theory of optimal AC power flow

AC OPF is considered as the most precise representation of the power flow, therefore the results determined by the optimization of the chosen objective function are near to reality [14]. Compared to DC OPF, AC optimal power flow increases accuracy and considers voltage, reactive power, currents and transmission losses [91]. Nevertheless, it has drawbacks, since The power "is dependent on the square of the voltage" [95]. This will transform the equations to quadratic ones that can not be incorporating into an optimization problem as an equality constraints. Otherwise the problem will be transformed to a "non-linear and non-convex problem"[95] complicated to solve.

- Modelling transmission lines: the π-model

The π-model shown in Figure B.1 is the most usual presentation of a transmission line between 25 km and 250 km in power systems [14].

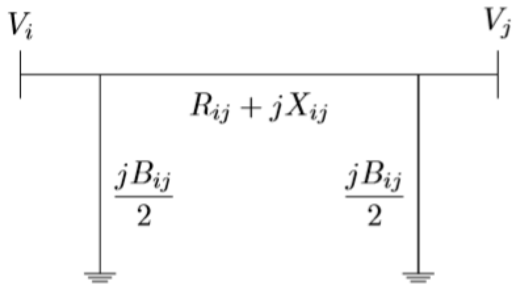

Figure B.1: π-model of the transmission line [14]

The series impedance of the line connected at the nodes i and j is represented by K_{ij}, where $K_{ij} = R_{ij} + jX_{ij}$, R_{ij} and X_{ij} are respectively the resistance and reactance of the line.

The series impedance can be expressed as:

$$K_{ij} = Y_{ij} - 1 \tag{B.4}$$

where Y_{ij} is the admittance of the transmission line.

On the other side the relationship between the conductance G_{ij} and B_{ij} the susceptance is:

$$L_{ij} = G_{ij} + B_{ij} \tag{B.5}$$

The conductance G_{ij} and the susceptance B_{ij} of the transmission line can be computed knowing both R_{ij} and X_{ij}. The equations can be expressed as:

$$G_{ij} = \frac{R_{ij}}{R_{ij}^2 + X_{ij}^2} \tag{B.6}$$

$$B_{ij} = \frac{-X_{ij}}{R_{ij}^2 + X_{ij}^2} \tag{B.7}$$

As a result, the π-model can be represented by the series admittance L_{ij}, and the shunt susceptances at the edges of the transmission lines is: $jB_{ij}/2$

Formulation of the optimization problem

Considering N_b is the number of buses and N_g the number of generation units, the mathematical formulation of the AC optimal power flow problem for power system can be formulated as [91]:

$$minF = \sum_{m=1}^{Ng} C(P_{Gm}) \tag{B.8}$$

Where,

The total generation cost to minimize is F.

$C(P_{Gm})$ and (P_{Gm}) are respective the cost of generating a unit m (expressed in EUR for example), and the power generated of the m^{th} generator.

Subject to different constraints, namely: Nodal power Balance constraints, power Flow Constraints, generators Capacity Constraint and voltage Constraint [14].

- Nodal power balance constraints

It is considered as the most important constraint, as the power balance equation need to be respected at every node i in the network [59]. The equality constraint is represented as: P_{Gi} the total generated power at bus i minus P_{Di} the total power demand in every node i need to be equal to the power flow through the lines both the generation and demand are connected to [91]. This constraint hold for both active and reactive power.

- PF constraints

The apparent power flow through a transmission lines need to be "within the upper bound of the thermal power rating limit" [91]:

$$|T_{ij}| \leq \bar{T_{ij}} \tag{B.9}$$

Where:

T_{ij} is "the apparent power flow throughout the transmission line i,j", and

$\bar{T_{ij}}$ is "the corresponding maximum apparent power transfer capacity limit".

- Generators capacity constraint

The active and reactive power generation capabilities need to be "within the maximum and minimum nominal power of the generations units at every node" [91]. This limit can not be exceeded and can be expressed as follow [91]:

$$\underline{N_{Gi}} \leq |N_{Gi}| \leq \bar{N_{Gi}} \tag{B.10}$$

$$\underline{M_{Gi}} \leq |M_{Gi}| \leq \bar{M_{Gi}} \tag{B.11}$$

Where

$\underline{N_{Gi}}$ and $\bar{N_{Gi}}$ are respectively the minimum and maximum active power generation limits.

$\underline{M_{Gi}}$ and $\bar{M_{Gi}}$ are respectively the minimum and maximum reactive power generation limits.

- Voltage constraint

At each bus j the voltage need to be within the max and min voltage magnitude [91].

$$\underline{V_j} \leq |V_j| \leq \bar{V_j} \tag{B.12}$$

Where:

$\underline{V_i}$ and $\bar{V_i}$ are respectively the minimum and maximum voltage magnitude at bus j.

B.2 Theory of economic dispatch

The economic dispatch (ED) is defined as the optimization process that determines the operation of the accessible generators at a minimum cost, given the total electricity load and the operation limits of each generator at node i [1]. This definition excludes any constraints related to network constraints as line thermal limits, generation constraints as ramp limits and security constraints [1].

- Merit-order curve

The merit-order curve serves as an excellent tool to dispatch the available power generation at a minimum operation cost [14]. The generators are ranked based on their current merit which is based on their marginal cost [14]. Therefore, generators with lower marginal costs have high merit. Figure B.2 shows an example of the economic dispatch of generators based on the merit-order.

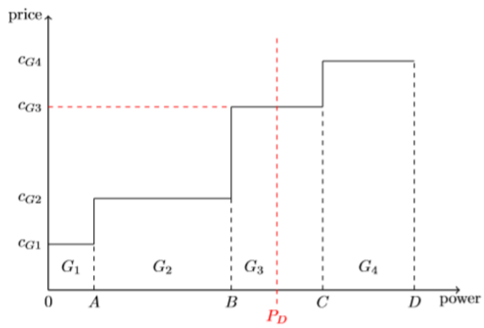

Figure B.2: Economic dispatch based on the merit order [14]

X-axis and y-axis represent respectively the power production and the marginal generator cost of every generator, Where the power production is distributed as follow: $A = P_{maxG1}$, $B = A + P_{maxG2}$, $C = B + P_{maxG3}$, $D = C + P_{maxG4}$, and $C_{G1} \leq C_{G2} \leq C_{G3} \leq C_{G4}$.

In order to perform the generation dispatch, the total load P_D need to be determined. The intersection of P_D with the x-axis and y-axis shows that all the generators on the left of P_D must generate power and the rest of the right should not produce anymore.

- Formulation of the optimization problem

the formulation of the economic dispatch problem as an optimization problem can be described as follow [14]:

$$\min_{P_{Gi}} \sum_i c_{Gi} P_{Gi} \tag{B.13}$$

Subject to

$$\sum_i P_{Gi} = P_D \tag{B.14}$$

$$P_{Gi}^{min} \leq P_{Gi} \leq P_{Gi}^{max} \tag{B.15}$$

The objective function minimizes the total power generation cost, in which each generator is characterized by two elements: the marginal cost c_{Gi}, and the generated power P_{Gi} [14]. The equation (1.15) represent the constraint that the generators should not violate, in which all generators must operate within the minumum and maximum power limits. Moreover, all generated power need to be equal to the load equation (1.14).

C Appendix III: ETM sectoral electricity demand

The Table C.1 gives an overview of the different sub-sectors in ETM.

Households	households cooker halogen electricity
	households cooker induction electricity
	households cooker resistive electricity
	households cooling air-conditioning electricity
	households cooling heatpump air water electricity
	households cooling heatpump ground water electricity
	households final demand for appliances electricity
	households final demand for hot water electricity
	households final demand for space heating electricity
	households lighting efficient fluorescent electricity
	households lighting incandescent electricity
	households lighting led electricity
Industry	industry final demand for chemical fertilizers electricity
	industry final demand for chemical other electricity
	industry final demand for chemical refineries electricity
	industry final demand for other food electricity
	industry final demand for other ICT electricity
	industry final demand for other non-specified electricity
	industry final demand for other paper electricity
	industry other metals process electricity
	industry steel blast furnace current consumption use able heat
	industry steel electric furnace electricity
	industry aluminum electrolysis current electricity
	industry aluminum smelt oven electricity
Industry	buildings cooling collective heat pump water electricity
	buildings final demand for space heating electricity
	buildings lighting efficient fluorescent electricity
	buildings lighting led electricity
	buildings lighting standard fluorescent electricity
Transport	transport bicycle using electricity
	transport bus using electricity
	transport car using electricity
	transport freight train using electricity
	transport motorcycle using electricity
	transport passenger train using electricity
	transport tram using electricity
	transport truck using electricity
Agriculture	final electricity agriculture

Table C.1: Sub-sectors in ETM

D Appendix IV: Netkaart Nederland

Figure D.1 shows the high voltage electricity grid of the Netherlands at 110kV to 380kV voltage level.

Figure D.1: Netkaart Nederland [35]

E Appendix V: Transport electricity demand

The national hourly electricity demand of transport is given by ETM model divided into different types (e.g. bus, car, freight, tram). Klimaatmonitor provides the number of electrical cars (fully and hybrid) and electrical buses (Table E.1). Therefore, the hourly electricity demand of cars and buses provided by ETM is scaled down to the regional hourly electricity demand based on the number of cars and buses in each energy region. Regarding the other types of transport, the national electricity demand is scaled down equally between the energy regions.

	bussen	personenauto's (FEV en PHEV)
RES-regio Holland Rijnland	0	3.799
RES-regio Achterhoek	0	1.803
RES-regio Drechtsteden	0	3.307
RES-regio Drenthe	0	3.204
RES-regio Flevoland	0	30.659
RES-regio Foodvalley	0	2.871
RES-regio Friesland	166	4.897
RES-regio Goeree-Overflakkee	0	387
RES-regio Groningen	109	2.918
RES-regio Hart van Brabant	0	6.724
RES-regio Hoeksche Waard	0	748
RES-regio Metropoolregio Eindhoven	62	5.347
RES-regio Rotterdam–Den Haag	78	19.577
RES-regio Midden-Holland	0	1.628
RES-regio Noord Holland Noord	0	5.077
RES-regio Noord Holland Zuid	241	31.001
RES-regio Noord Veluwe	0	1.171
RES-regio Noord- en Midden Limburg	0	2.588
RES-regio Noord-Oost Brabant	1	5.829
RES-regio Alblasserwaard	0	583
RES-regio Amersfoort	61	10.361
RES-regio Arnhem / Nijmegen	41	4.485
RES-regio U10/U16	0	17.535
RES-regio Rivierenland	0	3.040
RES-regio Cleantech regio	2	2.809
RES-regio Twente	1	6.396
RES-regio West-Brabant	2	16.068
RES-regio West Overijssel	15	3.351
RES-regio Zeeland	2	2.158
RES-regio Zuid-Limburg	0	2.966
Nederland	781	203.287

Table E.1: Number of buses and electrical cars within the energy regions [48]

F Appendix VI: Zeeland region modelling

The modelling of the energy regions consist of affiliating one bus to each region. In some cases, the energy regions incorporate several 380kV buses like in the case of Zeeland region. The region Zeeland incorporates two 380kV buses: Borssele and Rilland (Figure F.1).

Following the two criteria defined in Subsection 4.2.1.1, Zeeland region will be affiliated to Borssele bus. First, Borssele bus is located at the edge of Zeeland. Second, the transmission line connecting Zeeland to West-Brabant can be represented with the 380kV transmission

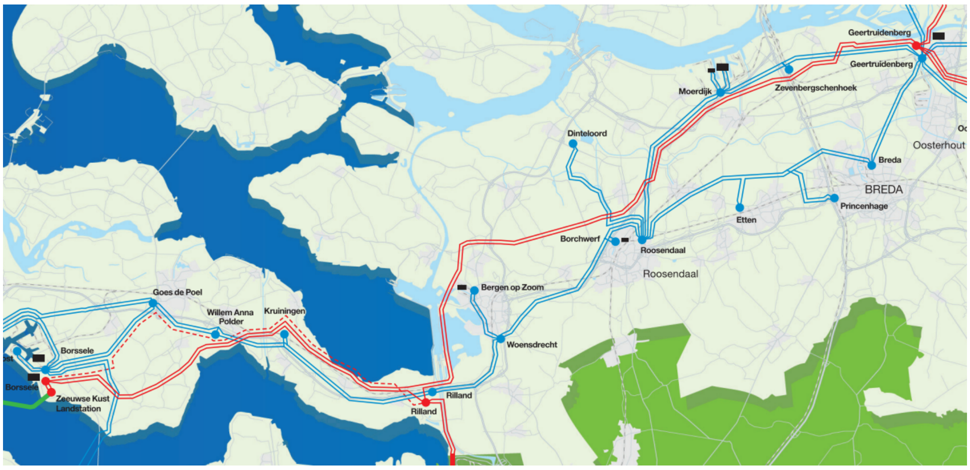

Figure F.1: Substations in Zeeland region [35]

line connecting Borssele bus to Geertruidenberg. The 380kV transmission line Borssele-Geertruidenberg was modelled by adding the 380kV transmision line Borssele-Rilland in series to the 380 kV transmission line Rilland-Geertruidenberg. The transmission lines in the electricity network are redundant. Therefore, all the transmission lines in the model were added in parallel.

G Appendix VII: Electricity demand growth (Scenario ES)

In this section, the development of electricity demand chosen for the different sectors is analyzed as described by the National Energieverkenning 2017 report [18] and the energy system scenario made by Kalavasta[21].

G.1 Households

Electricity demand in households by 2030 is expected to have two different trends: a decrease between 2020-2025 and an increase between 2025-2030 (green and yellow solid lines in Figure G.1). The decrease in electricity demand in households is mainly due to the slow increase in electrical appliances that are expected to fall under the European Eco-design requirements (meaning that the new electrical appliances will use less electricity) [18]. Moreover, the electricity demand is expected to be met mainly by gas supply in existing buildings, and a combination of heat network and hybrid heat pumps (electrical and green gas) in new buildings [18]. After 2025, the growth of electricity demand is forecast to rise because of the increase in the number of households and the use of electric heat-pumps (which is expected to reach 14 PJ by 2030) [18]. As a result, the electricity demand in households sector is expected to reach 82 PJ in the established policies scenario (yellow solid line (V) in Figure G.1) [18].

Solar panels are foreseen to generate a surplus of electricity to meet the long-term increasing electricity demand by households. Therefore, the electricity supply from the electricity grid to households will decline (green and yellow dashed lines in Figure G.1). The electricity demand of electrical vehicles is incorporated in the transport sector.

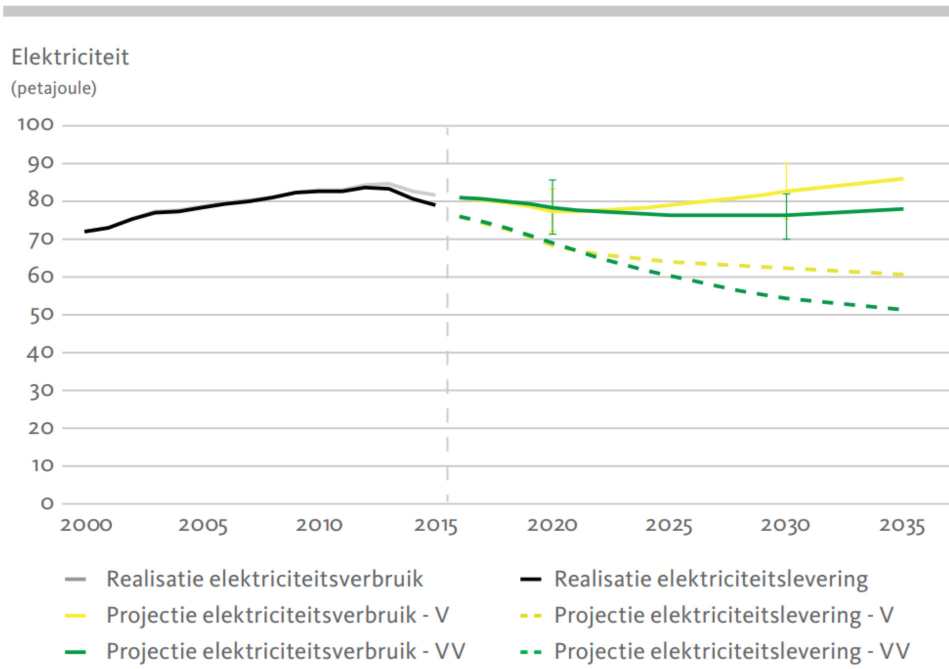

Figure G.1: The development of electricity demand and supply in households sector in the period 2000-2030 (V is the projection of established policies, VV is the projection of established and proposed policies) [18]

Two main policies play a role in the electrification of households sector [18]:

- Abolition of gas supply from new buildings.
- Disconnection of 1.5 millions of existing buildings from gas supply.

The first policy is translated in the ER scenario by: 35% of new buildings will be connected to the heat network and 65% will be equipped by heat-pumps (where, 70% are related to heat-pumps (ground) and 30% to heat-pumps (air)) [21]. The second policy is translated in the ER scenario by: 50% of existing buildings will be connected to the heat network, 25% will be equipped by heat-pumps (air) and 25% will be equipped by hybrid heat-pumps [21].

G.2 Buildings

Similarly to electricity demand in households, the electricity demand in buildings is expected to decrease as well between 2020-2025 and to increase between 2025-2030 (Figure G.2). The decrease in electricity demand in buildings is mainly due to energy savings in Information and communications technology (ICT) equipment in companies [18]. Moreover, even though the number of data centers is increasing, they are becoming more efficient in term of electricity consumption. In addition, electricity consumption in space heating will be mainly met by gas-fired heater, and by extracting heat from the ground and outside air by heat-pumps. The use of heat-pumps (air and ground) already increased since 2016 [18].

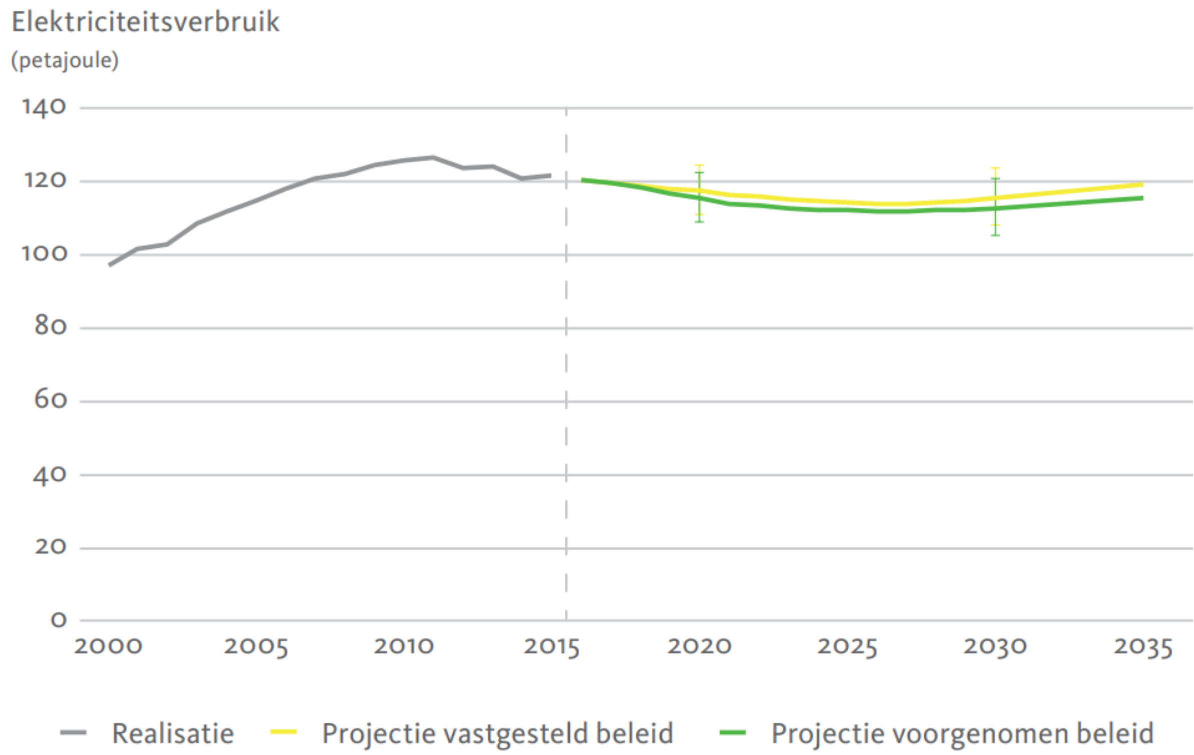

Figure G.2: The development of electricity demand in buildings sector in the period 2000-2030 (V is the projection of established policies, VV is the projection of established and proposed policies) [18]

G.3 Industry

The electricity consumption in industry sector is expected to remain at approximately the same level in the period up to 2030 (Figure G.3), where two assumptions were made: non-extensive electrification of the industrial energy supply and an efficiency of 0.8 [18].

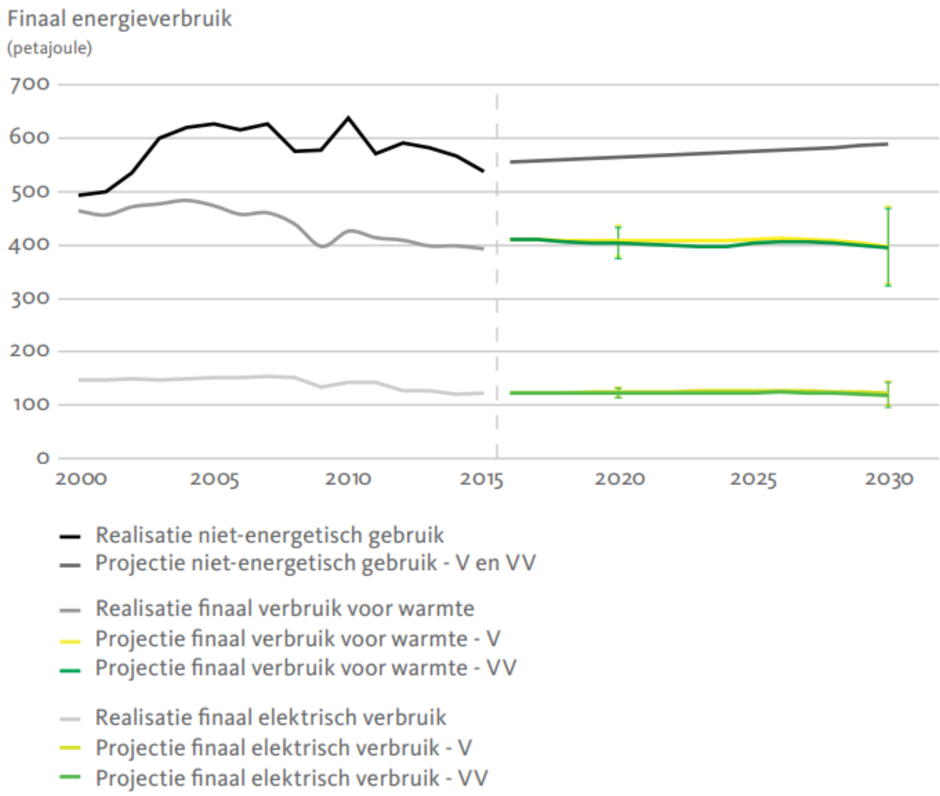

Figure G.3: The development of non-energetic use, heat and electricity consumption in industry sector in the period 2000-2030 (V is the projection of established policies, VV is the projection of established and proposed policies) [18]

In the Scenario ES more electrification in heat production is expected in the industry sector based on the Climate and Energy Agreement 2019 [21]:

- Chemical industry: more use of mechanical vapour re-compression and heat-pumps.
- Food industry: more use of electric boilers.
- Paper industry: more use of electric boilers.

G.4 Agriculture

The electricity demand in agriculture sector is expected to reach 34 PJ by 2030 (Figure G.4). In order to reduce CO_2 emission in agriculture sector, a decrease in gas-fired heater supply is expected and an increase in both heat-pumps and geothermal supply is foreseen. Moreover, a negative energy-saving is expected by 2030 (-0.8%) due to the decrease in co-generation use [18].

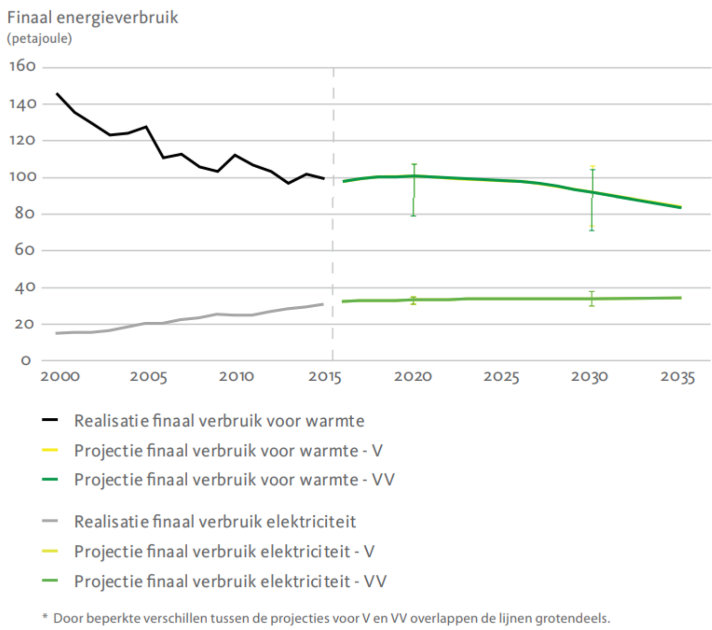

Figure G.4: The development of heat and electricity consumption in agriculture sector in the period 2000-2030 (V is the projection of established policies, VV is the projection of established and proposed policies) [18]

G.5 Transport

The electricity demand in the transport sector is expected to increase due to several factors [18]:

- The increase in number of electric vehicles (under the European policy for passenger cars), electric bikes and electric motorcycles.
- The CO_2 emissions of buses are expected to reach 0 % (the ambition of using zero-emission in public transport).

In the scenario ES, 2 millions of EV are expected by 2030 [21]. Moreover, the energy-saving in transport sector is expected to reach 1.5% [18].

H Appendix VIII: Electricity generation

The summary of the different distribution key (for the reference case and the scenarios) and the sources used to model generation and demand variables is presented respectively in Table H.1 and Table H.2.

Category	Distribution key (2017)	Distribution key (2030)	Source
Solar PV	Installed capacity		Klimaatmonitor [48]
		Electricity generation	NP RES [63]
Wind onshore	Installed capacity		Klimaatmonitor
		Electricity generation	NP RES
Wind offshore	Installed capacity		TenneT [84]
		Installed capacity	TenneT
Gas	Installed capacity	Installed capacity (Based on 2017)	Powerplantsmatching [28]
Hard coal	Installed capacity	Installed capacity (phased out)	TenneT

Table H.1: Distribution key and sources for generation variables

Category	Distribution key (2017)	Source	Distribution key (Scenario ES 2030)	Source	Distribution key (Scenario RES 2030)	Source
Households demand	Yearly sectoral regional demand	Klimaat-monitor	Yearly sectoral demand	ETM and Kalavasta [21]	Yearly sectoral regional demand	RES 2020 [16]
	Hourly sectoral national demand	ETM	Hourly sectoral national demand	ETM [22]	Hourly sectoral national demand	ETM/ KEV 2019
Buildings demand	Yearly sectoral regional demand	Klimaat-monitor	Yearly sectoral demand	ETM and Kalavasta	Yearly sectoral regional demand	RES 2020
	Hourly sectoral national demand	ETM	Hourly sectoral national demand	ETM	Hourly sectoral national demand	ETM/ KEV 2019
Industry demand	Yearly sectoral regional demand	Klimaat-monitor	Yearly sectoral demand	ETM and Kalavasta	Yearly sectoral demand	KEV 2019
	Hourly sectoral national demand	ETM	Hourly sectoral national demand	ETM	Hourly sectoral national demand	ETM/ KEV 2019
Agriculture demand	Yearly sectoral regional demand	Klimaat-monitor	Yearly sectoral demand	ETM and Kalavasta	Yearly sectoral demand	KEV 2019
	Hourly sectoral national demand	ETM	Hourly sectoral national demand	ETM	Hourly sectoral national demand	ETM/ KEV 2019
Transport demand	number of vehicles	Klimaat-monitor	Yearly sectoral demand	ETM and Kalavasta	Yearly sectoral demand	KEV 2019
	Hourly sectoral national demand	ETM	Hourly sectoral national demand	ETM	Hourly sectoral national demand	ETM/ KEV 2019

Table H.2: Distribution key and sources for demand variables