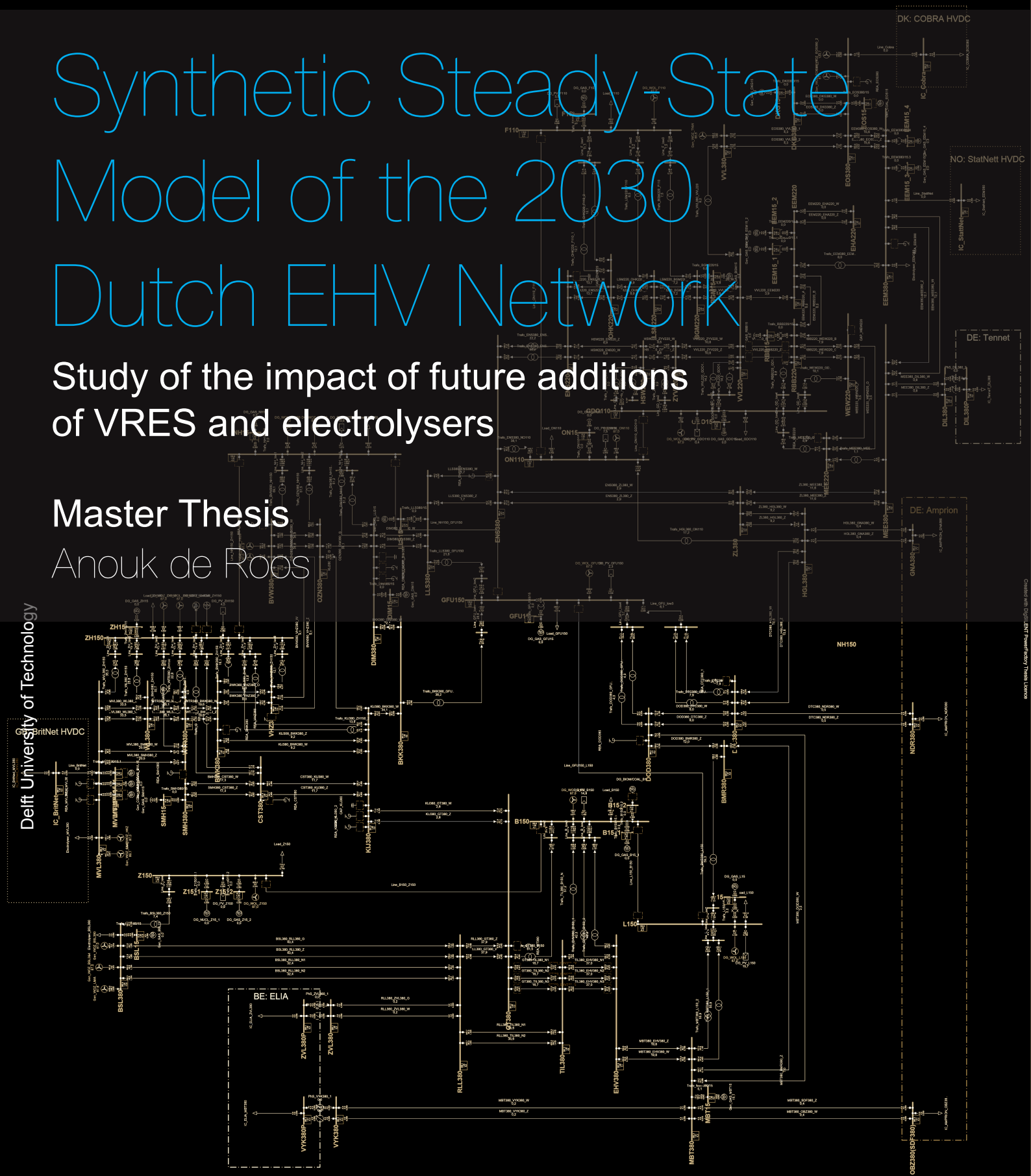
Synthetic Steady State Model of the 2030 Dutch EHV Network

Study of the impact of future additions of VRES and electrolysers

Master Thesis

Anouk de Roos

Delft University of Technology



TU Delft

Synthetic Steady-State Model of the 2030 Dutch EHV network

Study of the impact of future additions of VRES and electrolysers

by

Anouk de Roos

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Thesis committee:	Prof. Ir. M.A.M.M van der Meijden,	TU Delft
	Dr. Ir. J.L. Rueda Torres,	TU Delft
	Dr. H. Ziar,	TU Delft

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Abstract

Due to the much needed energy transition as agreed under the Paris climate agreement [1], it is expected that large amounts of variable renewable energy supply will be connected to the Dutch Transmission Network. Future social, economic and technological developments will determine both the amount of electrification as the central or decentral nature of the future supply of electricity. By investigating different reports with scenarios for 2030 and 2050, key uncertainties for the extra high voltage network can be identified. As of now, no open source model of the Dutch EHV network is available for research. In this thesis a synthetic model of the Dutch EHV network is created from publicly available data in DIgSILENT PowerFactory. Using this model together with a created method for generation of future scenarios in Python, simulations are performed to gain key insights into the Steady-State security of the future Dutch Transmission Network.

The main uncertainties for the Dutch EHV network are both the future level of electrification as well as the balance between central or decentral electricity supply. The amount of future installed wind generation capacity for 2030 is relatively certain due to the long lead time of projects as well as signed national agreements. The current amount of installed solar generation shows that most scenarios might be underestimating the potential installed capacity for 2030. Long- and short term flexibility measures will be key to ensuring security of supply. Besides this, a new focus towards integrating the gas, heat and electricity networks is expected. For 2050, the long time horizon leads to wide range of considered installed capacity of VRES.

A synthetic model of the Dutch EHV network was created in DIgSILENT PowerFactory. Using two different python scripts it is possible to switch between the initial base model for 2019 and the upgraded model for 2030 which is based on the ”klimaatakkoord” scenario described in KCD2020 [2]. These scripts are run within PowerFactory to adjust the topology, installed capacities and component parameters for either of the models. Using the same python scripts, automated simulations can be done for different operating conditions and dispatches. For the base model, two historical peak demand dispatches as well as one low demand dispatch were created. For the 2030 model, over 100 future dispatches were created for a case study into the impact of future additions of VRES and electrolysers. These dispatches vary in level of VRE production, national demand, addition of P2x demand at specific locations and the use of future interconnection capacities. A total installed capacity of 10 GW of electrolysers is considered for different distributions between the locations of Eemshaven, Maasvlakte and Borssele. Input parameters for the python script come from supplementary excel files, in which values can be adjusted. The created synthetic model can be used as a tool to investigate future steady-state power flows considering the sensitivities of the topology, component parameters and different operational scenarios. If this model is further developped, it could be used in the future for dynamic simulations.

The case study into the impact of future additions of VRES and electrolysers shows that as a consequence of large amounts of offshore wind production, significant power flows between different EHV regions such as from Zeeland to Brabant can be identified as well as large power flows from EHV (220/380kV) to lower voltage (110/150kV) regions. For high solar generation, there is a large power flow from the North to the South due to the large amount of expected future installed solar capacity in the North of the Netherlands. Also there are large power flows from lower voltages to EHV regions. These situations lead to future operating conditions with either under- or over voltages in specific regions as well as high power losses due to congestion issues. The large power flows over the Dutch EHV national ring in those cases will negatively affect the steady-state security of the system due to high component loadings in normal operating condition, which leads to less room for adjustments in case of unforeseen situations. Also, having high loadings of the national ring will lead to reduced capability to deal with expected future transit flows. Considering the under- voltages in the North and high component loadings on the national ring from North to South in cases of high solar generation, it is

recommended to have more installed solar capacity in the West and less in the North of the Netherlands.

By bringing demand and generation closer together and introducing flexibility in the system, security of supply can be increased and less investments to the Dutch Transmission Network will be necessary. In this case study, flexibility in the system is added through the addition of electrolysers at key locations at the border of the Dutch Transmission Network. The electrolyser demand will help to regulate the direction and size of the power flows in both North to South and West to East directions. By adjusting the electrolyser demand, component loadings on the national ring can be lowered, leading to less power losses and congestion issues. Also, situations of under- and overvoltages, due to large power flows between regions and high reactive power losses, can be mitigated. Proposed is a distribution of 6 GW electrolyser capacity in Eemshaven, 3 GW in Maasvlakte and 1 GW in Borssele. Using these electrolyser capacities in the ”klimaatakkoord” scenario of 2030, backflows are also possible. (reversed power flows between conventional generation and demand locations). This phenomena could be used as means of proactive netdesign which can increase the robustness of the transmission system and alleviate future congestion issues.

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Anouk de Roos
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"The most powerful force ever known on this planet is human cooperation - a force for construction and destruction." – Jonathan Haidt, The Righteous Mind: Why Good People Are Divided by Politics and Religion [3]

Nomenclature

Abbreviations

Abbreviation	Definition
Add. V./Tap	Additional Voltage per Tap
AT30	”Alternatieve Transitie 2030” Scenario
B	Brabant
B (uS)	Susceptance
BM18	Base Model Scenario
C (uF)	Capacitance
Cap.	Capacity
ConstQ	Constant Reactive Power
ConstV	Constant Voltage
Conv.	Conventional
Dem.	Demand
EHV	Extra High Voltage (220/380kV)
F	Friesland
FSI30	”Fundament for Systeem Integratie” Scenario
GD	Groningen & Drenthe
Gen.	Generation/Generators
GFU	Gelderland, Flevoland & Utrecht
HV	High Voltage (11/150kV)
IC	Interconnectors
Int.	Internal
Irated	Rated Current
Isum, rated	Summer Rated Current
Iwin, rated	Winter Rated Current
KA20	”Klimaat Akkoord 2020” Scenario
KA30	”Klimaat Akkoord 2030” Scenario
L	Limburg
L (km)	Length (km)
Max. Tap	Maximum Tap Position
Min. Tap	Minimum Tap Position
NH	Noord-Holland
ON	Overijssel & Noordoostpolder
OPF	Optimal Power Flow
p.u.	per unit
P2x	Power-to-gas
Par. No.	Parallel Number
Pcopper	Copper Losses (active power)
Pf	Power Factor
PF	Power Flow
Ph. Shift	Phase Shift
Pmax	Maximum Active Power
Pmin	Mininum Active Power
Pnom	Nominal Active Power
Pnom	Nominal Active Power
Qmax	Maximum Reactive Power Limit
Qmin	Minimum Reactive Power Limit

Abbreviation	Definition
r0	Zero sequence resistance
r1	Positive sequence resistance
r2	Negative sequence resistance
Re	Resistance
Reg.	Regional
rstr	stator resistance
Sn	Nominal Apparent Power
SOW	Selected Offshore Windfarms
Srated	Rated Apparent Power
TCA	Transfer Capacity Analysis
UHV	Voltage at higher voltage terminal
uk	short circuit voltage
ULV	Voltage at lower voltage terminal
Umax	Maximum Voltage
Unom	Nominal Voltage
Urated	Rated Voltage
VRE	Variable Renewable Energy
VRES	Variable Renwable Energy Supply
WOL	Onshore Wind
WOZ	Offshore Wind
x0	Zero sequence reactance
x1	Positive sequence reactance
x2	Negative sequence reactance
xd”sat	Subtransient reactance
xd’sat	Transient reactance
Xe	Reactance
Z	Zeeland
ZH	Zuid-Holland

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1 Introduction

In this chapter an introduction to this thesis is given. This includes the problem definition and a summary of the reported existing accessible related literature. The research objective as well as the approach is described. Finally, the structure of the thesis report is presented.

1.1. Problem Definition

Due to the much needed energy transition as agreed under the Paris climate agreement [1], it is expected that in the future large amounts of variable renewable energy based power plants (VRE) will be connected to the Dutch transmission network. Adding these technologies will result in large fluctuations of power flows and decreased grid stability due to their variability and uncertainty in production [4]. The amount and distribution of installed VRE capacity in the future depends on many different technological, economical, political and social factors. By creating different future scenarios, a range of possible outcomes and their consequences to the transmission system can be investigated.

To investigate the effects of different future scenarios with additional VRE capacities, a model of the Dutch Transmission system is needed. As of now, there is no open source model of the Dutch Transmission network available which models the physical flows and which can be used for steady-state analysis. Due to confidentiality reasons, much of the information needed to create a realistic model is unavailable [5].

1.2. Summary State of the Art

Work has been done by ENTSO-E to study different future scenarios and their effects on the European Transmission system as a whole [6]. For the simulations done by ENTSO-E of these scenarios an NTC-approach (net transfer capacity) was used to determine the amount of capacity available for electricity exchange between bidding zones. Within the bidding zones a copper plate (ideal model) is assumed [6]. As the system to be investigated is very large, specific assumptions and simplifications need to be made. However, assuming a copper plate model within bidding zones disregards many physical limitations of the transmission network as the Netherlands is currently a single bidding zone [7].

For the Netherlands, different studies have been done previously. In a study called ”Net voor de Toekomst” scenarios and their outcomes are studied for the entire Dutch energy system in a holisitic manner. More specific studies oriented at the transmission network are often commissioned by the TSO Tennet together with regional grid operators, the government or other energy companies [8] [9] [10] [11]. A Dutch Study called Pathways II by Tennet and Gasunie, looks specifically at internal flows of electricity and gas within the Netherlands. Here transmission capacities are defined as single numbers between regions [8]. This study was a follow up of the Infrastructure Outlook 2050, a study done by Tennet [12].

In a more recent report called ”Het Energiesysteem van de Toekomst - Integrale Infrastructuurverkenning 2030 - 2050” published by Netbeheer Nederland many different parties were involved in investigating scenarios for the future Dutch energy infrastructure. Within this report, it is mentioned that TenneT used DC-network model to research the impact of 2050 scenarios on the Dutch Transmission Network [13].

Throughout these different studies, the importance of new solutions for system flexibility and energy storage is emphasized [6] [8] [9] [14]. Different synergies such as TSO2020, are currently investigating the potential benefits of introducing electrolysers at specific locations in the North of the Netherlands [15]. In the most recent report by Netbeheer Nederland, the addition of electrolysers at key locations of offshore wind farm infeed to the grid is considered for 2050 scenarios. Depending on the scenario the amount of electrolyser capacity installed differs between 16-51 GW. The results show that for situations of high offshore wind production, line loadings of important 220/380kV connections can be reduced if electrolyser demand is introduced. However, there could also be increased congestion issues on some 110/150kV connections depending on where the electrolyser is connected to the grid [13]. The distribution and exact locations for this electrolyser demand that is considered for 2050 scenarios are not discussed. This thesis aims to show the potential benefit of the addition of flexibility in the form of electrolyser demand at different locations and distributions in a transparent manner.

Within the scientific community much work is done to correctly model new technologies that will be added to the transmission network [16]. However, as mentioned before, data on the transmission network of the Netherlands is not open for the general public and only shared with knowledge institutions under specific conditions [5]. Test systems and other synthetic models of transmission networks in other countries are available, such as the Nordic Test System, which are used to investigate long- and short-term electrical phenomena [17].

1.3. Research Objective and Scope

The objective of this thesis is to create a synthetic model of the Dutch EHV network such that we can study the impact of future additions of VRES for the Steady-State performance of the Dutch transmission network in 2030 and 2050. This will be done through means of a literature study as well as by performing simulations. The outcomes of this thesis are:

1. A study of the impact of future additions of VRES and the potential of adding electrolysers for the SS performance of the transmission network in 2030 and 2050
2. A synthetic model of the Dutch EHV Network in DIgSILENT PowerFactory 2020 SP3 for 2030, based on public data as well as generic models and parameters from existing literature.
3. A method (script in Python) for the generation of future scenarios with possibilities to adjust for different uncertainties regarding installed capacities, demand and dispatches.

The model of the Dutch EHV Network will contribute to the need of having test system models available that will take into account the limitations of physical flows [5] [8]. The model could be used in the future as a base for a more detailed generic model of the Dutch EHV network. For example, a generic model could be created to study dynamic behavior from a electromechanical- or electromagnetic point a view. The method in Python will allow for easy adjustment of different parameters and provides an example on ways to integrate Python and PowerFactory.

1.4. Approach and Structure of the Thesis Report

The approach during this thesis was to first focus on the different scenarios currently available for the Dutch electricity network of 2030. By doing this insights are gained into the future challenges for steady state security of the Dutch EHV network.

Following this study, a synthetic model of the Dutch EHV network was created in DIgSILENT PowerFactory using only publicly available data. Other exisiting examples of transmission network modelling

and different literature was used to model the system and different sources of public data on generation and demand were consulted. Also, a method (python script) was created to perform simulations for these scenarios.

Using this model and method a case study is performed for the transmission system of 2030. For this case it is investigated what the effect of future additions of VRES, and selected locations of electrolysers, would be on the Dutch Transmission network.

The outlook of this report is as follows:

1. Discussion of future scenarios: In Chapter 2 different scenarios of 2030 and 2050 are compared and elaborated upon. Using these insights scenarios are chosen to be subsequently used for simulations.
2. Development of Synthetic Model: Chapter 3 describes both the creation of the model of the Dutch EHV network and the method for performing simulations for scenarios of 2030. First the topology of the base model is considered as well as components parameters and installed capacities. After initial simulations, the model is updated and improved to represent a more realistic transmission network in 2030.
3. Case Study: In Chapter 4 a case study is performed considering the addition of large amounts of VRES and investigating the consequences of potential locations for 10 GW of electrolysers.

Following this, a general conclusion and discussion of the results of this thesis is given in Chapter 5.

2

Comparison of Scenarios

This chapter provides a high level discussion on future scenarios for the Dutch Transmission Network for 2030 and 2050. First, a short summary of the common scenarios used in existing reports is given. After this a discussion of the main takeaways from the comparison of these different reports is given. The reason for this analysis is to gain insights into which scenarios should be included for analysis of the future Dutch Transmission System of 2030-2050. Using these new insights, this chapter proposes numbers for the installed capacities that could be used in simulations for 2030 and 2050 for the synthetic model of the Dutch EHV network which will be presented in chapter 3. For 2030, the considered numbers are based on KCD2020 [2] as specific numbers per region were available and the range of installed capacities for VRES is the widest of the considered reports. For 2050, new numbers are proposed, based on the storyline of the most common scenarios.

For the case study, presented in chapter 4, only the reference scenario for 2030, taken from the climate agreement scenario ”KA30” from KCD2020 [2] will be used. However the numbers for alternative scenarios are presented at the end of this chapter in section 2.4 can be used for future simulations.

2.1. Translating uncertainties to scenarios

Within the scientific community, knowledge is shared about the different uncertainties that should be taken into account, as well as discussions about which approach is most suitable for the analysis of long term power system planning (e.g. 5-10 years) [4]. The main uncertainties generally taken into account can be grouped into the following categories: increase in demand, renewable energy supply, the generation mix, new market players, power markets and their regulations, new transmission technologies, the generation portfolio, policy, and different environmental considerations [4]. Considering these uncertainties different possible scenarios can be drawn. This is done in many different ways, generally either through backcasting (giving target-based scenarios) or forecasting (for explorative scenarios) to create scenarios [18]. Sometimes, a combination of these approaches is used, such as for the study of the Ten Year Network Development Plan 2020 [6]. Also there is an increasing focus on involving different stakeholders in the participatory process [18].

2.2. Overview of consulted studies and scenarios

The studies considered for the scenario comparison are listed in table 2.1. The organisation which published the report as well as the year in which it was published and for which years scenarios were created are listed. To make the comparison of the different studies the abbreviations listed in the second column of table 2.1 will be used when referring to specific studies. The relevance of the different studies for inclusion in the comparison is shortly highlighted in table 2.2.

Table 2.1: List of consulted studies and used abbreviations for comparison of scenarios

Report Title	Abbreviation Used	Organization	Year Published	Scenario Years
Infrastructure Outlook 2050	IO2050	TenneT	2020	2050
Net voor de Toekomst	NVDT	CE Delft	2017	2050
Nederland klimaatneutraal in 2050: vier scenarios	KE2050	Berenschot	2020	2050
Pathways II - Pathways to 2050	Pathways II	TenneT, Gasunie	2021	2050
Het Energiesysteeem van de Toekomst	EVDT	Netbeheer Nederland	2021	2050
Kwaliteits- en Capaciteitsdocument 2017	KCD2017	TenneT	2017	2030
Kwaliteits- en Capaciteitsdocument 2020	KCD2020	TenneT	2020	2030
Ten Year Network Development Plan 2018	TYNDP2018	ENTSO-E, ENTSO-G	2020	2040
Ten Year Network Development Plan 2020	TYNDP2020	ENTSO-E, ENTSO-G	2020	2050
Monitoring Leveringszekerheid 2017	MLZ2017	TenneT	2017	2032
Monitoring Leveringszekerheid 2019	MLZ2019	TenneT	2019	2030
Demand and Supply of Flexibility in the Power System of NL 2015-2020	FLEXNET	ECN, Alliander	2017	2050

Table 2.2: List of consulted studies and their relevance for inclusion

Report Title	Relevance	Key words
Infrastructure Outlook 2050	Planning for 2050 of the electrical transmission network	Electrical, study II for 2050
Net voor de Toekomst	First study for 2050 of the whole Dutch energy system	Whole energy system, study I for 2050
Nederland klimaatneutraal in 2050: vier scenarios	Commissioned by Tennet for target-based scenario of 2050	Electrical, study IV for 2050, target based
Pathways II - Pathways to 2050	Study with integrated approach of gas and electricity networks for 2050	Gas and Electrical integration, study III for 2050
Het Energiesysteeem van de Toekomst	Latest comprehensive study for 2050 considering gas, electricity and heat networks	Most comprehensive, latest, study V for 2050
Kwaliteits- en Capaciteitsdocument 2017	Document with main investment plans and regional developments by Dutch TSO	Electrical, Investment Planning, 2030
Kwaliteits- en Capaciteitsdocument 2020	Document with main investment plans and regional developments by Dutch TSO	Electrical, Investment Planning, 2030
Ten Year Network Development Plan 2018	Report from TSO's internationally on the future European transmission network	EU, Electrical, 2030 and 2040
Ten Year Network Development Plan 2020	Report from TSO's internationally on the future European transmission network	EU, Electrical, 2030 and 2040
Monitoring Leveringszekerheid 2017	Adequacy assesment of installed capacities for the Netherlands for the future	Adequacy Installed Capacities, 2030
Monitoring Leveringszekerheid 2019	Adequacy assesment of installed capacities for the Netherlands for the future	Adequacy Installed Capacities, 2030
Demand and Supply of Flexibility in the Power System of NL 2015-2020	Report considering future flexibilty measures at 380/220/150/110kV voltage levels	Flexibility measures for 2050

For Dutch studies such as Net voor de Toekomst [10], Infrastructure Outlook 2050 [12], Nederland klimaatneutraal in 2050 [9], kwaliteits- en capaciteitsdocument 2017 [19] and Het Energiesysteem van de Toekomst [13] scenarios often consider more regional or central developments with high levels of electrification as well as scenarios that are more focused on international trade and importing molecules. Below, a description of general characteristics for each of the scenarios is given:

1. **National Scenario:** In this scenario the government acts in a proactive manner stimulating large central projects. Self-sufficiency is important and there is a shared interest for solar power, wind generation and solutions for flexibility. This scenario often shows the largest amount of installed capacity of offshore and onshore wind. The amount of considered offshore wind capacity for 2050, could be in the range of 52-72 GW [10] [9] [12] [13] according to this scenario. The amount of onshore wind capacity considered is between 16-20 GW. The amount of installed solar capacity is also much higher than today, at between 34-107 GW [10] [9] [12] [13] where the more recent studies EVDT and KE2050 show more ambitious numbers. To accomodate these developments, flexibility through the use of batteries or hydrogen are considered, up to installed capacities of 50 GW and 60 GW respectively [10]. This scenario generally shows a high level of electrification, for example in IO2050 the annual electricity demand is expected to be around 150 TWh, making up 35% of our national energy demand. The total energy demand however is expected to decline (from 669 TWh in 2017 to 416 TWh in 2050) [12].

2. **Regional Scenario:** In this scenario the general public is leading the transition. Politics is focused on maximizing the local self-sufficiency. There is a large increase in decentral generation of solar energy, where installed capacities range between 84 GW - 125 GW in 2050 depending on the study [10] [9] [12] [13]. Offshore wind capacity ranges between 26-43 GW, while onshore wind is estimated between 16-20 GW [13] which is a bit lower than the numbers considered for the National Scenario but still much higher than numbers used for the Internaional and European Scenario [12] [12] [9]. This scenario often shows the largest amount of installed capacity for flexibility solutions, with up to 75 GW of P2x as well as 60 GW of batteries [10] [9] [12] [13]. It also shows the highest level of electrification, in the study IO2050, up to 39% of our total national energy demand (158 TWh) will be electricity [12]. Overall energy savings are also largest in this scenario.

3. **International Scenario:** This scenario focuses on an increase in international trade. The Dutch government steers the economy in the direction of renewable fuels such as biomass and green gas. Self-sufficiency will not be a priority for the Netherlands. For target-based studies such as KE2050, this scenario will still meet targets by importing green fuels for gas powered generation (biomass, hydrogen, methane) [9] [12]. This means that lower amounts of VRES installed capacity and flexibility are needed, for example for IO2050 and NVDT only 6 GW of offshore wind capacity, 5 GW onshore wind capacity, 16 GW of solar capacity is considered [10] [12]. For more recent studies the amount offshore wind capacity is higher (28-38 GW instead of 5 GW [9] [13]), this can be explained by the new climate agreements which guarantee at least 10,8 GW of installed capacity already in 2030 [20]. For recent studies such as EVDT, greater potential is seen for using hydrogen powered generation in times of low VRES or for back up generation, compared to older studies such as IO2050 and NVDT [13] [9] [12].

4. **European Scenario** (also called Generic Scenario): This scenario often follows the idea that the future supply of energy will be determined without any specific government regulations other than a clear CO2 price. Transparent but binding instruments can be used. The energy market will be run by the invisible hand [10]. This scenario is not always included, as it shows large overlap for installed capacities of VRES with the International Scenario. One main difference between this scenario and the international scenario for the study of EVDT is that green gas is considered instead of hydrogen for conventional electricity production [13].

Other variations of created scenarios can be seen for example in KCD2020, Pathways II and TYNDP [6], [8], [2]. In KCD2020 three scenarios are considered: a reference scenario called **Climate Agreement**, a more ambitious scenario called **Fundament for Sytem Integration**, and a less ambitious scenario called **Alternative Transition**. The reference scenario is based on the Dutch climate agreement [20]. The less ambitious scenario assumes some of these developments will not happen, while the more ambitious scenario includes agreements that were made but for which specific numbers were not yet decided [2].

In Pathways II, scenarios are created based on IO2050 [12] but are focused more on the level of ambition for VRES and whether the future will show higher gas demand or a higher electrification rate. In cases where the Netherlands is self-sufficient, a very ambitious amount of VRES is always needed. The reason for this is the need to produce large volumes of electricity which can either be used for direct supply or can be converted to molecules through electrolysis. The scenarios created for this study are the following: **EL&VRES** which has high electrification and ambitious VRES, **GAS&VRES+** which has high gas demand and very ambitious VRES, **EL&VRES+** which has high electrification and very ambitious VRES.

For international studies such as TYNDP 2020 [6], three scenarios are often created: one more centrally focused, one decentrally focused and one reference scenario. The reference scenario, called **National Trends**, is built from the bottom up using national plans making it an explorative scenario (which does not meet the same targets as the other scenarios). The other two scenarios are both target-based and show either decentrally focused developments, called **Distributed Generation** or more central developments, called **Global Ambition**.

2.3. Qualitative Analysis of Scenarios from Consulted Studies

Using insights from the various reports, a list of criteria is created to qualitatively asses the different scenarios:

1. The range of considered generation capacity (of VRES) and final electricity demand
2. Comprehensiveness of analysis and transparency of data
3. Types of created scenarios: Explorative or Target-based Scenarios
4. Participatory involvement of other stakeholders and the inclusion of feedback
5. Consideration of emerging technologies

In the following sections, motivation for inclusion of the criteria in the qualitative analysis is given as well as the most insightfull findings from the qualitative analysis of the compared studies listed in table 2.1.

2.3.1. Considered Generation Capacity and Demand

The reason for inclusion of the range of considered generation capacity of VRES, and the level of demand, in the comparison is that for transmission systems it is most insightfull to investigate situations that are significantly different from the status quo. Scenarios with ambitious installed capacities of VRES and high electrification rates are most interesting to investigate. The reason for this is that the increase in electricity demand paired with the variability of large volumes of VRES will likely place the most strain on the existing transmission network with larger power flows and higher loaded components. Scenarios with lower rates of electrification, lower amounts of installed VRES, more flexible demand or more de-central self-sufficient electricity generation will place less strain on the existing transmission network.

Development of Conventional Generation

In all of the scenarios considered, the amount of fossil fuels used in the future decreases [12] [8] [2] [21] [13] [12] [10]. In the reports of MLZ the amount of installed capacity in the future of gas turbines is higher than in KCD publications [2] [14]. Among others this has to do with the recent decrease in gas prices as well as the closing of coal plants [22]. In most scenarios neither coal nor nuclear will play a large role for the Netherlands. The first assumption is due to new agreements for the closing of all coal generation units in the Netherlands. Building a nuclear plant can take around 10 years, and currently there are no plans for this [2] [13]. The developments for conventional generation will also depend on the amount of flexibility that will be introduced into the system.

Installed Capacities for Solar PV

For solar generation, the installed capacities for different scenarios mentioned in KCD2020 are quite conservative for 2030 considering that the amount of installed capacity has roughly doubled every past two years [23], as is illustrated in figure 2.1 and 2.2. According to a study by Deloitte, an estimated 80 GW of installed capacity of solar PV could be acheived using rooftops alone and assuming a growth rate of 40% per year, this amount could be achieved by 2028 [24], making the suggestion that the amount of installed capacity could possibly surpass the scenario levels reasonable.

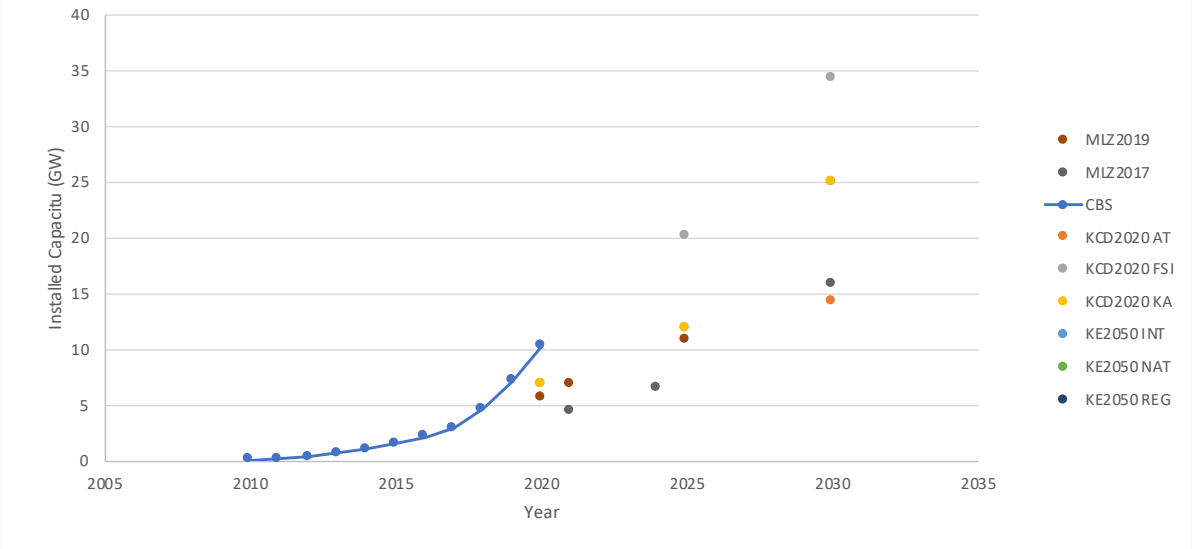


Figure 2.1: Scenarios for Installed Capacities of Solar PV in the Netherlands for 2030

For 2050, a new study by Netbeheer Nederland [13] is now considering a higher amount of installed capacity than before. The red arrow in figure 2.2 illustrates the highest capacity considered by KE2050 while the green arrow shows the highest new value considered by the study EVDT [13][9].

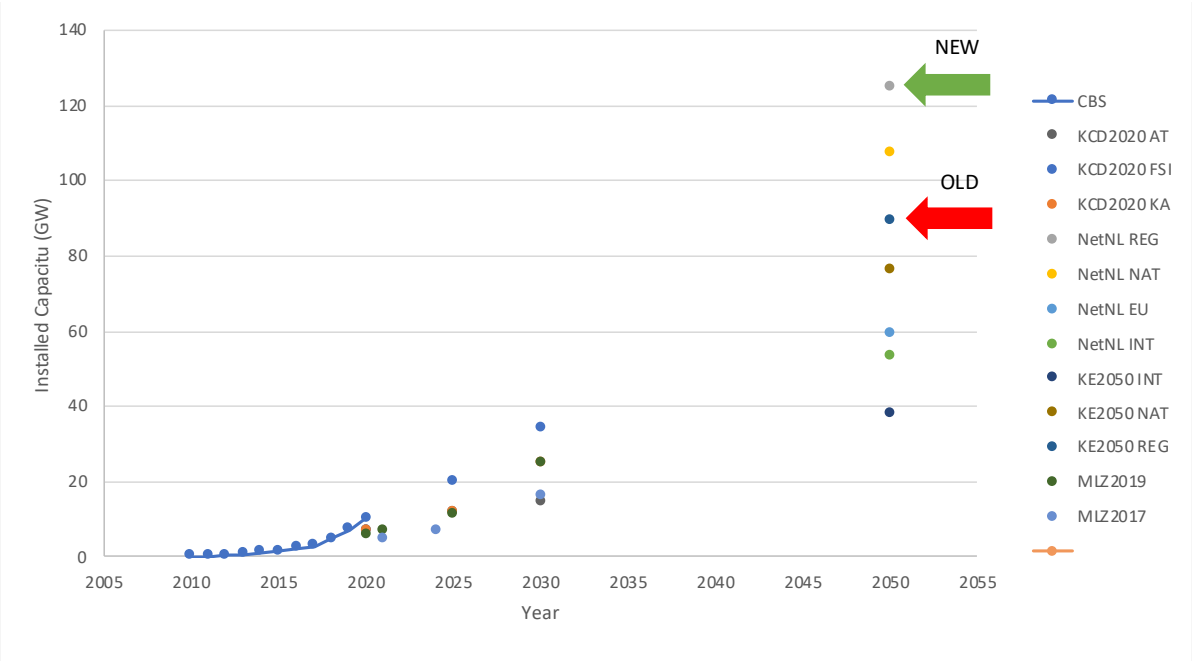


Figure 2.2: Scenarios for Installed Capacities of Solar PV in the Netherlands for 2050

Installed Capacities for Offshore Wind

For offshore wind generation in 2030, the amount of installed capacity considered in different scenarios is pretty robust. This can be explained by the long lead time of projects and the agreements made in the Dutch climate agreement [20]. An illustration of these developments for 2030 is given in figure 2.3.

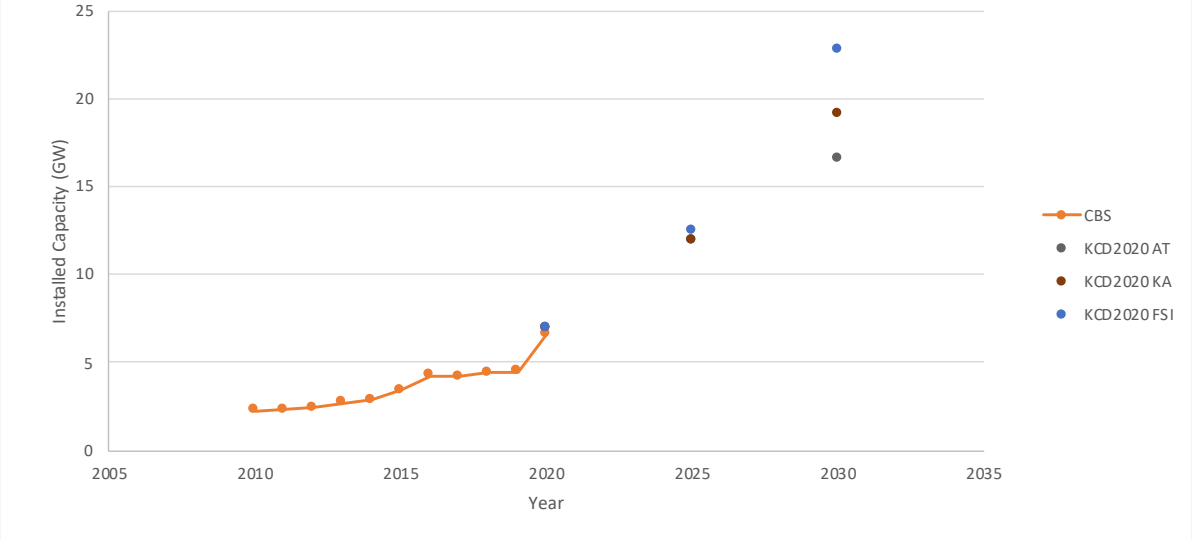


Figure 2.3: Scenarios for Installed Capacities of Wind Powered Generation in the Netherlands for 2030

For the generation capacities of wind 2050 the scenarios differ quite a bit due to the long time horizon. The study KE2050 by Berenschot shows a more ambitious development than previously considered [9][13], see also the red arrow in figure 2.4. In a more recent study, EVDT by Netbeheer NL, the considered installed capacities have been adjusted to a lower value, illustrated the green arrow in figure 2.4 [13].

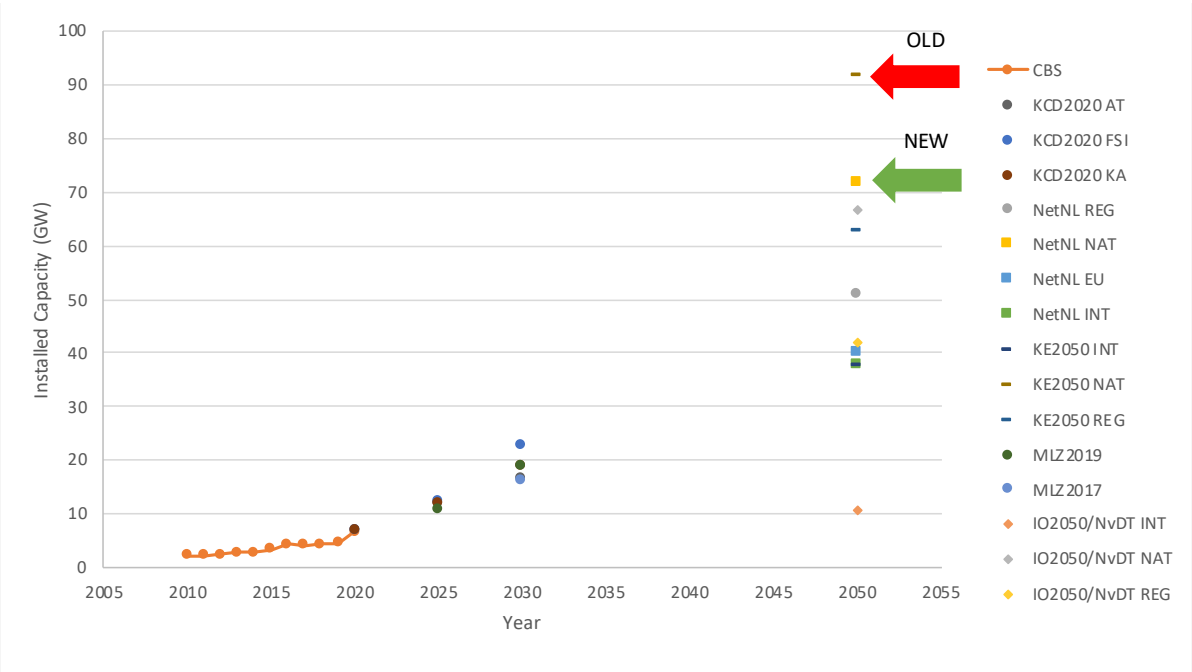


Figure 2.4: Scenarios for Installed Capacities of Wind Powered Generation in the Netherlands for 2050

Development of Demand

One of the most important uncertainties to consider is the amount of electrification we can expect [8] [12] [2] [4]. Depending on future pathways the Netherlands might stay a molecule oriented country running mainly on (imported) fuels such as (renewable) gas or we might shift to a higher level of electrification [8]. Different studies show that the future electricity demand could potentially be very high or stay quite similar to todays values, depending on the different uncertainties such as future energy

savings, flexibility such as demand response as well as the expected electrification rate.

The peak demand in 2030 is expected to be between 18-28GW depending on whether P2x is considered [2]. For 2050, a peak demand of 40 GW is considered, which is twice as much as the peak demand today [13]. Considering the total energy demand, between 110 TWh and 150 TWh is considered for 2030 [2]. For 2050, the numbers differ quite a bit. For example, in the study IO2050 the total electricity demand is expected to be between 78 to 158 TWh.[12]. However, for the study KE2050 a higher level of total electricity demand is considered of between 115 to 239 TWh.

2.3.2. Comprehensiveness, depth of study and transparency of report

Comprehensive reports also take the integration of other sectors, such as including the gas and heat networks, as well as other economical, social and technical constraints into account when creating scenarios. Examples of such studies are EVDT and Pathways II [13] [8]. Several national studies show careful consideration of the numbers chosen for the installed generation capacities such as KE2050, EVDT, Pathways II and KCD2020 [9] [8] [2] [13] while other studies take a more holistic/system wide approach such as NvDT [10] or consider the Netherlands to be a copperplate model for the purpose of studying the whole EU transmission system such as is done in TYNDP [6]. Transparency of the report leads to clearer insights about the chosen assumptions and data. To investigate the Dutch Transmission network effectively, detailed data such as regional installed capacities and demand is needed as is available in KCD2020 [2].

2.3.3. Types of created scenarios: Explorative or Target-based Scenarios

An important distinction to make is whether scenarios are explorative or target based [25]. Explorative scenarios often show differing levels of ambition such as is done in KCD2020 [2]. Both types of scenarios have pro's and con's. Target scenarios such as studied in KE2050 and Pathways II might disregard other possible futures that don't meet the target [9] [8]. For KCD2020 the choice for explorative scenarios can be explained by the fact that for transmission network development planners it is important to not just consider more popular scenarios with a huge ambitions to meet the 95% reduction in CO2 emissions target but to also to consider scenarios based on current national trends [2]. Scenarios that don't meet the targets of decarbonisation might send a negative message and are often unpopular with stakeholders [6]. Also, as these scenarios would mean a conventional electricity generation portfolio closer to that of the status quo, they are less interesting to investigate.

2.3.4. Participatory involvement of other stakeholders and feedback

Often scenarios are only considered if they are deemed plausible by the creators, such as for KCD2020, Pathways II, EVDT and KE2050 [2] [8] [9] [13]. Therefore it is vital to involve other stakeholders that might have different insights or perspectives on what future developments could be. For example in the study of TYNDP feedback is incorporated from external participants to asses their perspective on the plausibility and direction of the different created scenarios [26]. For EVDT, many different organisations were involved in creating the report [13]. Also, for recent transmission network studies such as KCD2020 both TenneT and Gasunie are involved in the scenario creation and an external study into plausible scenarios was also commissioned such as KE2050 [9]. There is however discussion about the validity of this "intuitive-logics" approach and whether the created scenarios that come from this approach really improve decision making or whether they are more about challenging conventional thinking and creating mutual understanding [27]

2.3.5. Consideration of emerging technologies

It is mentioned by some critics, that there is lack of consideration for new emerging technologies or other disruptive developments in created energy scenarios [28][6]. Though this might send a clear general message to keep thinking outside the box, taking the possibility of disruptive technologies into account could mean that the created scenarios might be deemed unrealistic by stakeholders. Another counterargument is that for the transmission system it is more interesting to keep a focus on what would be the most critical developments currently foreseeable for managing security of supply. From there focus and message towards necessary "new developments" or emerging technologies can be given

from the analysis. When assessing the different reports, attention is paid to whether different flexibility measures are included, such as the new developments for backup generation and P2x considering methane, hydrogen and other green fuels.

Flexibility Measures

In studies pubished in 2020 and 2021, there is often a large role to play for hydrogen as a source of electricity generation. In the KE2050 report the potential for hydrogen production is emphasized by the much larger amount of installed flexible generation than in previous studies [9]. In previous studies power generation from flexible gas-fired plants running on renewable fuels such as ”green hydrogen” or ”green methane” is not yet considered. The amount of installed backup capacity in the KE2050 report however exceeds the current amount of installed capacity. Options for alternative measures to lower peak demand or provide alternative back up are proposed and are said to be further investigated in Pathways II [9].

In the study of Pathways II, flexibility is considered mainly through battery systems and gas storage. Besides this emphasis is also placed on market trade, interconnections and demand response [8]. This is in slight contrast to an earlier study by Alliander and ECN where flexibility supply is considered to be mainly through either interconnections, demand response or VRE curtailment after 2030 [11]. In the same report gas storage as well as battery systems are deemed economically unattractive when considered only for congestion management and conventional gas power plants will only be used in back up situations [11]. Regarding long-term flexibility, there is discussion on whether seasonal storage of hydrogen is feasible or whether in this case market trade and strong interconnections are more favourable [11].

These different reports illustrate that there are many alternatives available for flexibility, though which one is most favorable depends on future developments. The introduction of hydrogen as a source of electricity generation and not just as P2G flexibility, as is done in KE2050, illustrates how new developments can radically alter future scenarios based on new economic, social or technological developments only in matter of a few years [9].

2.4. Proposal for Installed Capacities for Simulations

Based on the qualitative analysis of the different studies and their scenarios in section 2.3, installed capacities are proposed for future studies into the Dutch EHV transmission network. The proposed installed capacities that could be used for simulations of 2030 scenarios in the created synthetic model described in chapter 3 are listed below in table 2.3. For 2030, the installed capacities are based on scenarios from KCD2020 [2]. It was chosen to use these numbers as this report showed the widest range of installed capacities considered as well as an availability of specific regional numbers that could be used in the simulations, which are further discussed in section 3.2.5. For the case study in chapter 4, only the numbers for the reference scenario based on the climate agreement ”KA30” from KCD2020 are used, however the installed capacities listed in table 2.3 for other 2030 scenarios could easily be implemented in the created model by adjusting the input files in excel, for which the approach is discussed in chapter 3.

For 2050, new numbers are proposed as there was a large gap of considered installed capacities in scenarios from the different studies consulted such as IO2050, NVDT, KE2050 and EVDT as can be seen in figure 2.5 [13] [12] [10] [9]. The newly created scenarios reflect the uncertainty of the level of electrification as well as more central or decentral developments for electricity supply. The ranges of installed capacities for some scenarios are so large (69 GW - 282 GW) that additional controls for flexibility in the sytem (such as VRE curtailment, demand response etc.) would have to be introduced in order to be able to run reasonable simulations. Also topological upgrades to the model according to the new report EVDT by Netbeheer Nederland should then be considered [13] .

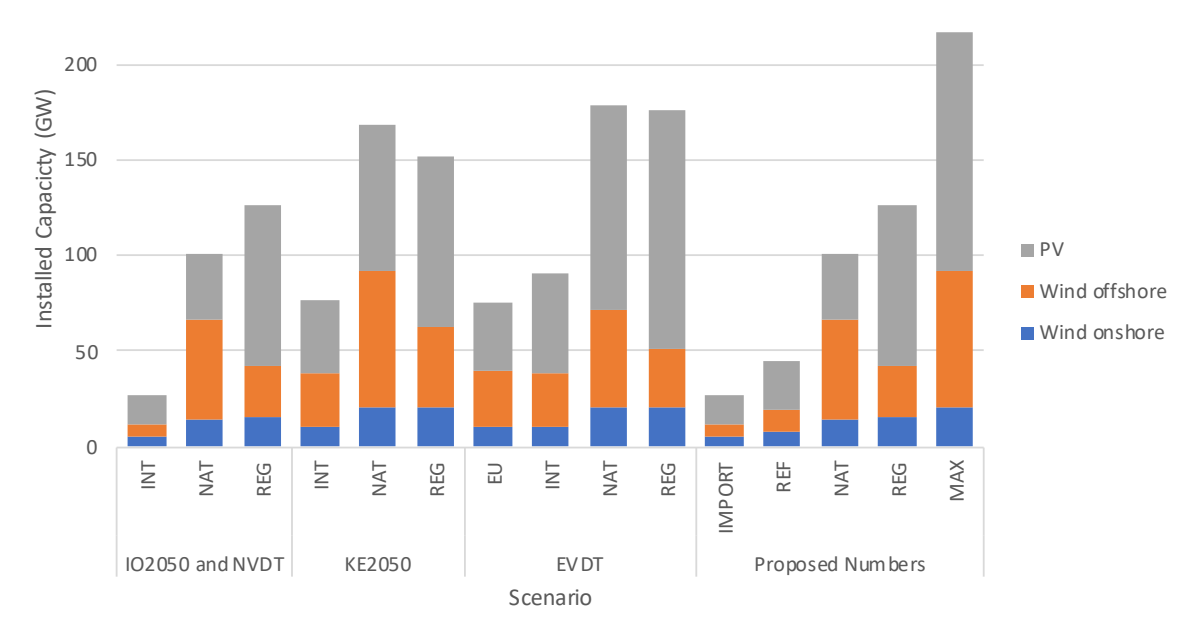


Figure 2.5: Installed Generation Capacity of Solar and Wind for 2050 for Different Studies, where REG = regional, NAT = national, INT = international, EU = European, MAX = maximum

Table 2.3: Generation Capacity for Chosen Scenarios 2030/2050

		2030			**2050**				
	Unit	**AT30**	**KA30**	**FSI30**	**IM50**	**REF50**	**NAT50**	**REG50**	**MAX50**
Onshore Wind (WOL)	GW	6.0	7.8	8.1	5.0	7.8	14.0	16.0	20.0
Offshore Wind (WOZ)	GW	10.6	11.3	14.6	6.0	11.3	53.0	26.0	72.0
Solar (ZON PV)	GW	14.3	25.0	34.3	16.0	25.0	34.0	84.0	125.0
Gas	GW	8.9	8.9	7.5	13.0	15.0	16.0	27.0	5.0
Wkk and other	GW	4.3	4.3	4.3	0.0	0.0	0.0	0.0	0.0
Nuclear	GW	0.5	0.5	0.5	0.0	0.0	0.0	0.0	0.0
Coal and Biomass	GW	0.0	0.0	1.4	0.0	0.0	0.0	0.0	0.0
Hydrogen	GW	0.0	0.0	0.0	2	35	60	75	75
Flex/Batteries	GW	0.0	0.0	0.0	5.0	10.0	50.0	60.0	60.0
Tot.Gen. Cap.	GW	**44.6**	**57.8**	**70.7**	**45.0**	**69.1**	**167.0**	**213.0**	**282.0**
Peak Demand	GW	21	21	21	40	40	40	40	40

3

Development of the Synthetic Model of the Dutch EHV network for 2030

In the following chapter the development of the synthetic model of the Dutch EHV network in PowerFactory Version 2020 SP3 as well as a method to perform simulations for 2030 is presented. First, an overview of the used programs is presented in section 3.1. Next, the development of the model as well as results of initial simulations in PowerFactory is described in section 3.2. Finally, the integration with Python is presented in section 3.3.

3.1. Overview of Used Programs

The transmission network is modelled in PowerFactory. To analyse future scenarios for 2030, a python script was created that automatically adjusts input parameters in PowerFactory, calls PowerFactory to run simulations and exports results. Python is used for reading and writing data (from Excel to PowerFactory and vise versa) and it also calls PowerFactory to perform simulations. The excel files are only used for providing input data or writing output data. An overview of what the different programs are exactly used for is given below in figure 3.1. A detailed flowchart that shows how calculations are automated and which data is exchanged between different softwares is given in section 3.3.



Figure 3.1: A short description of what each program is used for

3.2. Development of the PowerFactory Model

In this section the development of the synthetic model of the Dutch transmission system in PowerFactory Version 2020 SP3 is presented in a step-by-step manner. First the methodology for the development of the final model of the Dutch EHV network for 2030 will be discussed in section 3.2.1. Next, an

overview of the initial topology as well as the final version of the topology for 2030 is presented. After this, more detailed information on the modelling of the different system components is provided. In section 3.2.4 and 3.2.5, the installed capacities for the Base Model as well as the 2030 Model is given respectively. In section 3.2.7 the initial simulations and corresponding results are discussed. After this adjustments made to the model as well upgrades for the final model for 2030 are presented in section 3.2.10.

3.2.1. Methodology for Modelling in PowerFactory

The model of the transmission system was created in a few steps. A complete flowchart of how the PowerFactory model was created is shown in figure 3.2. First a base model was created for the current EHV transmission system using publicly available data for the topology, installed capacities as well as historical dispatches. Then, initial simulations were run to see how realistic the model was and results were compared to KCD2020 [2]. Using these insights adjustments were made to the model to make it more representative for the Dutch EHV network of 2019. Finally, to create a model of the Dutch EHV network for 2030, installed capacities were adjusted and the topology of model was updated according to the projects listed for 2030 [2] [29]. Setting the dispatches for 2030 and testing the model with simulations was done during the case study described in chapter 4.

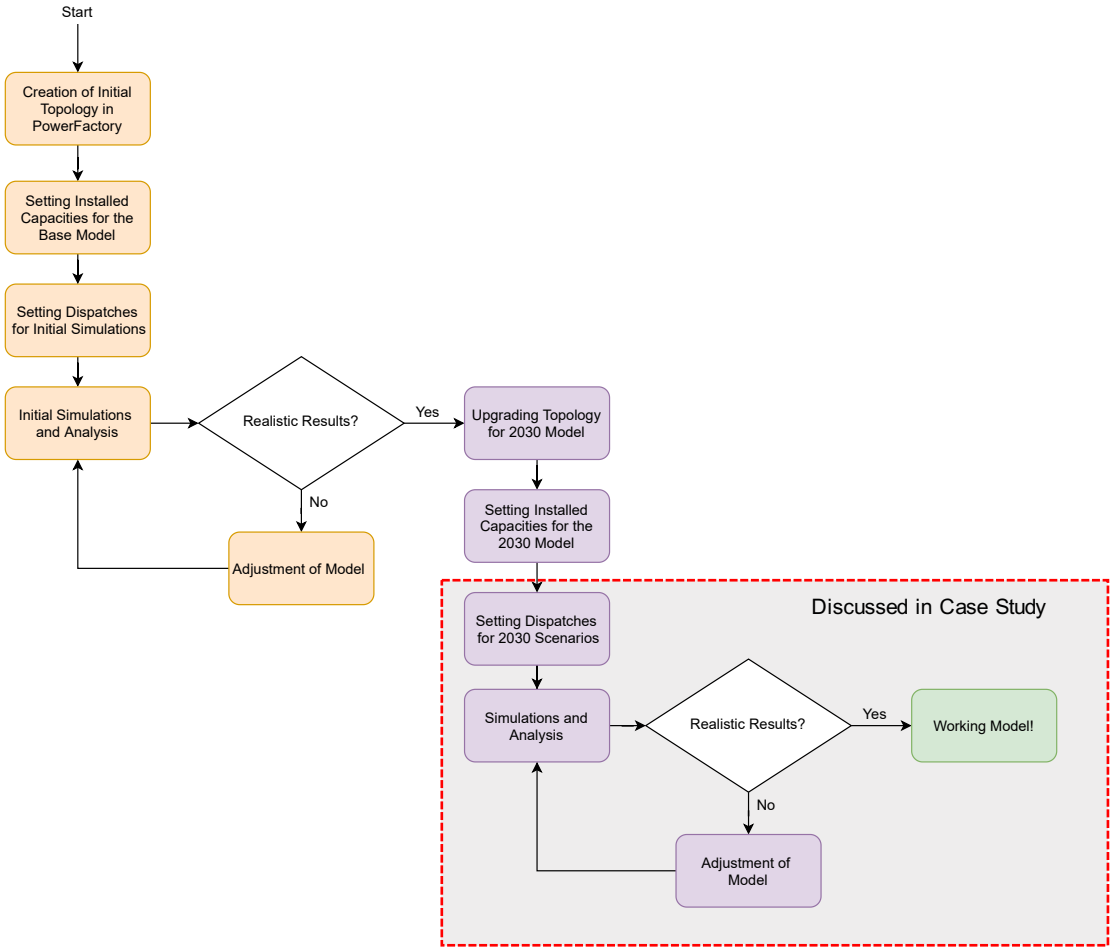


Figure 3.2: Flowchart of how the Synthetical Model for the Dutch EHV Network of 2030 was created in PowerFactory

3.2.2. Overview of the Topology

The grid topology is based on two single line diagrams of the Dutch EHV network from the TenneT transparency pages [29] and from hoogspanningsnet.nl [30] which are publicly available. The network was expanded according to different ongoing or planned projects mentioned in KCD2017 as well as KCD2020 for a model of the network for 2030, which is further discussed in section 3.2.10 [31] [2]. The single line diagram of the final system for 2030 is given in figure 3.3. The colors indicate the different voltage levels of the system. More details on the modelling of the topology (for each different region) can be found in appendix B.

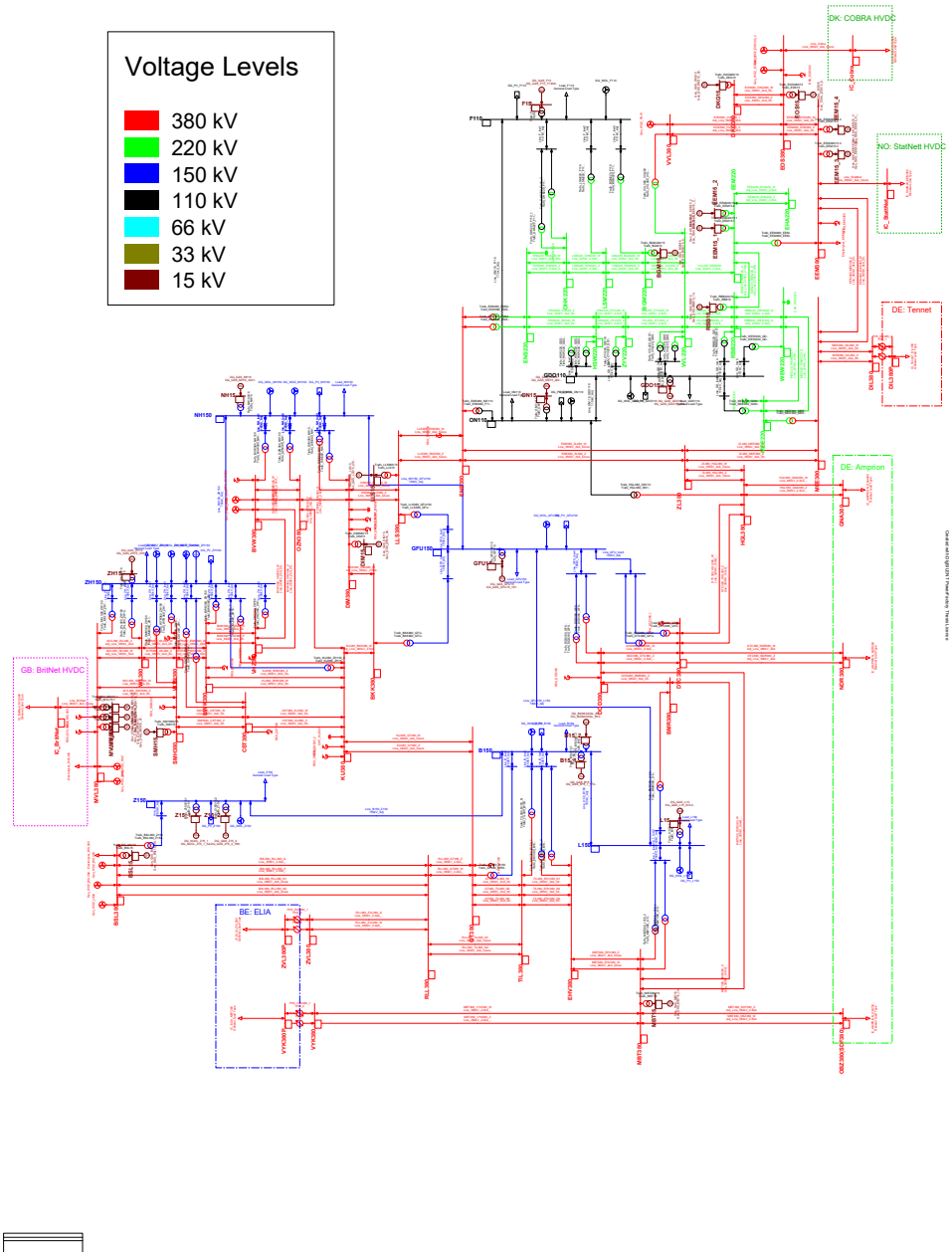


Figure 3.3: Initial Single Line Diagram for 2020 according to voltage level

The model is divided into different geographical zones. The division of zones are made according to the different regions defined in the KCDs and can be seen in figure 3.4 [31] [2]. A simplified geographical diagram of the main 220/380kV connenctions was created in PowerFactory as well as a diagram showing the power flows between different regions. These will be further explained in section 3.2.6.

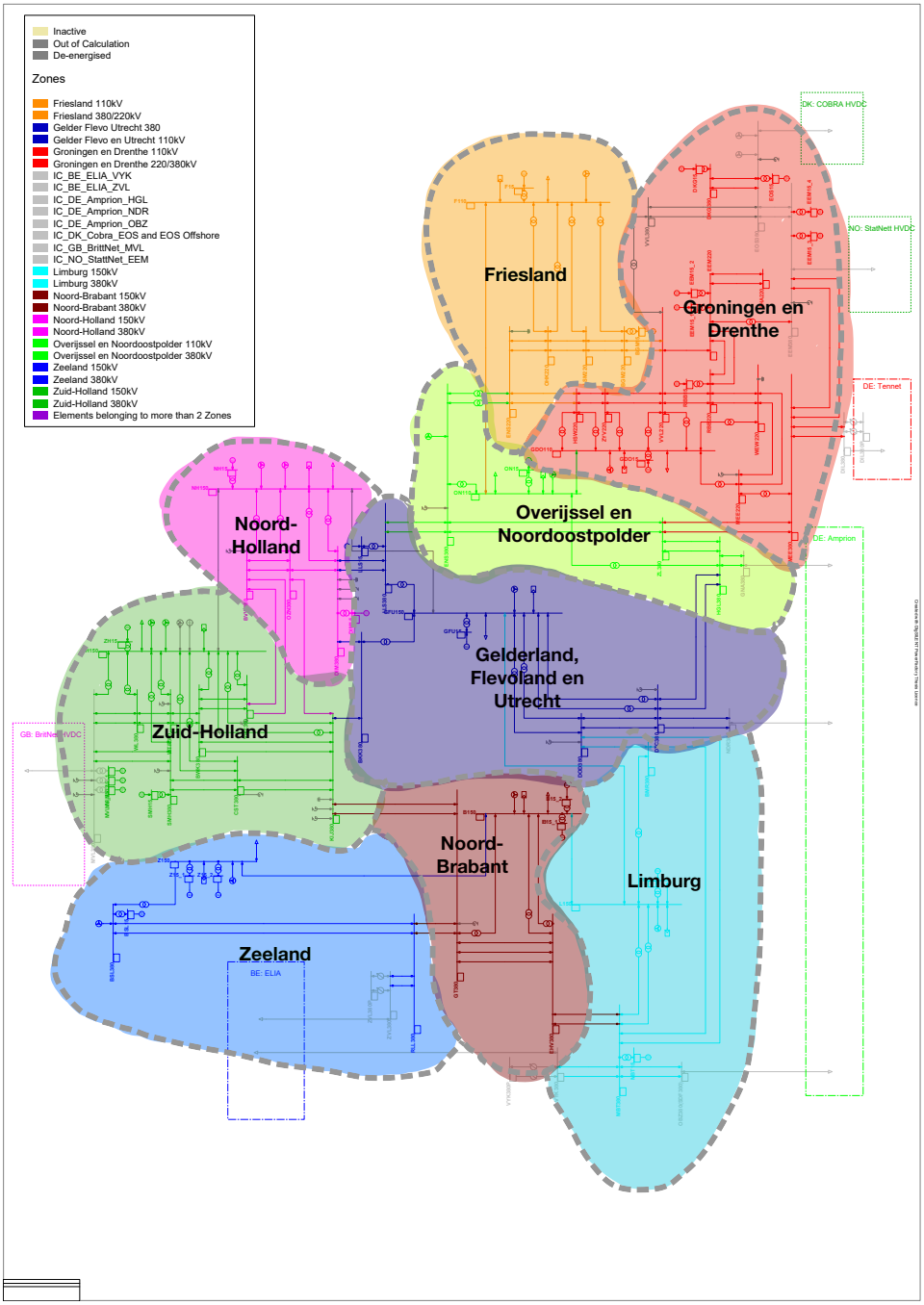


Figure 3.4: Division of the zones within the single line diagram of the PowerFactory Model

3.2.3. Modelling of System Components

In this section a short description of the method by which individual components in PowerFactory were modelled is discussed. Further assumptions and more detailed information on the modelling of the components is given in appendix C.

Terminals *(*.ElmTerm)*

The busbars are respresented as simple terminals *(*.ElmTerm)* in PowerFactory operating at exactly nominal voltage (110/150/220/380kV). The synchronous generator terminals are modelled to operate at 15kV. The static generators, shunts and the interconnections without phase shifters are directly connected as can be seen in figure A.3.

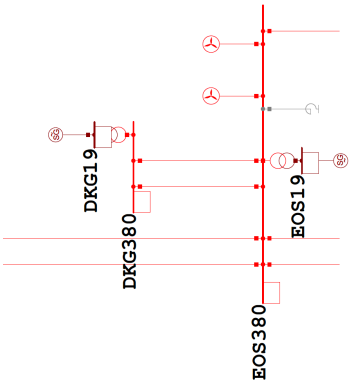


Figure 3.5: Example of the a 380kV busbar

Generators *(*.ElmSym and *.ElmGenstat)*

The modelling of the generators was done by taking examples already available in PowerFactory as well as from the Nordic Test System [32]. As there was no data available for the specifics of each generator, all generators in the system currently have identical parameters, see table 3.1 and 3.2. Side note: In PowerFactory the static generators don't have a seperate "type" but the parameters are defined within the actual network component themselves, hence the type is only defined for synchronous generators.

Table 3.1: Detailed Synchronous Generator Parameters

General	**Unit**	**Parameters**
Nominal Voltage U_{nom} (kV)	kV	15
Nominal Power Factor	p.u.	0,9
Connection	-	YN
Load Flow Parameters	**Unit**	**Parameters**
Q_{min}	p.u.	1
Q_{max}	p.u.	1
$x0$ (zero sequence reactance)	p.u.	0,1
$r0$ (zero sequence resistance)	p.u.	0
$x2$ (negative sequence reactance)	p.u.	0,2
$r2$ (negative sequence resistance)	p.u.	0
Short Circuit VDE/IEC	**Unit**	**Parameters**
$xd"sat$ (subtransient reactance)	p.u.	0,2
$rstr$ (stator resistance)	p.u.	0
$xdsat$	p.u.	1,2
Machine Type IEC909/IEC60909	-	Salient Pole Series 1

The parameters for the initial power flows are given below in table 3.2. For the case study different settings are used, these are discussed in chapter 4 section 4.5.2.

Table 3.2: Load Flow Generator Parameters

Generator Type	Controller	Dispatch Volt. U (p.u.)	Dispatch Pow. Fact.	P_{max} (MW)	P_{min} (MW)	Q_{max} (p.u.)	Q_{min} (p.u.)
Synchronous	Const V	1	0,96	P_{nom}	0.1*P_{nom}	1	-1
Static	Const Q	1	1	P_{nom}	0	1	-1

Transmission Lines *(*.ElmLne)*

Data for the transmission lines was provided on the Tennet Transparency Platform [29]. However it was found that the listed Susceptance (uS) contained unrealistic values when converting to per kilometer (uS/km) values. It seemed these original values were more likely to be the Capacitance (uF) and thus were taken as such.

General Values In table 3.3 an overview is given of the range of rated current, line rating [1], resistance, reactance and capacitance for each line type per voltage level.

Table 3.3: General Ratings of Transmission Lines

U_{rated} (kV)	I_{rated} (kA)	S_n (MVA) [1]	R' (Ohm/km)	X' (Ohm/km)	C' (uF/km)
110	1,15	219,1	0,09	0,374	0,018
150	0,85	220,8	0,09	0,374	0,018
220	2,3 - 2,5	876,4-952,6	0,0166 - 0,0247	0,245 - 0,307	0,0115-0,0150
380	1,5 - 4	987,3 - 2632,7	0,0136 - 0,0254	0,163-0,298	0,0088-0,0156

Adjusted Transmission Lines Some line parameters were adjusted as their parameters seemed unlikely for overhead transmission lines. A reason for the odd values could be that in real life these lines might partially be underground cables, in the base model however all lines are considered overhead due to lack of information. These lines and their new parameters are listed in appendix C.1.3.

New Transmission Lines For the addition of new transmission lines or the upgrading of old lines, values were used for typical 400 kV - 50HZ Overhead Lines [33].

Table 3.4: Parameters for upgrades and system expansion using 380kV Transmission Lines

Type in PowerFactory	U_{rated} (kV)	I_{rated} (kA)	S_n (MVA) [1]	R' (Ohm/km)	X' (Ohm/km)	B' (uS/km)	C' (uF/km)
Line_380kV_4kA_future	380	4	2633	0,0148	0,232	4,8042	0,0153

110/150kV Transmission Lines For the connection of the HV aggregated busses, line parameters were used that are given below in table 3.5. These parameters were chosen following an example of the Nordic test system [34]. However as the Base Voltage for the Nordic system was 138 (kV) the rated current was adjusted for the 110/150 (kV) lines to keep around the same line rating. These lines were also used to add impedance to HV areas to reduce parallel flows, being connected between the HV busbar and the transformer.

Table 3.5: List of Line Parameters for Connecting HV Regions

Description	Type in PowerFactory	U_{rated} (kV)	I_{rated} (kA)	S_n (MVA) [1]	R' (Ohm/km)	X' (Ohm/km)	B' (uS/km)	C' (uF/km)	L (km)
110kV Connection	110 kV_Adj	110	1,15	219,1	0,090	0,374	5,655	0,018	50
150kV Connection	150kV_Adj	150	0,85	220,8	0,090	0,374	5,655	0,018	50

Loads *(*.ElmLod)*

The loads are modelled according to simple "General Load Types". There is currently there is no voltage dependency of the loads modelled, as can be seen in table 3.6.

Table 3.6: Parameters of Load Type

Type	Technology	Balanced/Unbalanced	U_{disp} (p.u.)	PF_{disp} (-)	Volt. Dep. of P	Volt. Dep. of Q
General Load Type	3PH-'D'	Balanced	1	1	none	none

[1] calculated as $\sqrt{3} * U * I$

Interconnections and Electrolysers Currently, the interconnections and electrolysers are modelled as loads. The interconnections can be set to have a negative active power dispatch when there is infeed into the Dutch grid. A list of different interconnections and electrolysers for the base model is provided in section A.2.5.

Transformers *(*.ElmTr2)*

All the transformers used are modelled as a 2-winding transformer type *(*.ElmTr2)*. There was some basic data provided by the marketing department of SGB-Smit with three examples of delivered transformers, see table 3.7 [35]. However, in these example the short circuit voltage seems to be quite high and there was no other data available on the tap changers etc. Therefore the transformers have been modelled following the example of the Nordic Test System [34]. The parameters for the grid transformers is given in table 3.8. The parameters for the step up transformers for the generators is given in table 3.9. For more details on the parameters see figure C.2 and C.3 in the Appendix.

Table 3.7: Transformer Examples from SGB Smit

Description	U_{rated} (KV)	S_{rated} (MVA)	U_{max} (kV)	P_{copper} (kW)	uk (%)
750 MVA, 380/220 kV	380	750	420	800	14.5
500 MVA, 380/150 kV	380	500	420	1025	20
370 MVA, 380/110 kV	380	370	420	660	16

Table 3.8: Parameters of Grid Transformers Used

Name	S_{rated} (MVA)	U_{HV} (kV)	U_{LV} (kV)	uk (%)	P_{copper} (kW)	Ratio X/R	$x1$ (p.u.)	$r1$ (p.u.)
Trafo 220/110 (200MVA)	200	220	110	8,4	400	42	0,084	0,002
Trafo 380/110 (350MVA)	350	380	110	8,4	700	42	0,084	0,002
Trafo 220/110 (350MVA)	350	220	110	8,4	700	42	0,084	0,002
Trafo 380/110 (370MVA)	370	380	110	8,4	740	42	0,084	0,002
Trafo 220/110 (370MVA)	370	220	110	8,4	740	42	0,084	0,002
Trafo 380/150 (450MVA)	450	380	150	8,4	900	42	0,084	0,002
Trafo 380/150 (500MVA)	500	380	150	8,4	1000	42	0,084	0,002
Trafo 380/200 (500MVA)	500	380	220	8,4	1000	42	0,084	0,002
Trafo 380/200 (750MVA)	750	380	220	8,4	1500	42	0,084	0,002

Table 3.9: Parameters of Step up/down Transformers Used

Name	S_{rated} (MVA)	U_{HV} (kV)	U_{LV} (kV)	uk (%)	P_{copper} (kW)	Ratio X/R	$x1$ (p.u.)	$r1$ (p.u.)
Step up 15/110kV	255	110	15	15,0	765	50	0,15	0,003
Step up 15/150kV	255	150	15	15,0	765	50	0,15	0,003
Step up 15/220kV	255	220	15	15,0	765	50	0,15	0,003
Step up 15/380kV	255	380	15	15,0	765	50	0,15	0,003

Phase Shifting Transformers *(*.ElmVoltreg)*

For some of the interconnections there are phase shifters installed at various locations to be able to control the cross-border power flow [30]. Considering the modelling of the component itself, there was no model available for reference in PowerFactory, so assumptions were made based on infromation from hoogspanningsnet.nl as well as a data sheet provided on the TenneT transparency platform [30] [29]. An overview of the phase shifters and their parameters is given in appendix C.1.6.

Static Reactive Power Compensation *(*.ElmShnt)*

According to the single line diagram from hoogspanningsnet there are various locations at which reactive power compensation is provided in the EHV network [30]. A list of these reactor coils and capacitor banks is given in appendix C.1.5. For the simulations however these compensation devices are disabled.

3.2.4. Installed Capacities for the Base Model

The base model is used to simulate scenarios for 2017-2020. The generation capacity and demand are modelled according to KCD2017 for 2018 [31]. The model has been adjusted to include all the generators currently listed by ENTSOE transparency platform to be able to perform simulations for 2019 and 2020 [36]. More details about the modelling of the generation, such as the exact installed capacities of each generator and the distribution of conventional as well as static generations among regions can be found in appendix section A.1.

Installed Generation Capacity

In table 3.10 and 3.11 the total amount of generation and demand that was used in the base model for each of the different regions at 220/380 kV and 110/150 kV parts of the network is given. For generation located in the 220/380kV part of the network, separate generators are introduced in the model according to the nominal power found in public sources [37] [30] [29]. For the generation located at the 110/150kV parts of the network, single aggregated generators are introduced for each technology type, so 1 generator for offshore wind, 1 for onshore wind etc. Synchronous generators are used to model gas, wkk, nuclear and coal generation. Static generators are used for wind and solar generation. For a more detailed discussion of the installed capacities of conventional generation as well as VRE for each region and among the 220/380kV and 110/150kV parts of the network, see appendix A.1.1. For the modelling of the nominal voltages, active and reactive power flow limits as well as other load flow parameters see section 3.2.3.

Table 3.10: Overview of Generation Capacity at 220/380kV for the base model

	Unit	F	GD	ON	GFU	Z	B	L	NH	ZH	*Totals*
Onshore Wind	MW	0	0	0	0	0	0	0	0	0	*0*
Offshore Wind	MW	0	600	0	0	752	0	0	0	0	*1352*
Solar	MW	0	0	0	0	0	0	0	0	0	*0*
Gas	MW	144	3339	0	426	870	0	1304	435	1270	*7788*
Nuclear	MW	0	0	0	0	0	0	0	0	0	*0*
Coal	MW	0	1580	0	0	0	0	0	0	1801	*3381*
Total	**MW**	**144**	**5519**	**0**	**426**	**1622**	**0**	**1304**	**435**	**3071**	***12521***

Table 3.11: Overview of Generation Capacity at 110/150kV for the base model

	Unit	F	GD	ON	GFU	Z	B	L	NH	ZH	*Totals*
Onshore Wind	MW	350	560	450	1046	486	240	70	350	590	*4142*
Offshore Wind	MW	0	0	0	0	0	0	0	228	129	*357*
Solar	MW	210	340	290	289	71	476	288	200	178	*2342*
Gas	MW	0	0	0	992	440	869	245	2208	1585	*6339*
Wkk and other	MW	70	320	200	511	250	700	360	700	1800	*4911*
Nulear	MW	0	0	0	0	494	0	0	0	0	*494*
Coal	MW	0	0	0	0	0	620	0	0	0	*620*
Total	**MW**	**630**	**1220**	**940**	**2838**	**1741**	**2905**	**963**	**3686**	**4282**	***19205***

Table 3.12: Total Amount of Generation and Demand for the Base Model

		F	GD	ON	GFU	Z	B	L	NH	ZH	*Totals*
220/380kV Gen Cap	MW	144	5519	0	426	1622	0	1304	435	3071	*12521*
110/150kV Gen Cap	MW	630	1220	940	2838	1741	2905	963	3686	4282	*19205*
Total Gen Cap	**MW**	**774**	**6739**	**940**	**3264**	**3363**	**2905**	**2267**	**4121**	**7353**	***31726***

Demand

For the demand, it is currently assumed that all the national power consumption is located at the HV busbars representing each region (110/150kV). The demand is modelled per region by adding a single aggregate load at each of the HV buses, see also figure A.3. On the ENTSOE transparency platform only the total load for the whole of NL is available. Therefore, a distribution key was created according to the peak demands mentioned in KCD2017 [38].

Table 3.13: Peak demands per region for the year 2018 [31]

	Unit	F	GD	ON	GFU	Z	B	L	NH	ZH	*Totals*
Peak Demand	MW	590	1460	1258	3251	625	3550	1650	3333	4355	-
Distribution	%	2,9	7,3	6,3	16,2	3,1	17,7	8,2	16,6	21,7	*100*

This approach was validated by comparing the peak demand to the annual electricity consumption per region. The annual electricity consumption was taken from klimaatmonitor.nl which uses statistics from CBS [39]. In table A.9 the peak demand and average annual electricity consumption are expressed as % of the national total. It can be seen that both approaches lead to approximately the same distribution.

Table 3.14: Distribution of national demand according to peak and average electricity consumption in 2019

	F110	ON110	GD110	GFU150	Z150	B150	L150	NH150	ZH150
Peak Demand (%)	2,94	6,27	7,27	16,20	3,11	17,69	8,22	16,61	21,70
Average Electricity Consumption (%)	3,01	5,72	8,77	17,09	2,93	16,18	8,56	18,19	19,55
Difference (%)	0,07	-0,55	1,49	0,90	-0,18	-1,51	0,34	1,59	-2,15

Interconnections

For the base model the interconnection capacities given KCD2017 are used [19]. The capacities were determined using KCD2017 as well as the ENTSO-E transparency platform [19] [36]. For each country the amount of transfer capacity to and from the Netherlands is specified. The capacities for specific connections to Belgium (ELIA) and Germany (AMPRION) were unclear. An even distribution among the two connections was assumed as both the connections have equal line ratings according to a public document with grid data taken from the Tennet transparency pages [29]. In the same manner, an equal distribution is assumed for the three connections facilitated by Amprion. One of the connections to Germany has been upgraded in 2018 to have a larger transmission capacity (connection from Doetinchem to Wesel/Niederrhein, NDR380), this has been taken into account for the 2030 model [29].

Table 3.15: Interconnection Capacities for the Base Model

Connection Names	Country	Cap. per Country 2018	Pmax (MW) 2018
IC_ELIA_MBT380	Belgium	1400	700
IC_ELIA_ZVL380	Belgium		700
IC_COBRA_EOS380	Denmark	700	700
IC_AMPRION_GNA380	Germany Z	3950*	650
IC_AMPRION_NDR380	Germany Z		650
IC_AMPRION_OBZ380(SDF380)	Germany Z		650
IC_TenneT_DIL380	Germany N		2000
IC_StatNett_EEM380	Norway	700	700
IC_BritNed_MVL380	UK	1000	1000
Total Exchange		*7750*	*7750*

3.2.5. Installed Capacities for the 2030 Model

For the 2030 Model the amount of generation and demand was determined according to numbers and graphs found in KCD2020 [2]. For the case study the numbers from the reference scenario KA30 are used, therefore only these numbers are discussed. More information about the numbers for alternative scenarios can be found in appendix section A.2.

Installed Generation Capacity

In table 3.16 and table 3.17 the amount of installed capacity according to the type of technology at 380/220kV and 110/150kV within the PowerFactory model for each of the regions is given. In table A.16 the total amount of generation and demand for each of region for the 220/380kV and the 110/150kV part of the network model is given. For the conventional generation located in the 220/380kV part of the network, the installed capacity of the existing generators within each region of the base model are scaled proportionally to the new values listed in table 3.16. For the introduction of offshore wind generation, static generators were introduced. The location and initial capacity was modelled according to KCD2020 and government publications for offshore wind [40] [41], which is elaborated upon in section B.2.2 of the appendix. The total installed capacity in each region was slightly adjusted for the KA30 scenario to reflect a total amount of 10920 MW nationally.

Table 3.16: Total Installed Generation Capacity at 220/380kV level for the 2030 Model

	Unit	F	GD	ON	GFU	Z	B	L	NH	ZH	*Totals*
Onshore Wind	MW	0	0	0	0	0	0	0	0	0	*0*
Offshore Wind	MW	0	1378	0	0	3712	0	0	2226	3604	*10920*
Solar	MW	0	0	0	0	0	0	0	0	0	*0*
Gas	MW	85	1972	0	252	514	0	770	257	750	*4600*
Wkk	MW	0	0	0	0	0	0	0	0	0	*0*
Nuclear	MW	0	0	0	0	0	0	0	0	0	*0*
Coal	MW	0	0	0	0	0	0	0	0	0	*0*
Total	**MW**	**85**	**3350**	**0**	**252**	**4226**	**0**	**770**	**2483**	**4354**	***15520***

Modelling of the generators for the 110/150kV parts of the network follows the same approach as for the base model. For each technology type, single aggregated generators are presented, so 1 generator for offshore wind, 1 for onshore wind etc. The only exception is that in the 2030 model the gas and wkk generators are aggregated into one ”gas” generator. The reason for this was to be able to create a clearer overview of the total gas powered generation present in specific lower voltage areas for the analysis of 2030 scenarios in which there was no VRES production (so there are still separate generators for coal and nuclear plants). Static generators are used for wind and solar generation. For a more detailed discussion of the installed capacities of conventional generation as well as VRE for each region and among the 220/380kV and 110/150kV parts of the network, see appendix A.2.3. For the modelling of the nominal voltages, active and reactive power flow limits as well as other load flow parameters see section 3.2.3.

Table 3.17: Total Installed Generation Capacity at 110/150kV level for the 2030 Model

	Unit	F	GD	ON	GFU	Z	B	L	NH	ZH	*Totals*
Onshore Wind	MW	700	700	540	2400	700	260	30	800	1150	*7280*
Offshore Wind	MW	0	0	0	0	0	0	0	230	150	*380*
Solar	MW	1600	5200	2400	5500	1150	2550	1250	2400	2700	*24750*
Gas	MW	0	500	80	850	380	390	450	650	1000	*4300*
Wkk	MW	70	250	260	400	150	620	280	700	1700	*4430*
Nuclear	MW	0	0	0	0	494	0	0	0	0	*494*
Coal	MW	0	0	0	0	0	0	0	0	0	*0*
Total	**MW**	**2370**	**6650**	**3280**	**9150**	**2874**	**3820**	**2010**	**4780**	**6700**	***41634***

Table 3.18: Total Generation and Demand for each region for the 2030 model

	Unit	F	GD	ON	GFU	Z	B	L	NH	ZH	Totals
220/380kV Gen Cap	MW	85	3350	0	252	4226	0	770	2483	4354	15520
110/150kV Gen Cap	MW	2370	6650	3280	9150	2874	3820	2010	4780	6700	41634
Tot.Gen. Cap.	**MW**	**2455**	**10000**	**3280**	**9402**	**7100**	**3820**	**2780**	**7263**	**11054**	**57154**

Demand

The distribution of the demand for each of the 110/150kV areas is modelled according to the peak demands listed in KCD2020 per region [2], presented in table A.18. The approach for the distribution of the national demand follows the same approach as for the base model, see section 3.2.4.

Table 3.19: Peak Demand and share of total national assumed for each region for 2030

	Unit	F	GD	ON	GFU	Z	B	L	NH	ZH	Totals
Peak Demand	MW	750	1600	1700	4300	1180	3900	2200	5500	5300	-
Distribution	%	2,84	6,05	6,43	16,27	4,46	14,76	8,32	20,81	20,05	100

Interconnections

For the base model the details concerning interconnections are discussed in section A.1.5. For the 2030 model, there is an increase in capacity between Germany and the Netherlands due to a new connection between Doetinchem and Niederrhein (NDR380) as well as upgrades made to other parts of the Dutch Transmission Network. These developments are based on the numbers provided in KCD2017 as well as from Tennet transparency pages [19] [29].

Table 3.20: Interconnection Capacities for base and 2030 model

Connection Names in PowerFactory	Country	P_{max} (MW) per Country 2018	P_{max} (MW) 2018	P_{max} (MW) Country 2030	P_{max} (MW) 2030
IC_ELIA_MBT380	Belgium	1400	700	3400	1700
IC_ELIA_ZVL380	Belgium	-	700	-	1700
IC_COBRA_EOS380	Denmark	700	700	700	700
IC_AMPRION_GNA380	Germany	3950*	650	5000*	750
IC_AMPRION_NDR380	Germany	-	650	-	1500
IC_AMPRION_OBZ380(SDF380)	Germany	-	650	-	750
IC_TenneT_DIL380	Germany	-	2000	-	2000
IC_StatNett_EEM380	Norway	700	700	700	700
IC_BritNed_MVL380	UK	1000	1000	1000	1000
Total Exchange		*7750*	*7750*	*10800*	*10800*

3.2.6. Visualisation of Results

Regional Flow Diagram

The regional power flow diagram shows the active power flows between defined regions. An example of the diagram is presented in figure 3.6 where the different regions are highlighted.The boxes on the outer edge of figure 3.6 represent interconnections.

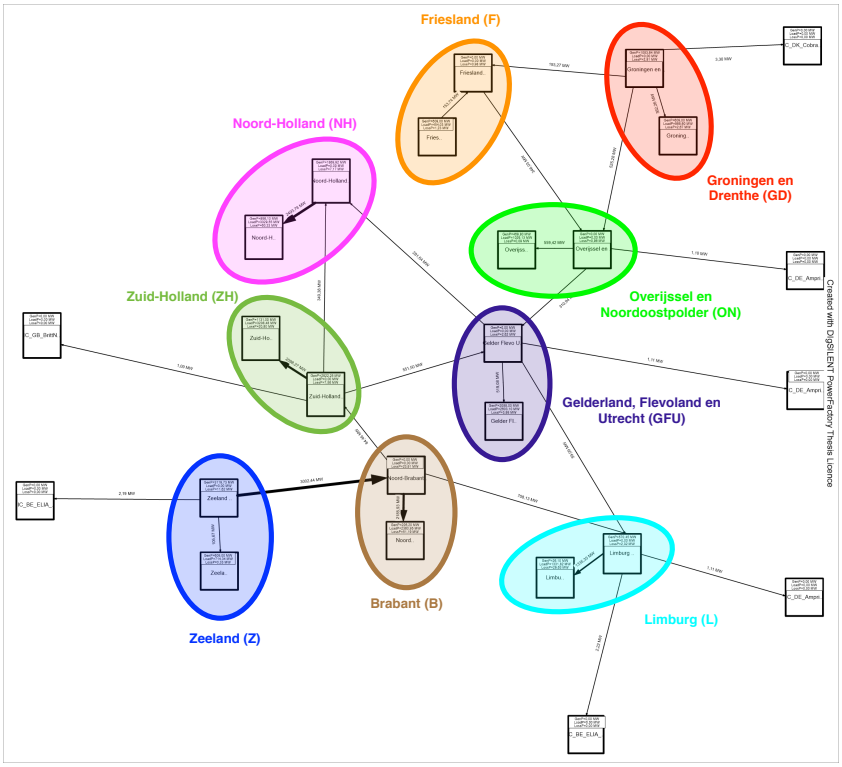


Figure 3.6: Diagram for Regional Power Flows, where the different regions are illustrated according to the colors earlier discussed in section 3.2.2.

Each region within the diagram has a 220/380 kV and 110/150 kV part, illustrated in figure 3.8 for the example of Noord-Holland.

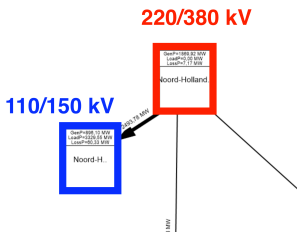


Figure 3.7: Example of the 110/150kV region and 220/380 kV region for Noord-Holland, where the 220/380 kV area is marked in red and the 110/150 kV area is marked in blue.

Geographical Diagram

The second diagram that is used is the geographical diagram. In this diagram only 220/380 kV connections are represented. The arrows indicate the direction of the power flow. If components are above 70% of their apparent power, the arrows are no longer black but become colored. The color ranges from yellow to red depending on the amount of overloading (yellow=70%, orange=80% while red=>100%).

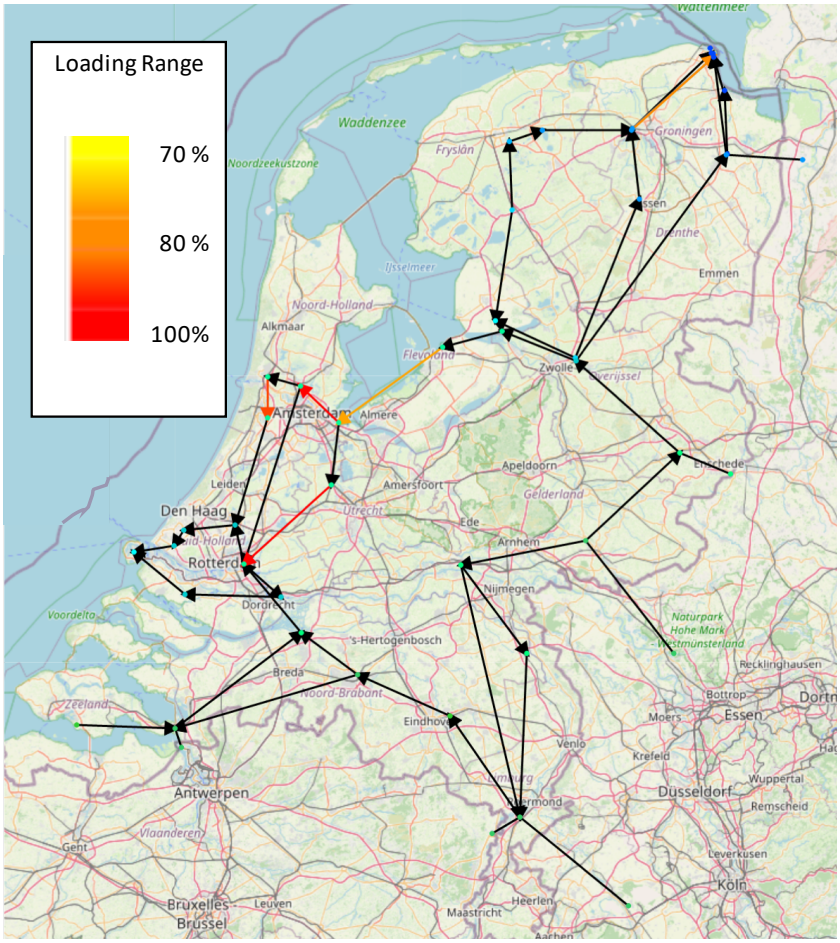


Figure 3.8: Example of Geographical Diagram used for Analysis, where colored arrows indicate component loadings above 70%

Single Line Diagram

The last diagram that is used is the single line diagram, an example of which is given in figure 3.9. In this diagram all the components are visualized. This diagram is used to identify specific overloaded components, as well as voltages of specific busbars. Components loaded higher than 70% of their apparent power are colored yellow (70%) to red (=>100%) according to their loading. Also, the voltages of the busbars are indicated by the color of the busbar. Voltages of around 1 p.u. give a green colored busbar, while undervoltages turn blue and overvoltages turn red (see also legend in figure 3.9. An example of this is shown in figure 3.9, where highly loaded components (in this case transformers) are circled in pink and a large area or under voltages of around 0.95 p.u. is colored in light blue.

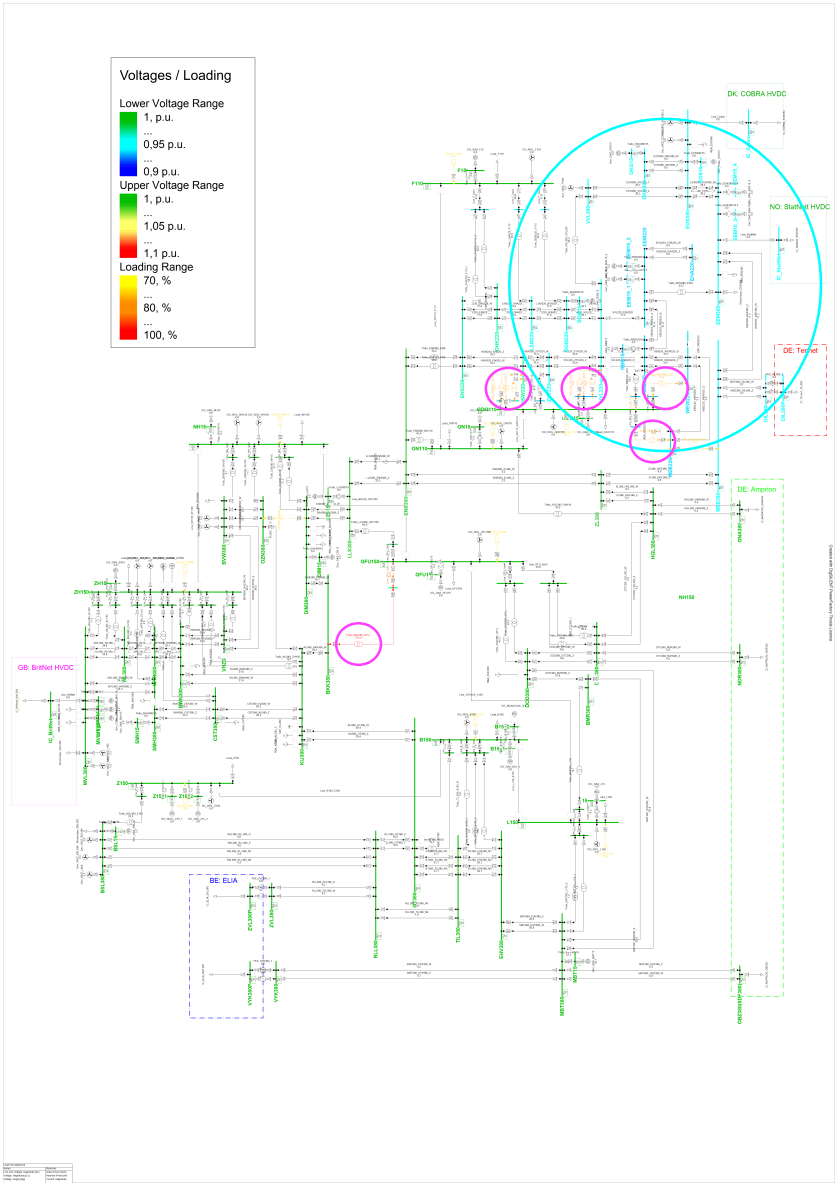


Figure 3.9: Example of Single Line Diagram used for Analysis

3.2.7. Initial Simulations for the Base Model

To test whether the model was representative for the actual Dutch EHV network, power flows were simulated according to different approaches. The first approach was to simulate a power flow (PF) using data from historical dispatches during peak demands of 2017 and 2018. Besides this, it was also investigated what happened in the network when the generation within one region is increased to 90% while the other regions evenly distribute the remaining generation (often at around 60-70% for a peak demand scenario). These types of simulation will be called transfer capacity analyses (TCA). Finally optimal power flow (OPF) studies were also performed for the peak demand scenarios. A detailed description of these initial simulations is given in appendix D. In the following sections first a description of the different types of simulations will be given. After this the general results and findings of the different simulations are discussed.

Power Flow Analysis (PF)

Below in figures 3.10 and 3.11 an example of visual results for the peak demand simulation of 2017 is given. In this simulation, the large amount generation capacity in the north leads to power flows going from North to South as can be seen by the direction of the arrows in figure 3.10. The single line diagram shows loadings of 72-89% for selected transformers as can be seen in figure 3.11. For a full discussion of the results for the simulations of the base model as well as the simulation settings see appendix D.

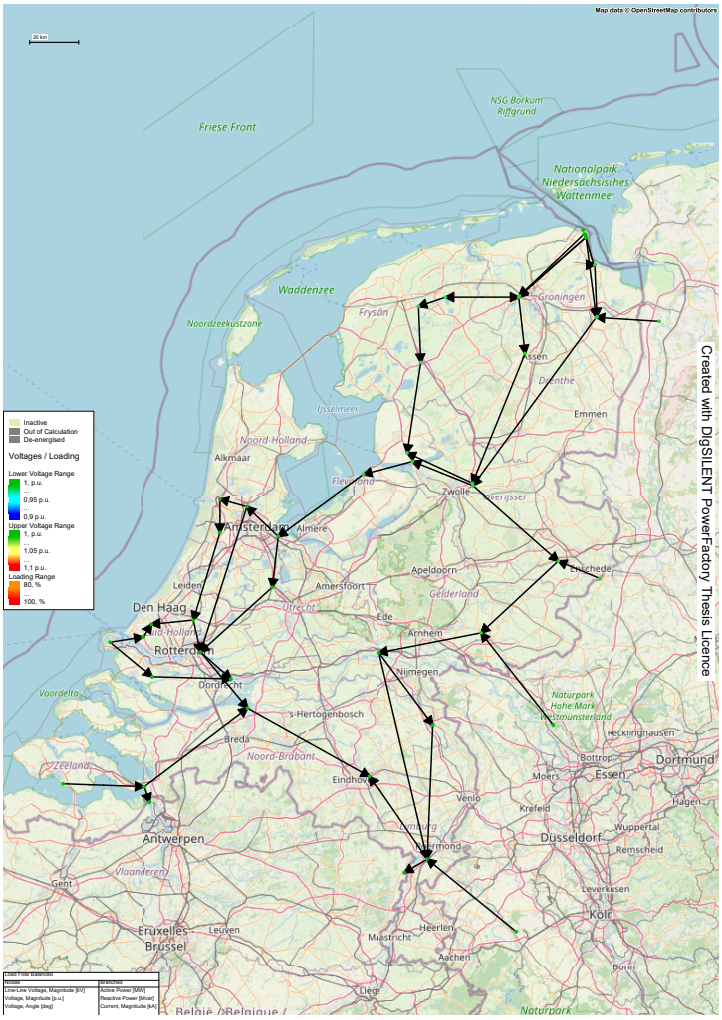


Figure 3.10: Geographic Representation of Power Flow for Peak Demand 2017

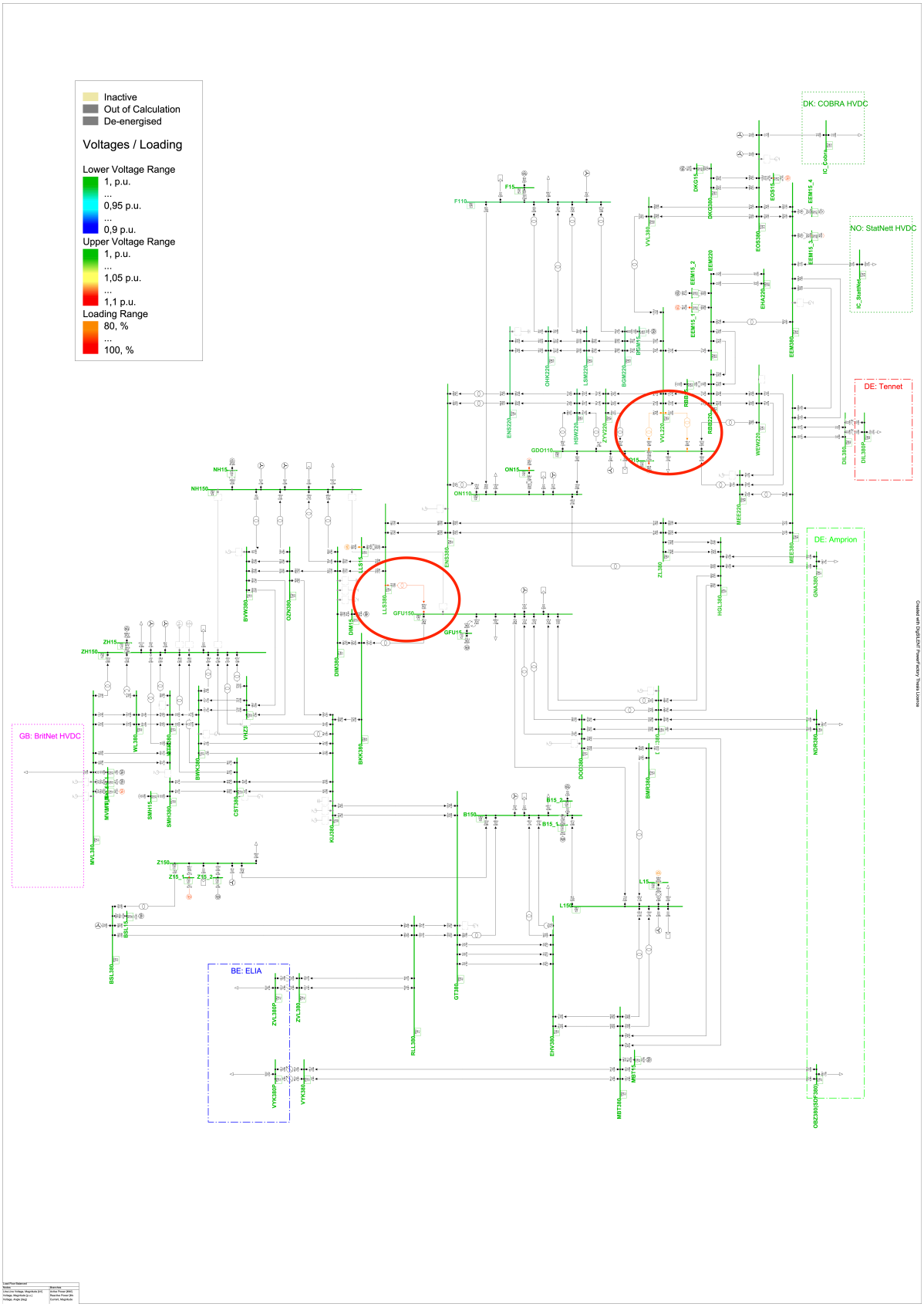


Figure 3.11: Single Line Diagram of Power Flow for Peak Demand 2017

TCA analysis (TCA)

To be able to get a more comprehensive view of the critical areas of the network, additional simulations were performed. It was investigated what the power flow would be if there is a high amount of export or import of power from/to a specific region. For a high export, this would mean that within one region the maximum amount of (synchronous) controllable generation was dispatched, while the other regions would supply the missing amount. For a high import, the minimum amount of controllable generation for that region was dispatched. Limits for the thermal loading of different components were adjusted to a maximum of 100%, so that the amount of capacity transferred between zones would be less limited. This analysis was performed for all the different zones.

For the initial (starting) power flow, all the generators were dispatched at the same capacity factor (of around 70%). The demand, interconnecting power flows and renewable generation of the peak demand scenario of 2018 was used. The static generators couldn't participate in the re-dispatching. Two groups of simulations were performed. In the first, the interconnecting capacities were used according to the initial power flow. For the second group of simulations the interconnections were disabled, making the Netherlands completely self-supplying.

An example of the results for the power flow between areas for two different simulations is given in figure 3.12 and 3.13. In figure 3.12 the power flow is given for when Groningen & Drenthe is considered as the main exporting region, while in figure 3.13 Groningen & Drenthe is set to be the main importing region.

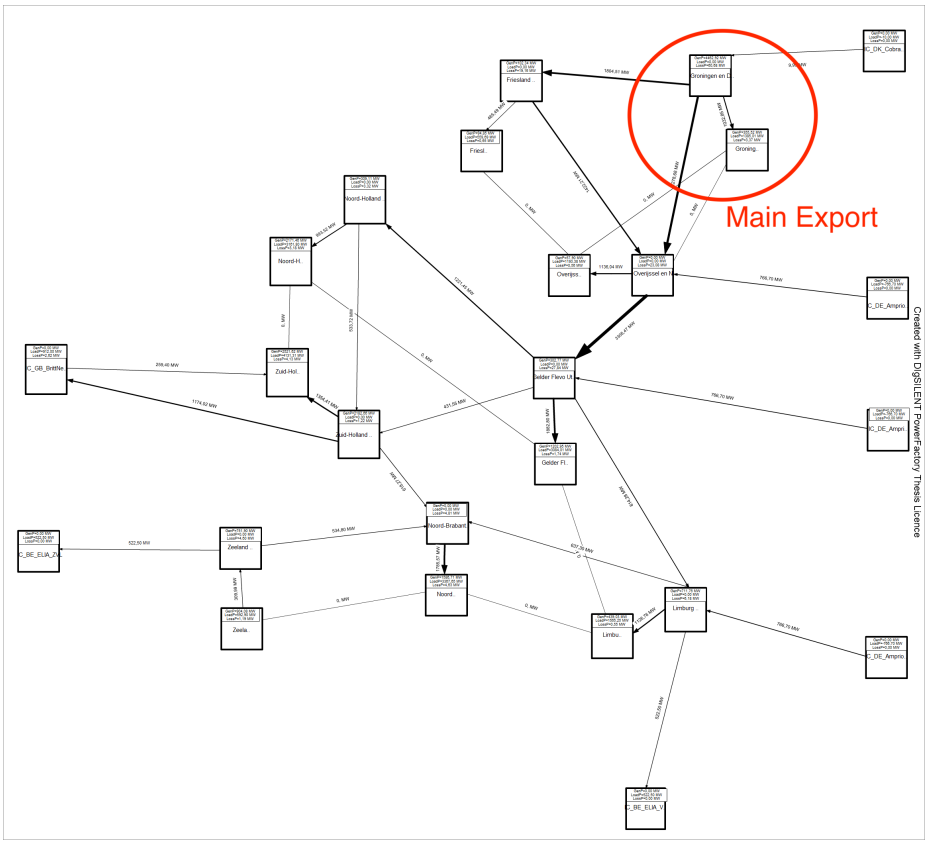


Figure 3.12: TCA for Groningen & Drenthe (GD) as exporting region

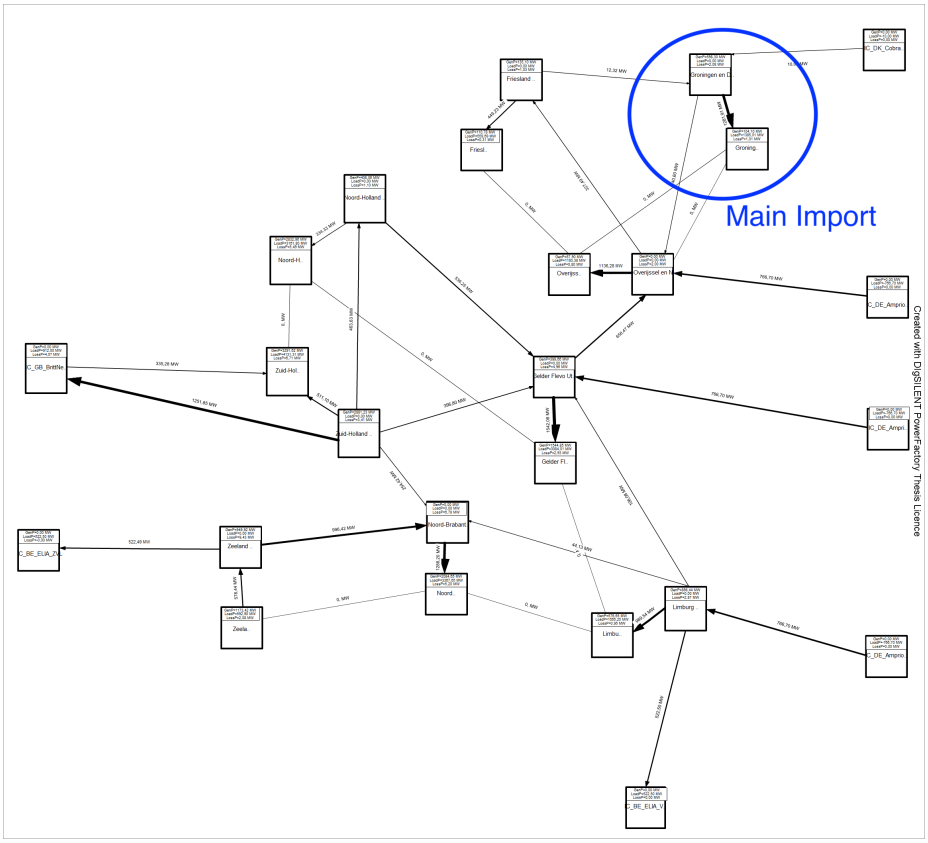


Figure 3.13: TCA for Groningen & Drenthe (GD) as importing region

Optimal Power Flow (OPF)

For each of the different initial peak demand power flows, it is interesting to investigate what happens if an optimal power flow study is added. Using the power flow as a basis, the generators are redispatched to minimize or maximize a chosen objective function, in this case to minimize either the system costs or system losses. By defining the generator cost functions, different merit order effects can be investigated. In the future, it is likely that the merit order will always favor gas over coal [22]. Therefore, in the base scenario, it was chosen to increase the marginal price of coal to be above the price of gas. Introducing these cost functions should lead to re-dispatching units in the following merit order: Wind & Solar, Nuclear, Gas&Wkk, Coal. The costs of renewable technologies are set to zero.

To create a cost functions that could be used for the conventional generators, different papers were consulted that already investigate or use quadratic cost functions for thermal generation [42], [43], [44], [45], [46], [47], [48].

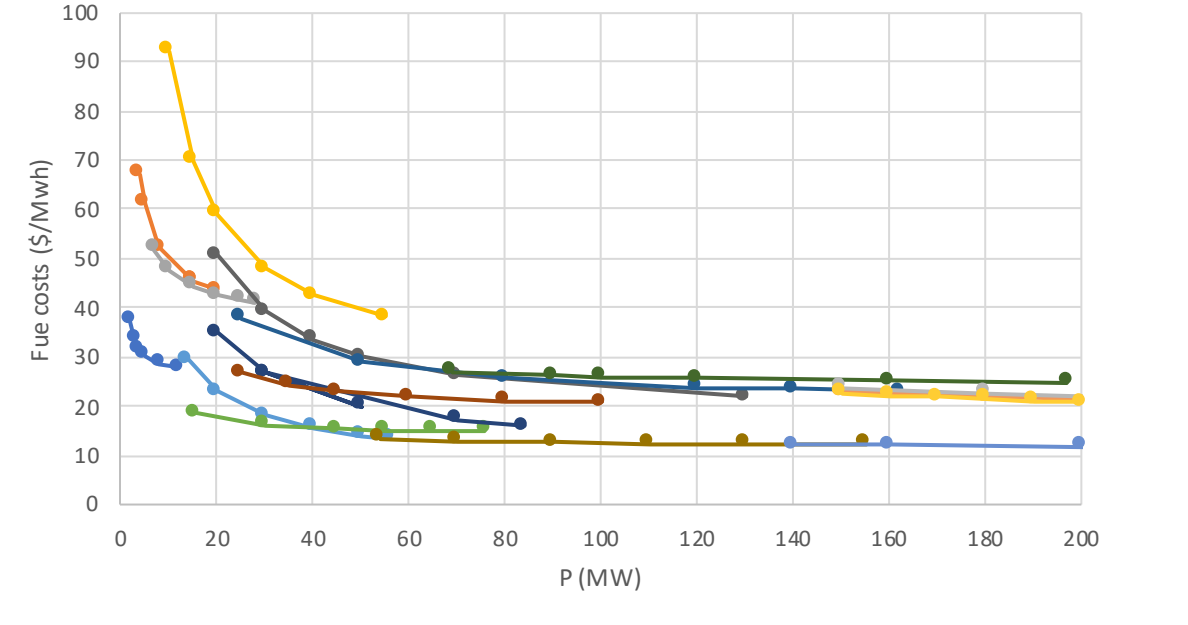


Figure 3.14: Example of Cost Functions (LCOE) for thermal Generators (13 units) from paper by Zhai et. al [42]

In section D.4.1 of appendix D the approach to defining the generator cost-functions is discussed as well as the settings and predefined limits for different components. The final values used during the OPF for the generator costfunctions are given in table 3.21. The cost function is calculated as: Cost ($\frac{e}{-}$) = $a + b * P + c * P^2$ with P in MW, a in $(\frac{€}{h})$, b in $(\frac{€}{MW*h})$, c in $\frac{€}{MW^2*h}$.

Table 3.21: Cost coefficients used for the quadratic cost function

Technology	a (€/h)	b (€/MWh)	c (€/MW^2h)
Gas	680	14	0,002
Coal	1000	20	0,002
Nuclear	0	8	0

3.2.8. Results of Initial Simulations

In this section a short summary of the main findings of the initial simulations is given. A more extensive discussion the results is given in appendix D.

In the initial power flow for the peak demand simulations large power flows occur from the North and West of the Netherlands to the South. This can be explained by higher amounts of installed generation capacity in the exporting areas. These power flows lead to the overloading of transformers and the increase in total grid losses. Whether the simulations are representative for the actual power flow at the time, also depends on how the interconnections were being used at that time. As there is only public information available per bidding zone, the amount of cross-border flow was assigned evenly among the different connections of a bidding zone as was discussed in section A.1.5. The elements that are often overloaded for the initial simulations are:

- Transformer between LLS380-GFU150
- Transformer between VVL220-GDO110
- Transformer between GT380-B150

Other components worth mentioning that are also sometimes overloaded:

- Transformer between ENS380-ENS220
- Transformer between WEW220-GDO110
- Transformer between DTC380-GFU380

The full list of critical network components are discussed and compared to those found in KCD2020 in chapter D.3 of appendix D. Using this analysis adjustments could be made to the model to make it more representative for the real EHV transmission network.

3.2.9. Adjustment of PowerFactory Model

From the initial power flows it was clear that parallel flows were occurring through different HV pockets (110/150kV) within the system. This significantly increased the loading of different transformers. The reason for this was that there was no impedance other than from the transformers between the 220/380kV part of the network and the 110/150kV part of the network. This means that in some cases it is easier for the power to flow through the lower voltage area and back to the EHV network instead of going through EHV transmission lines such as for the connection of ZYV-HSW.

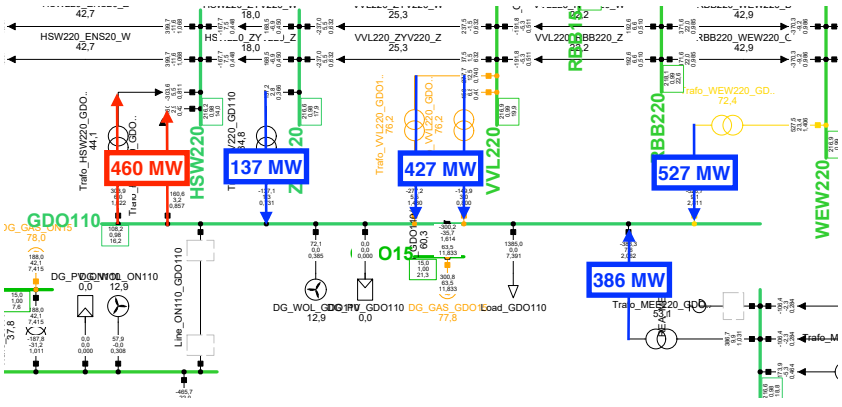


Figure 3.15: Example of a parallel flow of 460 MW occurring for peak demand simulation of 2017

For the real transmission system, it would not be realistic that more than 100 km of distance could be crossed without impedance (such as between for example Meeden and Hessenweg). In the recent report by Netbeheer, it is discussed that the amount of lower voltage pockets will be increased in the future to decrease the amount of parallel flows. The reason for this is that parallel flows increase the loading of the different components within the lower voltage areas of the network and their connections

to the EHV grid. This in turn will limit the amount of transmission capacity available for general transport of electricity.

Therefore, to limit the amount of parallel flows extra impedance was added to the HV areas. This was done by adding extra transmission lines between the grid transformers and the HV areas according to the rated capacity of the transformer. The parameters are the same as the 110/150kV transmission lines discussed in section 3.2.3. For the same reason, the existing connections between different 110/150kV areas (for example between Groningen & Drenthe and Overijssel & Noordoostpolder) were disabled for the 2030 simulations. When the extra transmission lines are added to the peak demand simulation of 2017, the new import into the 110/150kV region of Groningen & Drenthe is 1087 MW of which 1041 is to meet the lower voltage demand and only 46 MW is exported to the EHV grid at Hessenweg (HSW380) as a parallel flow, shown in figure 3.16.

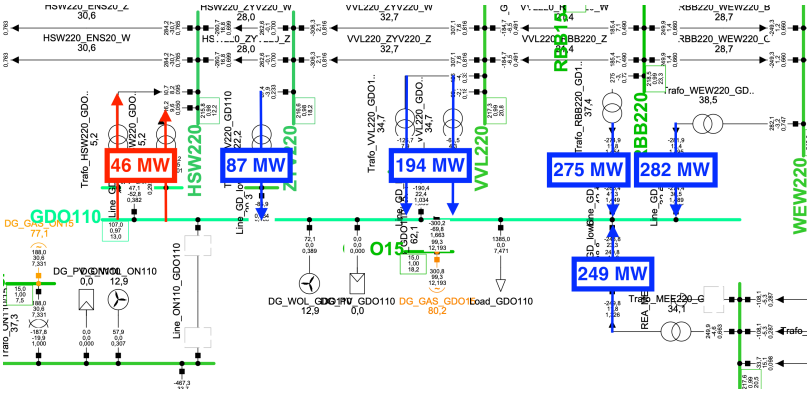


Figure 3.16: Example of a lower parallel flow of 46MW for peak demand simulation of 2017 due to added impedances

3.2.10. Upgrades to the Transmission Network for 2030

In this section, the different developments that lead to a change in network topology of the base model are mentioned. The initial model is based on a single line diagram of 2019 with corresponding network data, hence only the developments that occur after this time horizon are discussed. There are cases of upgrades to the existing system as well as addition or removal of certain network components. In appendix B a detailed description of the modelling of these projects as well as other upgrades are given according to the region in which they occur. Also a single line diagram for each region is shown. Projects that are already incorporated into the single line diagram of 2019 and thus are already in the base model (BM18):

1. Randstad 380kV Noordring (see section: Noord-Holland)
2. Doetinchen-Wesel 380kV (see section: Gelderland, Flevoland en Utrecht)

The most important new projects and developments that are added to the 2030 model are:

1. Noord-West 380kV (see section: Groningen en Drenthe)
2. Zuid-West 380kV (see section: Zeeland and Noord-Brabant)
3. Beter Benutten Bestaande 380kV

Besides these projects, interconnection capacities are adjusted, see section A.2.5 and the different offshore wind farms connected to 220/380kV areas of the grid are added according to their expected delivery date [2][40]. A final overview of the topology is given in figure 3.17, where upgrades to the model compared to the initial model are circled in green and important new components are circled in red. As mentioned before, for more details on the projects see appendix B.

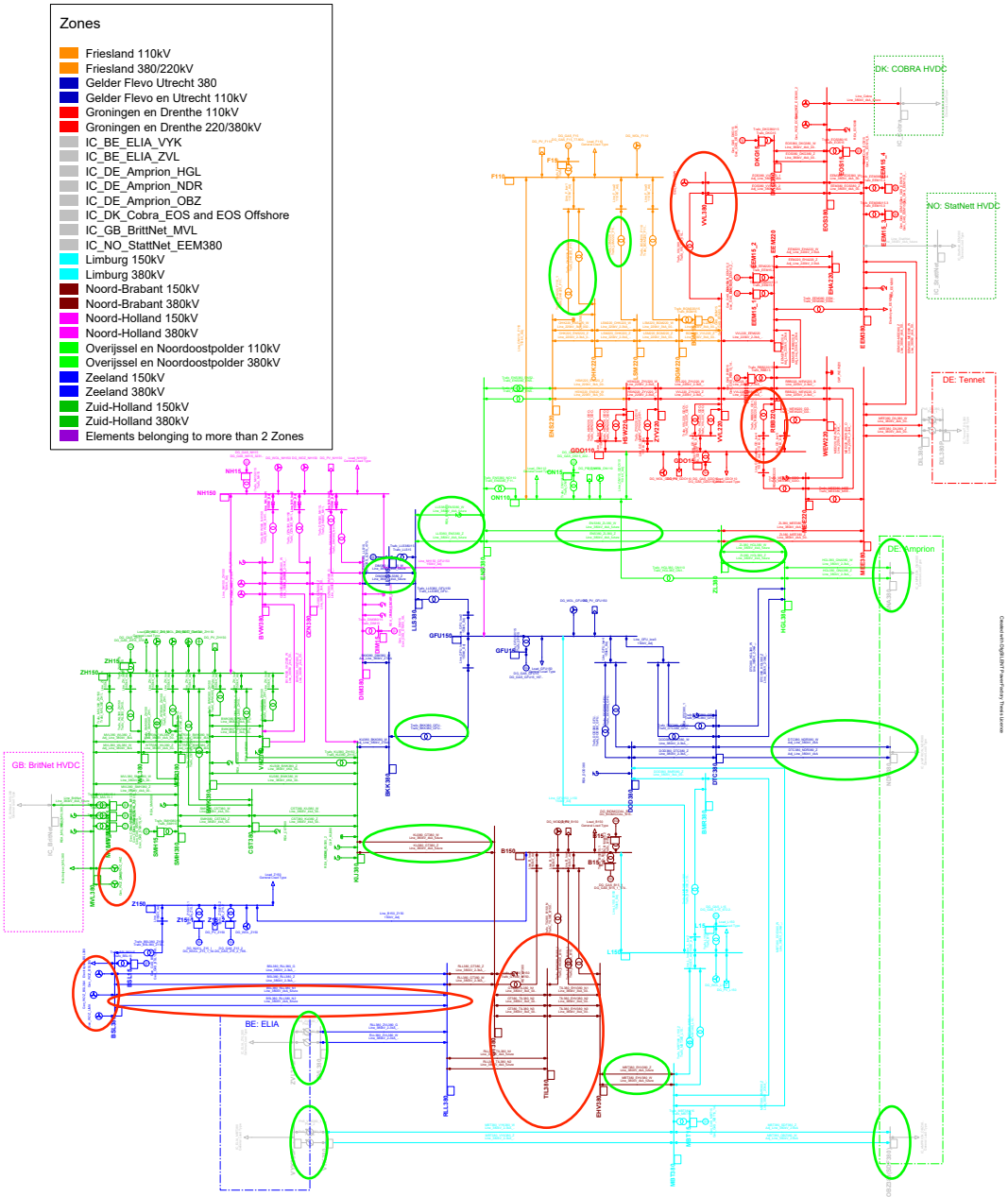


Figure 3.17: Single Line Diagram for 2030 according to region. Upgrades to the model are circled in green and new components are circled in red. For more details on the upgraded or added components see appendix B

3.3. Integration with Python

Using the integration of PowerFactory with Python it is possible to execute python scripts from within PowerFactory. A python script was created which can set new installed capacities and dispatches, initializes simulations and gather results which are exported to an excel file. A flowchart for an example analysis of Scenario X and Y using the model is shown in figure 3.18.

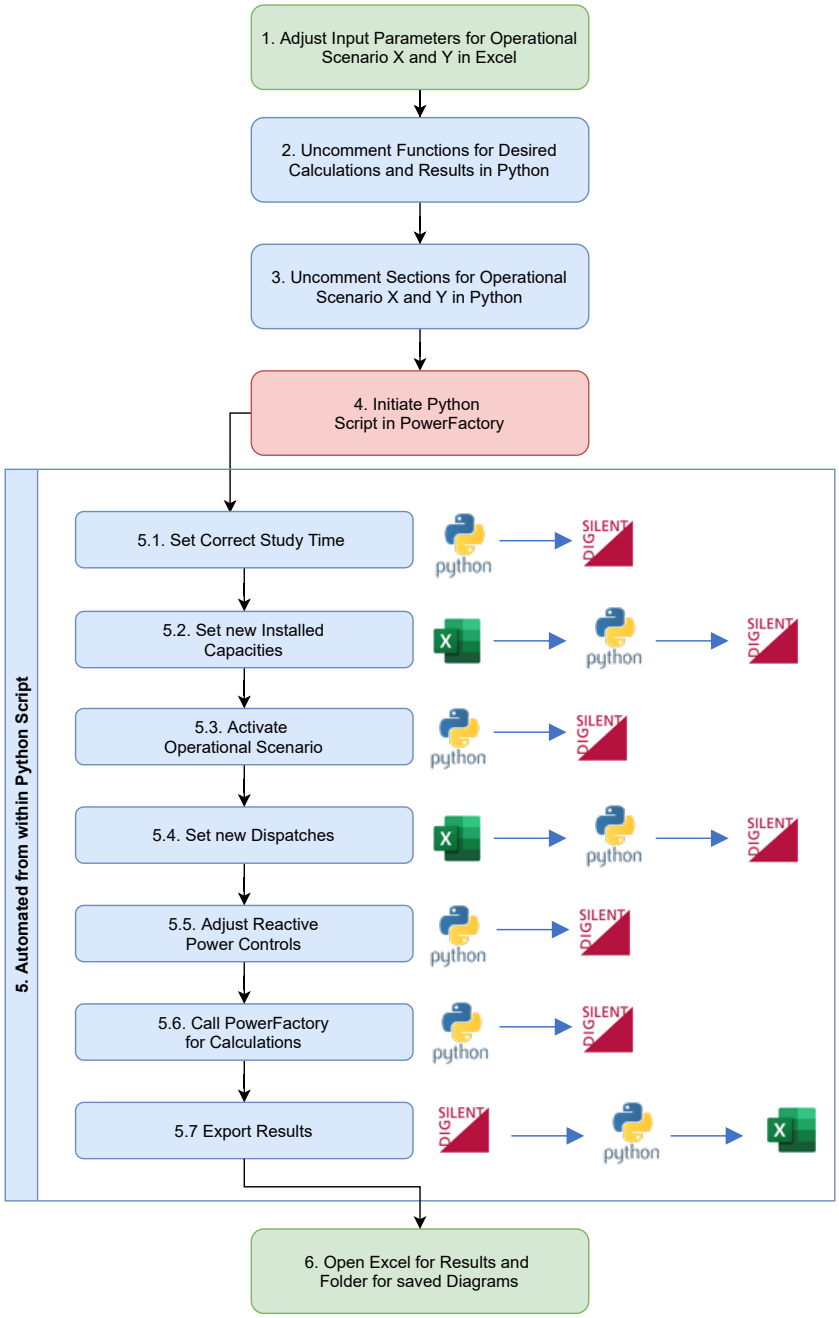


Figure 3.18: Flowchart of how model can be used for hypothetical simulations of Scenario X and Y. Green Rectangles indicates actions taken in Excel, Blue Rectangles in the Python script and Red Rectangles in PowerFactory. Within the box (step 5), all the actions are automated. The programs used in each step of the automated process are presented in the right hand side of the box.

The model of the transmission network is in PowerFactory. The python script is used to read and write data and calls PowerFactory to run simulations. The excel files are used for the input parameters as well as for storing the results. More guidelines on the Python script and the excel files can be found in

appendix F.

Step 1: Adjusting Parameters for Operational Scenarios in Excel
In Excel, the different input parameters for the dispatches can be adjusted as well as parameters for the installed capacities. For more information on the exact guidelines see appendix F

Step 2: Uncommenting Functions for Desired Calculations and Results in Python
Select the python script for either the base model or the 2030 model. In Python, the desired calculations can be uncommented as well as whether results need to be exported under the function: simulations(). The calculations can be performed for load flow analysis, optimal power flow analysis and contingency analysis.

Step 3: Uncommenting Section for Operational Scenarios in Python
Select the python script for either the base model or the 2030 model. In Python, the operational scenarios for the analysis need to be uncommented. The script will run the analysis for each of the different selected operational scenarios one-by-one.

Step 4: Running the python script from within PowerFactory
In PowerFactory, under library>scripts, either the Python script for the base model or the script for the 2030 model is executed to start the analysis.

Step 5: The Python Script (automated)
The created python script roughly consists out of 3 parts. In the first part of the script, the different input and output files are called and the exchange of information with PowerFactory is activated. The second part of the script consists out of different functions that were defined. The different functions are:

- *Adjust Installed Capacities*: Adjust the intalled capacities of the components already present in PowerFactory. This was done to allow adjustment of generation capacities for the different scenarios mentioned in KCD2020 [2] and which were quantified in section A.2.
- *Set dispatches*: Set the dispatches for an operational scenario according to the input parameters from excel.
- *Adjust Reactive Power Control*: Adjust the settings for reactive power in PowerFactory. This is done because for different sources of reactive power control can then be investigated depending on the scenario.
- *Execute Simulations*: Execute power flows (PF), contingency analysis (CA) and optimal power flows (OPF)
- *Export Results*: Get the results of the different simulations and export these to the output excel file [2]
- *Export Diagrams*: Export the different visual diagrams: single line, geographical and interchanges for the executed simulations

In the third section of the script, the actual commands are given to perform the analysis. These will be discussed according to the steps 5.1-5.7 indicated in the flowchart shown in figure 3.18. The analysis is carried out for each selected operational scenario (see step 2) one-by-one.

1. First, a command is given to adjust the study time using the excel files.
2. Installed capacities are set for either the base model vs 2030 model depending on the executed python script.
3. The operational scenario is activated.
4. The dispatches are set for the initial power flow using excel.

[2] The most time consuming part of the simulations is exporting the results to the excel files, as this is done with ”if” loops that only enters the value if it matches the component name listed in the excel file. This was done to ensure that no small mistakes in adjustment of the file or rearrangement of the names would lead to wrong result files. If faster analysis is required, these functions can be commented out of the script

5. The reactive power controls are adjusted depending on the type of operational scenario.
6. PowerFactory is called to run the simulations.
7. Results are exported to the result file in Excel and visual snapshots of the diagrams of each simulation are stored to a selected folder.

In this script the reading of input parameters and writing to an excel file of the results is done automatically. Therefore before starting the analysis, the location of the input files and desired location for the results files should be defined in the first section of the python script. For the adjustment of sheet names and the layout in excel (for example when adding components) the python script does need to be altered (as it is refers to specific sheet names and ranges).

Step 6: Reading Results in Excel and From Visual Diagrams

The results can be found in the excel result file for power flow, optimal power flow and contingency analysis. The file contains data on the generators, loads and interconnections such as active and reactive power dispatches and their loadings. The file also provides the regional results per zone such as the amount of import and export of active and reactive power. Finally, loadings are also stored for transmission lines and transformers. Visual diagrams are exported to a selected file that is defined in the beginning of the python script, also mentioned in step 5.

4

Case Study

4.1. Introduction

In this chapter the case study is discussed. Using the updated model, simulations are performed for the KA2030 scenario taken from KCD2020 [2]. The choice for using this scenario is because it can be seen as a reference scenario, being based on numbers from the Dutch climate agreement [20]. The new installed capacities for this scenario are discussed in section 3.2.5.

For the KA2030 scenario it is investigated what the power flow within the transmission network will be if electrolysers are introduced at locations that are close to new offshore wind connections. The choice of locations is based on a publication by Netbeheer Nederland [13] and are illustrated in figure 4.1. The following locations will be investigated: Eemshaven (EEM380), Borrsele (BSL380) and Maasvlakte (MVL380).

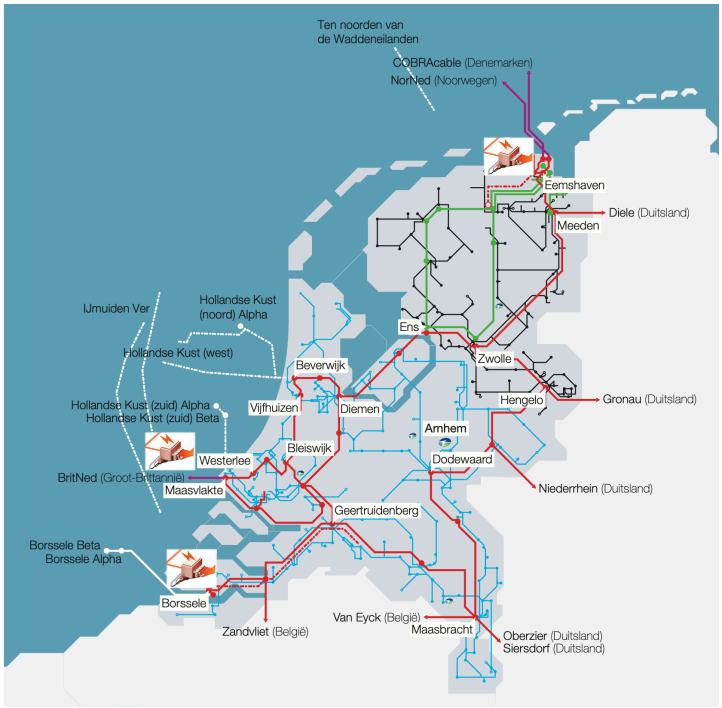


Figure 4.1: Illustration of the locations of electrolysers, grid map from Tennet adjusted with electrolysers (picture of electrolysers taken from TSO2020 website) [**TS02020**] [49]

For the investigated case(s) different distributions of the electrolysers are assumed. The total amount of installed capacity of the electrolysers is set to 10 MW. The motivation for this number is based on the most ambitious scenario used in KCD2020 which assumes a maximum installed capacity of 8.3 GW and a total maximum peak demand nationally of 26 GW [2]. For the case study, the total installed capacity of VRES is assumed to be 43 GW (25 GW solar and 18 GW wind) following the KA30 scenario in KCD2020 [2]. The total demand is varied between a low demand of 12 GW [36] and an expected peak demand of 21GW [14]. Adding a total installed capacity of 10 GW of electrolysers, this gives a maximum demand of 31 GW. (which will be investigated in one extreme case C).

4.2. Methodology

The approach was to first choose the most extreme cases (providing the biggest insights of VRES consequences) to be further studies. A case includes variations of generation, demand and imports or exports. For each case, 7 scenarios were created to investigate different distributions of the electrolysers among 3 exisiting locations, which is further explained in section 4.5.1. For each of these scenarios, first a power flow simulation was run to see if the system would converge. If multiple scenarios within a case did not converge, the case was adjusted for lower or alternative dispatches (based on an investigation into the reason for non convergence). If multiple scenarios converged, an initial power flow analysis was done investigating regional flows, grid losses and components loadings. This initial power flow was also used as a base for an OPF(Optimal Power Flow)[1] study and a CA (Contingency Analysis)[2] study. The OPF study was used to investigate redispatches while the CA study was used to see if any components on the national EHV ring would become loaded above 70% in case of failure of another component (for n-1 security). Using these insights a comparison was made between the different scenarios and the best scenario was selected for the specific case. In the end all the different ”best scenarios” of the different cases were compared to reach a final conclusion on the optimal distribution of electrolysers. A flowchart of the approach for each case is given in figure 4.2.

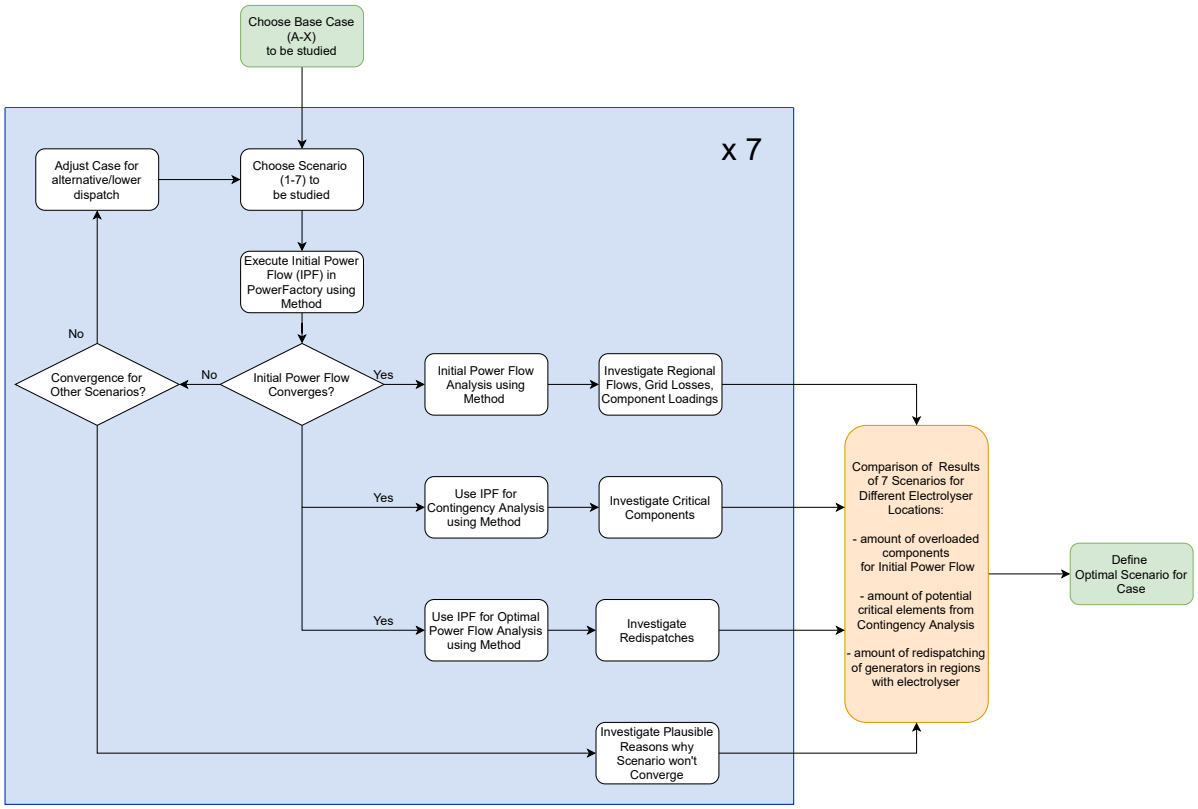


Figure 4.2: Approach for Simulations of Case Study

[1] for total system cost minimization
[2] for n-1 contingency cases for the whole system

4.3. Description of Cases

For the operational scenarios different combinations of VRES generation, demand and electrolyser distribution are considered. In all cases the Netherlands is assumed to be self-sufficient. This was chosen as it is expected that in the future 70% of the main transmission network transfer capacity should become available for the market (and thus also for cross-border power flows) [50]. Using these cases as a base it is possible to add transit flows using the interconnections. It is most insightfull to investigate situations that will heavily load the EHV network (hence not cases where VRES generation and flexible backup are brought closer to demand). The different cases that were chosen to be investigated are the following:

1. Case A: Wind as only source of electricity generation for a high demand
2. Case B: Solar as only source of electricity generation for a high demand
3. Case C: A mix of high wind and some solar generation during peak demand
4. Case D: Mix of wind and solar for average winter capacity factors for high demand
5. Case E: Mix of wind and solar for average summer capacity factors for high demand
6. Case F: No VRES generation, average demand and self-supplying
7. Case G: No VRES generation, peak demand and full use of interconnections

Three base cases were created where there are no electrolysers used and the generation and demand of the national system is balanced. These are cases: A0 for only wind generation, B0 for only solar generation and C0 for a mix of solar and wind generation. The Dutch transmission system is assumed to be self-sufficient so interconnections are disabled.

Next, 5 cases (A-E) were created which each have 7 scenarios in which different distributions for the electrolysers are considered, explained further in section 4.5.1. For these scenarios the generation of VRES exceeds the amount of demand, so electrolysers are used for P2x generation.

Besides this, cases F and G were introduced to investigate a situation of no VRES production (for example during a 'dunkelflaute'). Case F represents a day when there is a demand of 12GW and the amount of backup generation is sufficient to meet the demand. Case G is a more extreme scenario, where there is a peak demand of 21 GW during times of no VRES production. In this case the interconnections are used to their full capacity. For both these cases electrolysers are not used, therefore only 1 scenario is investigated.

An overview of the characteristics of the different cases is presented in table 4.1. In the first column, key words describing the case are given. In the second and third column, the percentage of the total installed capacity dispatched in the different scenarios for wind and solar generation is listed. In the following columns, it is indicated whether is dispatch of conventional generation (Conv Gen), interconnection capacities being used for import (IC import) or export (IC export) and whether there is electrolyser demand (P2x. Demand), where Y=Yes and N=No.

Table 4.1: Description of cases
Conv.Gen: Conventional Generation, IC: Interconnections, P2x Dem. = Electrolyser Demand

Case Type	Case Description	Solar (%)	Wind (%)	Conv Gen	IC import	IC export	P2x. Demand
A0	base case, only wind, no IC	0	87	N	N	N	N
B0	base case, only solar, no IC	65,5	0	N	N	N	N
C0	base case, mix solar and wind, no IC	18	90	N	N	N	N
A1-7	electrolyser cases, only wind, no IC	0	100	N	N	N	Y
B1-7	electrolyser cases, only solar, no IC	91	0	N	N	N	Y
C1-7	electrolyser cases, mix solar and wind , no IC	52	100	N	N	N	Y
D1-7	electrolyser cases, mix solar and wind , no IC	15	80	N	N	N	Y
E1-7	electrolyser cases, mix solar and wind , no IC	60	30	N	N	N	Y
F1	no VRES production, no IC, backup generation	0	0	Y	N	N	N
G1	no VRES production, IC, backup generation	0	0	Y	Y	N	N

Table 4.2 lists the active power dispatch for solar generation, wind generation, and conventional generation. Also the regional demand, electrolyser demand, import and exports using interconnections

are given. In the second to last column the systems active power balance is given when electrolyser demand is disregarded. The last column shows the total amount of active power grid losses.

The dispatching of the generators is done proportionally to the installed capacity, giving all generators of the same technology type the same loading. For example, for 16,2 GW of wind powered generation in case A0, the active power dispatch of all wind generators is 65.5% of their nominal installed capacity. The regional demand is divided among the regions according to the peak demand region, as described in section 3.2.5. The electrolyser demand is distributed according to the scenario number (1-7).

Table 4.2: Description of cases.
Conv.Gen: Conventional Generation, IC: Interconnections, P2x Dem. = Electrolyser Demand

Case Type	Solar (GW)	Wind (GW)	Conv. Gen. (GW)	Regional Demand (GW)	P2x. Dem. (GW)	Import (-)/ Export (+) (GW)	Gen. - Dem. (GW)	Active Power Surplus (GW)
A0	0,0	16,2	0,0	16,0	0,0	0,0	0,2	0,2
B0	16,2	0,0	0,0	16,0	0,0	0,0	0,2	0,2
C0	4,5	16,7	0,0	21,0	0,0	0,0	0,2	0,2
A1-7	0,0	18,6	0,0	12,0	6,5	0,0	6,6	0,1
B1-7	22,5	0,0	0,0	12,0	10,0	0,0	10,5	0,5
C1-7	12,9	18,6	0,0	21,0	10,0	0,0	10,5	0,5
D1-7	3,7	14,9	0,0	16,0	2,5	0,0	2,6	0,1
E1-7	14,9	5,6	0,0	16,0	4,2	0,0	4,4	0,2
F1	0,0	0,0	12,7	12,0	0,0	0,0	0,7	0,7
G1	0,0	0,0	21,4	21,0	0,0	-10,8	-10,6	0,2

4.4. Extra Transit Flow Cases

To investigate the effect of different possible transit flows, simulations are done for modified versions of case C. These cases were added to see how the addition of electrolysers could potentially help alleviate the transmission system in case of large transit flows. Currently, the Dutch Transmission System often has to facilitate large power flows from Germany through the Dutch EHV network to the West of Belgium (even going on to France) [51] [52]. This can lead to critical parts of the national ring being overloaded [51]. In the future it is expected that the amount of cross-border power flows will only increase. According to the development plans, it is likely that large exports of electricity will occur from Great Britain and the Nordics to the Continent. This is mainly due to the expected increase in offshore wind capacities in these countries. As the generation portfolio of more central continental countries is less focused on offshore wind and more on nuclear (France), solar or gas-powered generation (other central European countries), the expected direction will be from North to South/more inland [51].

Overview

A base case X was created without transit flows. Six cases were created to investigate different transit flows: North to South, West to East, Both and vice versa. An overview of the different imports and exports through different connections for each case is given below in table E.5.

Table 4.3: Cross-border power flows considered for each of the transit flow cases in MW

Name in PowerFactory	Country	Max. Capacity (MW)	X (MW)	NZ (MW)	ZN (MW)	WE (MW)	EW (MW)	ALL (MW)	ALLR (MW)
IC_AMPRION_GNA380	Germany	750	0	0	0	0	0	0	0
IC_AMPRION_NDR380	Germany	1500	0	0	0	800	-800	400	-400
IC_AMPRION_OBZ380(SDF380)	Germany	750	0	500	-500	0	0	500	-500
IC_BritNed_MVL380	United Kingdom	1000	0	0	0	-800	800	-900	900
IC_COBRA_EOS380	Denmark	700	0	-500	500	0	0	-600	600
IC_ELIA_MBT380	Belgium	1700	0	1000	-1000	0	0	1500	-1500
IC_ELIA_ZVL380	Belgium	1700	0	1000	-1000	0	0	1500	-1500
IC_StatNett_EEM380	Norway	700	0	-500	500	0	0	-600	600
IC_TenneT_DIL380	Germany	2000	0	-1500	1500	0	0	-1800	1800

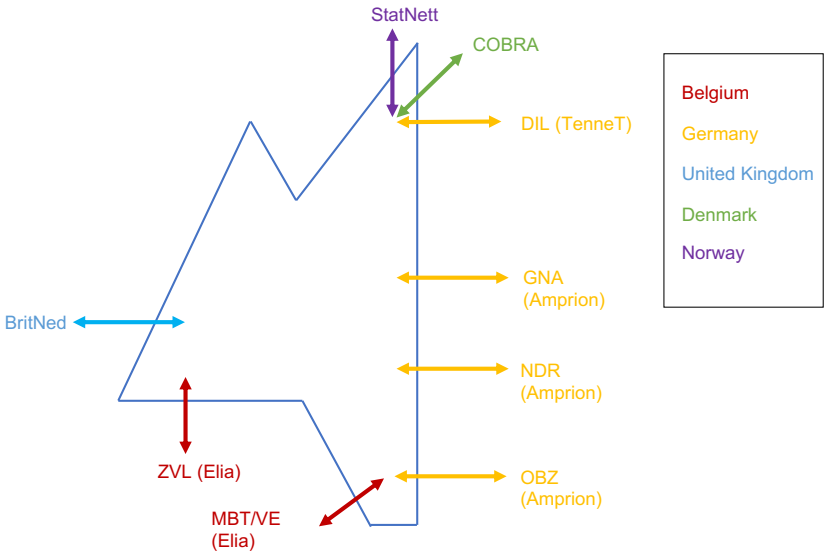


Figure 4.3: Illustration of cross-border electrical interconnections

The cases were modified from Case C to have a demand of 16 GW instead of a peak demand of 21 GW. The amount of solar production and wind production were adjusted to 38% and 90% respectively. In the same manner as for the initial cases, 7 different distribution scenarios were investigated for each transit case for a total demand of 10 GW for the electrolysers. An overview of the characteristics of the different cases is presented in table 4.4. In the first column, key words describing the case are given. In the second and third column, the percentage of the total installed capacity dispatched in the different scenarios for wind and solar generation is listed. In the following columns, it is indicated whether is

dispatch of conventional generation (Conv Gen), interconnection capacities being used for import (IC import) or export (IC export) and whether there is electrolyser demand (P2x. Demand), where Y=Yes and N=No.

Table 4.4: Description of cases with added transit flows.
Conv.Gen: Conventional Generation, IC: Interconnections, P2x Dem. = Electrolyser Demand

Case Type	Case Description	Solar (%)	Wind (%)	Conv Gen	IC import	IC Export	P2x. Demand
X1-7	electrolyser cases, no transit flows	38	90	N	N	N	Y
NZ1-7	electrolyser cases, transit flow North to South	38	90	N	Y	Y	Y
WE1-7	electrolyser cases, transit flow West to East	38	90	N	Y	Y	Y
ALL1-7	electrolyser cases, transit flow N-S, W-E	38	90	N	Y	Y	Y
ZN1-7	electrolyser cases, transit flow South to North	38	90	N	Y	Y	Y
EW1-7	electrolyser cases, transit flow East to West	38	90	N	Y	Y	Y
ALLR1-7	electrolyser cases, transit flow S-N, E-W	38	90	N	Y	Y	Y

Table 4.5 lists the active power dispatch for solar generation, wind generation, and conventional generation. Also the regional demand, electrolyser demand, import and exports using interconnections are given. In the second to last column the systems active power balance is given when electrolyser demand is disregarded. The last column shows the total amount of active power grid losses.

Table 4.5: Description of cases with added transit flows

Case Type	Solar (GW)	Wind (GW)	Conv. Gen. (GW)	Regional Demand (GW)	P2x. Dem. (GW)	Import (-)/ Export (+) (GW)	Gen. - Dem. (GW)	Active Power Surplus (GW)
X1-7	9,4	16,7	0,0	16,0	10,0	0,0	10,1	0,1
NZ1-7	9,4	16,7	0,0	16,0	10,0	0,0	10,1	0,1
WE1-7	9,4	16,7	0,0	16,0	10,0	0,0	10,1	0,1
ALL1-7	9,4	16,7	0,0	16,0	10,0	0,0	10,1	0,1
ZN1-7	9,4	16,7	0,0	16,0	10,0	0,0	10,1	0,1
EW1-7	9,4	16,7	0,0	16,0	10,0	0,0	10,1	0,1
ALLR1-7	9,4	16,7	0,0	16,0	10,0	0,0	10,1	0,1

4.5. Additional Modelling for 2030 Scenarios

In this section the modelling of the electrolysers as well as the newly introduced approach for reactive power is discussed.

4.5.1. Electrolysers

The electrolysers are modelled as extra loads added to the busbars mentioned above. For each of the cases where there is an excess of generation electrolysers are used for P2x production. The locations where the electrolysers are added to the model are given in table 4.6.

Table 4.6: Overview of locations for introduction of electrolysers

PowerFactory Name	Terminal	Zone
Electrolyser_EEM380	EEM380	Groningen and Drenthe 380kV
Electrolyser_MVL380	MVL380	Zuid-Holland 380kV
Electrolyser_BSL380	BSL380	Zeeland 380kV

For Case numbers 1-7 different distributions of a total installed capacity of 10 MW are investigated. An overview of the distribution per case is given in table 4.7. Note that the actual dispatch settings for the electrolysers may be lower than the full capacity of 10 GW.

Table 4.7: Distribution of Installed Capacities for Electrolysers

PowerFactory Name	Unit	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
Electrolyser_EEM380	GW	0	10	0	3,3	5	5	0
Electrolyser_MVL380	GW	0	0	10	3,3	0	5	5
Electrolyser_BSL380	GW	10	0	0	3,3	5	0	5

4.5.2. Reactive power control for simulations

For future scenarios with high levels of variable renewable energy generation, different sources of reactive power control are needed [53]. In a scenario where 100% of the electricity supply is VRE based, the conventional generators will not be able to provide reactive power control. Although the initial model has transformers with adjustable taps as well as switchable shunt reactors and capacitors this will not suffice for the amount of reactive power needed in the 2030 model. The need for added reactive power control is also due to the introduction of the extra impedance in the HV areas mentioned in 3.2.9, to mitigate the parallel flows that occurred in the initial simulations.

For the reactive power compensation it is assumed STATCOMs are present at the locations of offshore wind farms as well as at HV busbars. Instead of introducing extra static generators in the model, the assumption is made that selected VRE units are also able to supply reactive power within their operational limits of +-1 p.u. The VRE units that participate in reactive power control are solar generators located at 110/150 kV busbars and selected offshore wind farms (SOW) at 220/380 kV busbars. The motivation to not just select all VRE units is that only one generator is allowed to control a busbar. In this model different offshore wind farms are connected to the same busbars. The same is true for solar and wind generators in HV regions. A list of the SOW farms is given in table 4.8.

Table 4.8: List of Selected Offshore Wind (SOW) generators, chosen to represent STATCOMs

Generator Name in PowerFactory	Busbar
Gen_WOZ_HKW	BVW380
Gen_WOZ_IJMA	BSL380
Gen_WOZ_IJMB	MVL380
Gen_WOZ_TNW	VVL380
Gen_WOZ_EOS380_2	EOS380

A table of the reactive power settings for power flow analysis is given in table 4.9. For the initial power flow (PF) settings, *constv* means that the generator controls the voltage level by adjusting reactive

power dispatch whereas *constq* means the generator does not participate in voltage control.

A table of the reactive power settings for optimal power flow anlaysis (OPF) is given in table 4.10.*P* indicates active power participation for OPF (within generator limits defined) and *Q* reactive power participation. *SOW* stands for ”selected offshore wind” which are certain offshore wind farms that are also chosen to participate in reactive power control. Settings regarding the participation in active and reactive redispatching for OPF are automatically adjusted for each of the operational scenarios when using the python script. This is necessary because the settings for participation of a generator for optimal power flow is saved system wide and not per operational scenario.

Table 4.9: Reactive Power Settings for generators for Power Flow Analysis, where SOW = selected offshore wind farms, ”-” indicates that these generators do not participate

Technology for Dispatch	Solar Generators	Wind Generators	SOW Generators	Conventional Generators
Only Solar and Wind	constv	constq	constv	-
Only Solar	constv	constq	constv	-
Only Wind	constv	constq	constv	-
Also Conventional	constq	constq	constv	constv

Table 4.10: Reactive Power Settings for generators for Optimal Power Flow simulations, where SOW = selected offshore wind farms, ”-” indicates that these generators do not participate

Technology for Dispatch	Solar Generators	Wind Generators	SOW Generators	Conventional Generators
Only Solar and Wind	P,Q	P	P,Q	-
Only Solar	P,Q	-	Q	-
Only Wind	Q	P	P,Q	-
Also Conventional	-	-	Q	P,Q

4.6. Results of Case Study

In this section a brief summary of the results of the different case studies is given. More details and discussions about the results can be found in appendix E. For each of the scenarios (1-7) belonging to a case (A-Z) three different analyses were performed: power flow (PF), optimal power flow (OPF) and a contingency analysis (CA). For each of these types of analysis, visual diagrams can be used to illustrate the results, as is illustrated in figure 4.4. An explanation of the visual diagrams used in the discussion is given in section 3.2.6.

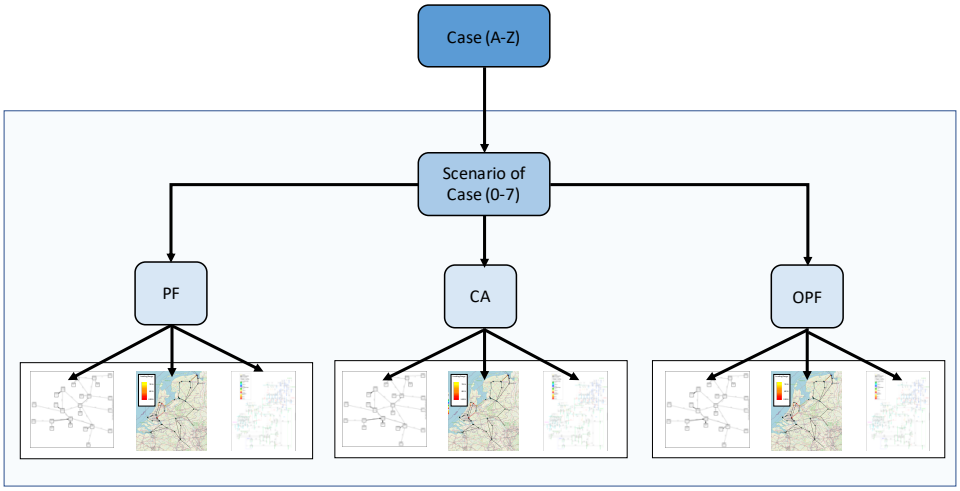


Figure 4.4: For each case, different scenarios were investigated (for different electrolyser distributions or transit flows as explained in section 4.3). For each of these scenarios, 3 analysis were performed: power flow analysis (PF), optimal power flow analysis (OPF) and contingency analysis (CA), the results will be explained according to three diagrams

4.6.1. Case A: Only Wind Generation

Table 4.11: Description of case A. Conv.Gen: Conventional Generation, Import/Export: Interconnections, P2x Dem. = Electrolyser Demand. Gen. - Dem = The amount of national generation minus the amount of regional demand. The active power surplus is used to balance the grid losses. All values are for Active Power (P) in (GW).

Case Type	Solar (GW)	Wind (GW)	Conv. Gen. (GW)	Regional Demand (GW)	P2x. Dem. (GW)	Import (-)/ Export (+) (GW)	Gen. - Dem. (GW)	Active Power Surplus (GW)
A0	0,0	16,2	0,0	16,0	0,0	0,0	0,2	0,2
A1-7	0,0	18,6	0,0	12,0	6,5	0,0	6,6	0,1

For scenarios A0-7 (with high wind powered generation) large transport of electricity can be seen from offshore wind farms towards more inland connections. This leads to large power flows between different 220/380kV connections. Especially large exports can be seen from the regions of Zeeland to Brabant. As most of the generation is located at 220/380kV parts of the network, there are also large power flows from 220/380 kV regions to 110/150 kV regions. An example of this is shown in the regional flow diagram for scenario A4 in figure 4.5. For this scenario there is an electrolyser demand of 6.5 GW evenly distributed over the locations of Eemshaven, Maasvlakte and Borrsele.

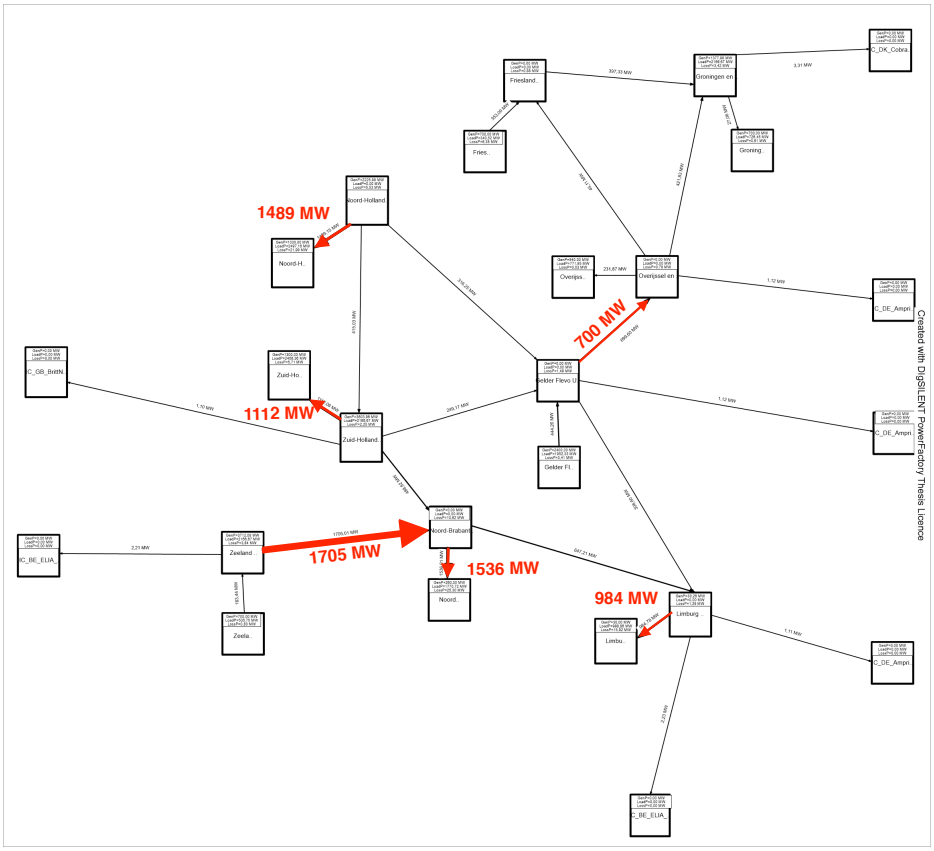


Figure 4.5: Regional Power Flow Diagram for Initial Power Flow for Electrolysers at Eemshaven, Maasvlakte and Borssele - Scenario A4

Contingency analysis shows that the most beneficial situation for distribution of the electrolysers is when the electrolysers are evenly distributed over the three locations. This is for a total electrolyser demand of 6.5 GW demand, so 2.17 GW demand at each location. In that scenario (A4) no elements on the national ring are identified as loaded above 70% for n-1 security, as is shown in figure 4.6.

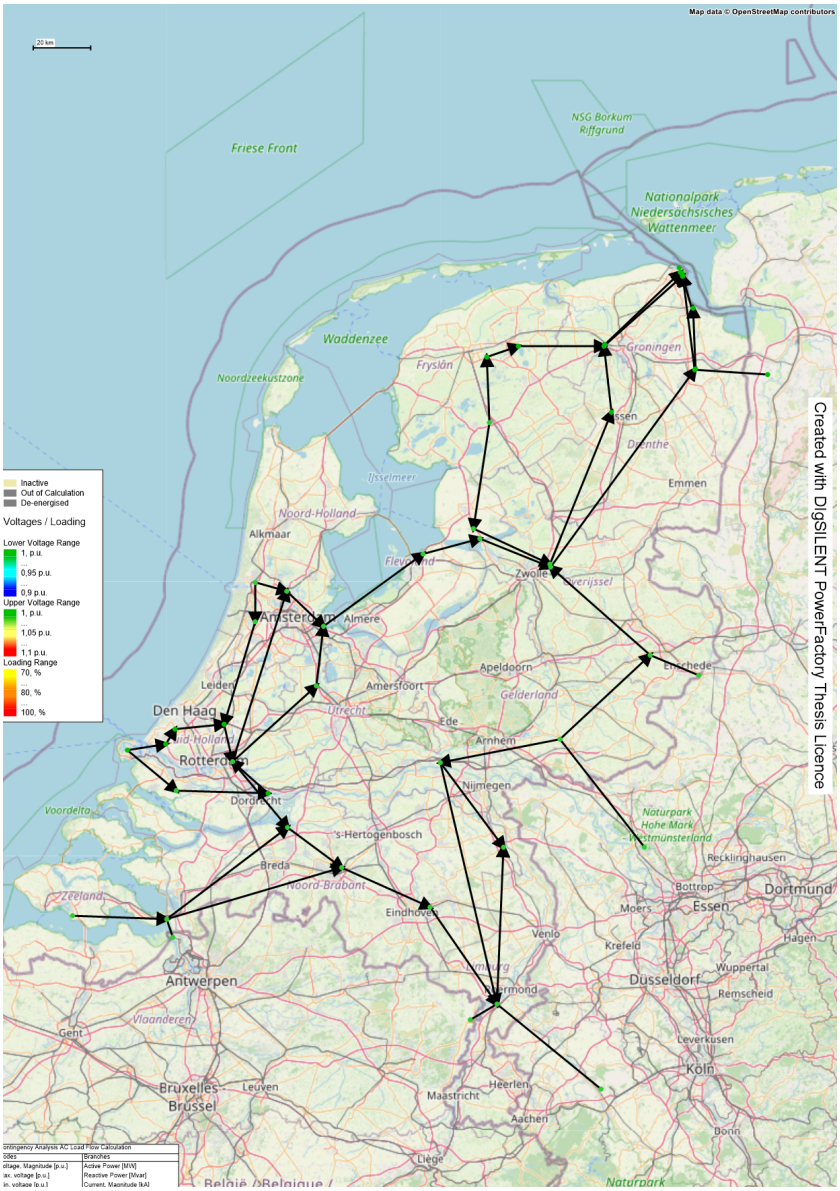


Figure 4.6: Geographical Diagram of the Contingency Analysis for Electrolysers at EEM380, MVL380 and BSL380 - Case A4

By introducing electrolyser demand at Borrsele, it is possible to control the power flow between Zeeland and Brabant, leading to a decreased loadings of these connections. When there is only a single electrolyser located at Borssele of 6.5 GW, there is a power flow of 2.6 GW in the direction of Brabant to Zeeland (in the investigated scenarios of a low national demand of 12GW). When equal distribution among the three locations of Eemshaven, Maasvlakte and Borssele is assumed (for an electrolyser demand of 2.18 GW in Borrsele), there is a power flow of 1,7 GW in the direction of Zeeland to Brabant.

4.6.2. Case B: Only Solar Generation

Table 4.12: Description of case B. Conv.Gen: Conventional Generation, Import/Export: Interconnections, P2x Dem. = Electrolyser Demand. Gen. - Dem = The amount of national generation minus the amount of regional demand. The active power surplus is used to balance the grid losses. All values are for Active Power (P) in (GW).

Case Type	Solar (GW)	Wind (GW)	Conv. Gen. (GW)	Regional Demand (GW)	P2x. Dem. (GW)	Import (-)/ Export (+) (GW)	Gen. - Dem. (GW)	Active Power Surplus (GW)
B0	16,2	0,0	0,0	16,0	0,0	0,0	0,2	0,2
B1-7	22,5	0,0	0,0	12,0	10,0	0,0	10,5	0,5

Considering the case of only solar generation B0-7, different results are visible than for case A. For the base scenario B0 without electrolysers, a large transport can be seen from the North of the Netherlands from to the South due to a larger amount of solar generation being installed in the North.

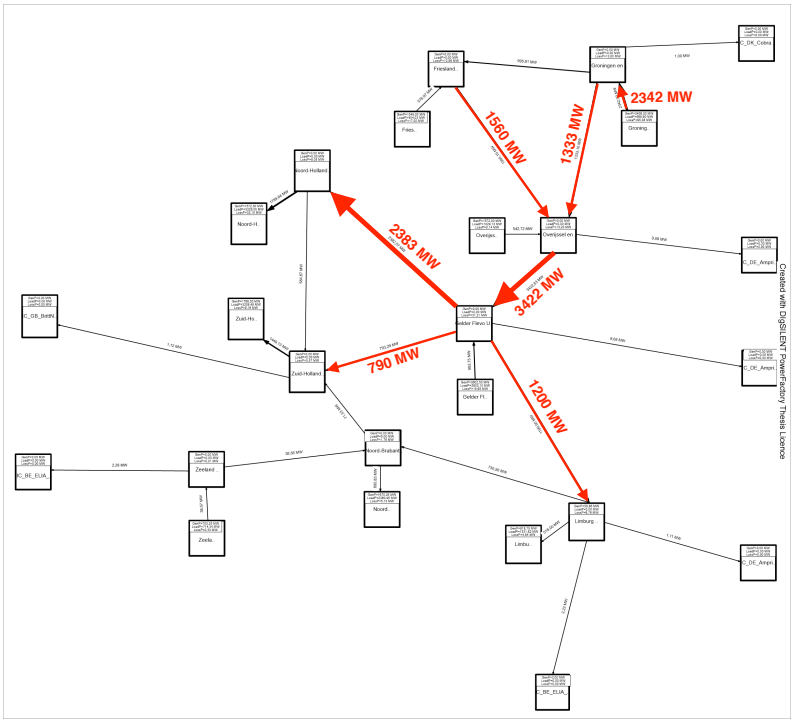


Figure 4.7: Regional Power Flow Diagram for Initial Power Flow Analysis for Initial Scenario B0 with no Electrolysers. High Active Power Flows from North to South can be seen

For the scenarios with 10 GW electolyser demand, the amount of power being exported from the HV region to the EHV region of Groningen & Drenthe leads to undervoltages in the area (of up to approximately 0.9 p.u.). This is due to the high amount of installed capacity of solar generation in Groningen & Drenthe combined with a low demand and insufficient transformer capacity between the HV and EHV parts of the network. An example of this is shown in the single line diagram of the initial power flow for scenario B4, where electrolysers are located at Eemshaven, Maasvlakte and Borssele in figure 4.8.

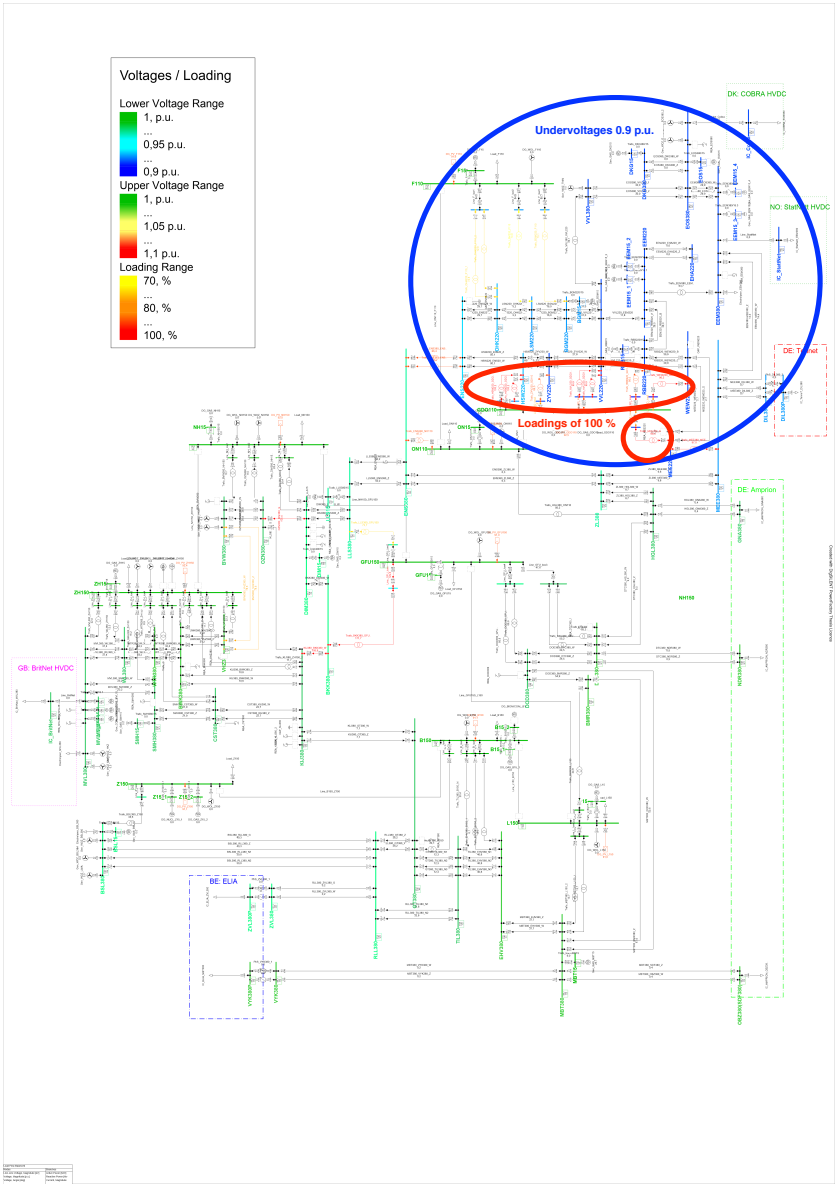


Figure 4.8: Single Line Diagram for Initial Power Flow Analysis for Electrolysers at Eemshaven, Maasvlakte and Borssele - Scenario B4. High loadings of transformers (100%) between the 110/150 kV and 220/380 kV parts of the Network in Groningen as well as low voltages (0.9 p.u.)

Alternative scenarios were created to investigate electrolyser distributions for a lower electrolyser demand of 6.5 GW and only 75% solar generation, to make a fair comparison to case A which also had only 6.5 GW of electrolyser demand. For these new scenarios optimal power flow and contingency analysis were possible. The details of the adjusted case are given below in table 4.13.

Table 4.13: Details for the Scenarios for adjusted Case B

Case Type	Solar (%)	Wind (%)	Solar (GW)	Wind (GW)	Regional Demand (GW)	Electrolyser Dem. (GW)
B1-7	91,0	0,0	22,5	0,0	12,0	10,0
B1-7*	75,0	0,0	18,6	0,0	12,0	6,5

Due to an increased total demand of 6.5 GW (because the added electrolyser demand) there is increased active power flow between different regions compared to the base scenario B0 (for B0 the regional power flows are shown in figure 4.7). When there is at least one electrolyser located at MVL380, the system experiences the least amount of undervoltages. The most favourable scenario is B6* where electrolysers are distributed over MVL380 and EEM380. For this scenario, the highest loading of a transmission line is between Oostzaan and Diemen (NH) which is loaded to 71,9%. The transformers connecting BKK380 to GFU150 are highly loaded indicating the need for more transfer capacity. Besides this transformers between the EHV and HV region of GD are loaded to 80%. The largest power flows between EHV regions in this scenario is between the center of the Netherlands (GFU) and Noord-Holland of around 1800 MW, shown in figure 4.9.

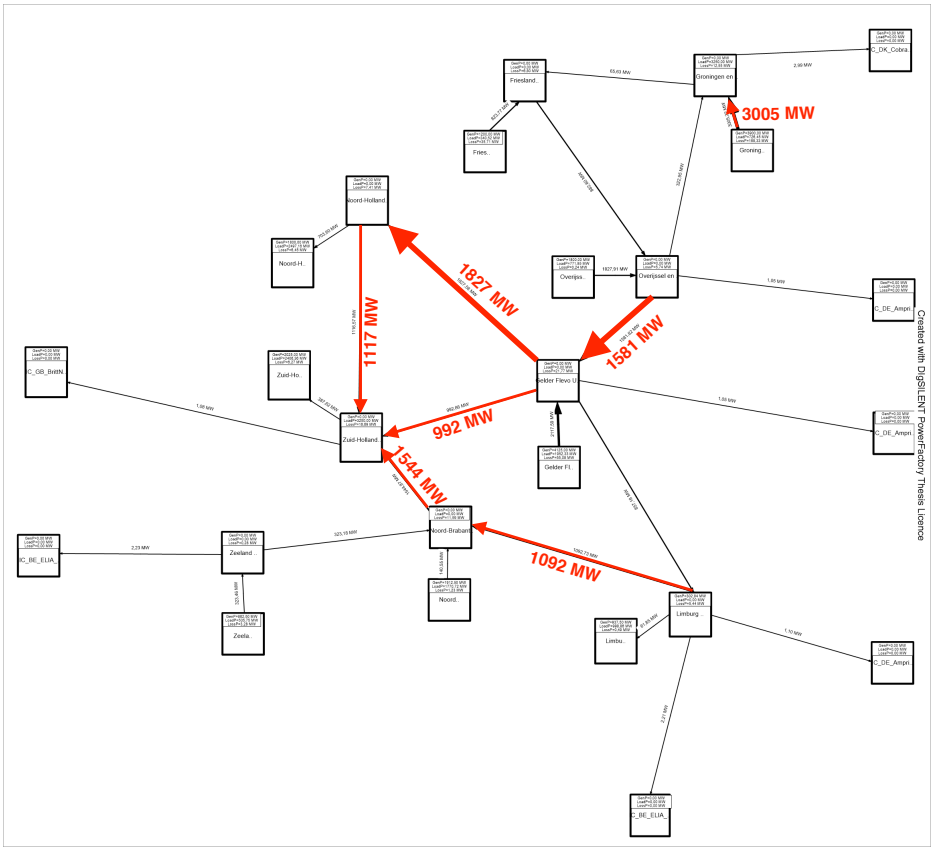


Figure 4.9: Regional Power Flow Results for Initial Power Flow for Electrolyser Demand of 3.25 GW at Eemshaven and 3.25 GW at Maasvlakte - Scenario B6*

Contingency Analysis for the adjusted scenario B6 indicates that parts of the ring can become overloaded between the areas of GFU-NH-ZH such as OZN-DIM and KIJ-BKK for specific connections due to the large power flow going from the North to the South West (to Maasvlakte). This is also the case for the connection BVW-VHZ, KIJ-BKK and between NH-ZH which is loaded to 87%. The results of the contingency analysis is given in figure 4.10.

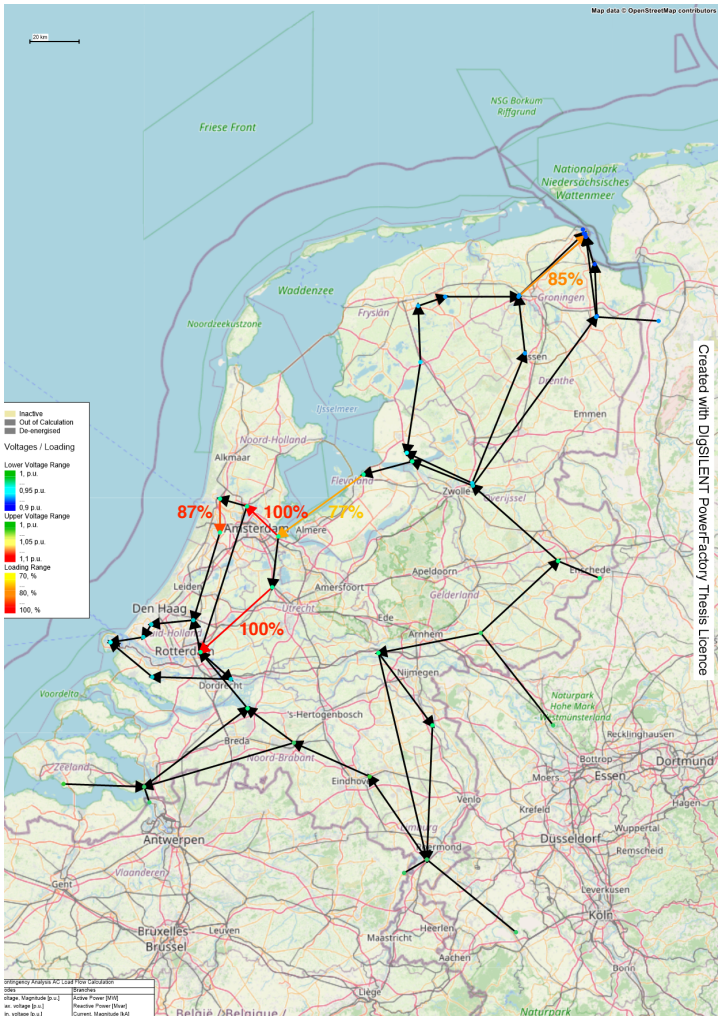


Figure 4.10: Geographical Diagram for Contingency Analysis for Electrolyser Demand of 3.25 GW at Eemshaven and 3.25 GW at Maasvlakte - Adjusted Scenario B6

When Optimal Power Flow analysis is done for these scenarios, the system redispatches the solar generation to more Southern Regions. Especially in the areas of Groningen & Drenthe (GD), Friesland (F), Gelderland, Flevoland & Utrecht (GFU) and Overijssel & Noordoostpolder (ON) the amount of generation declines. The results for these regions for two adjusted scenarios B4 and B6 are presented in figure 4.14. In other regions the dispatch of solar generation is increased to between 92-98 % of total installed capacity. The reason for these redispatches is that there is more generation than demand in the Northern regions whereas in the Southern regions the demand is higher than the generation. The reason for this imbalance is because the dispatch of the solar generation is done according to the amount of installed capacity in each region (loading all regions to 75% of their total installed solar capacity for the normal power flows, assuming the sun shines equally bright in all regions).

Table 4.14: OPF new dispatches of solar generation in % of total installed capacity for northern regions for adjusted Cases B4* and B6*

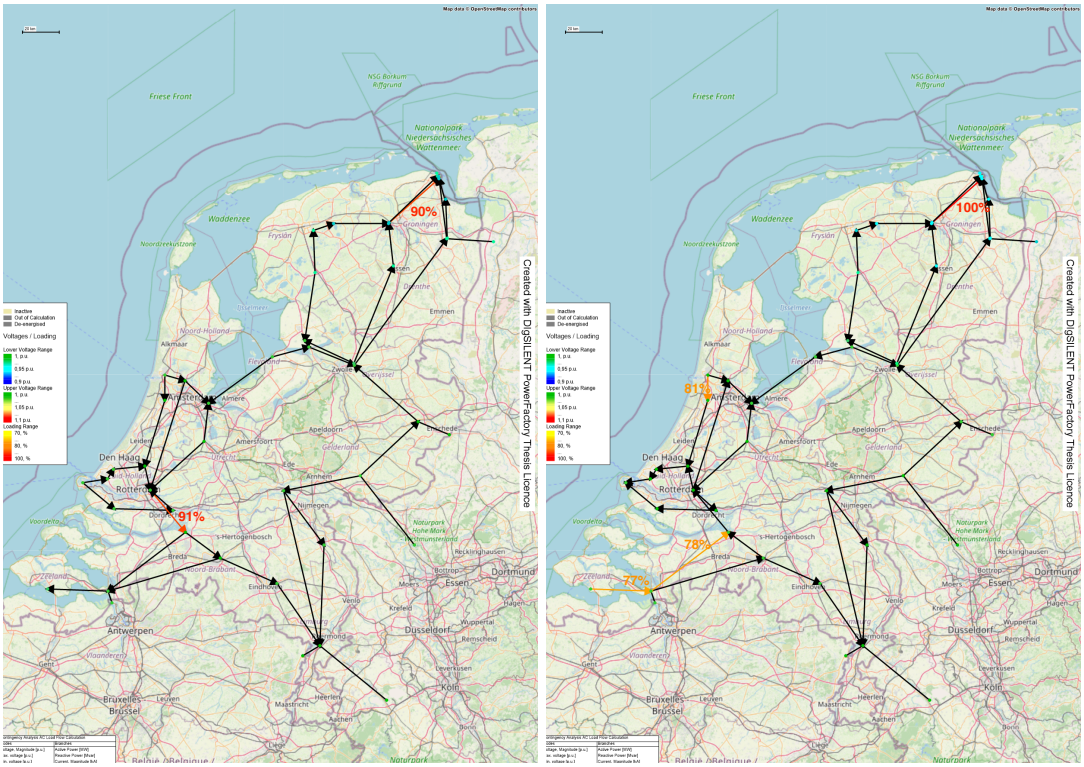
Electrolyser Location	P2x Dem. (MW)	Case Number	F (%)	GD (%)	GFU (%)	ON (%)
EEM, MVL, BSL	6500	B4*	52	45	56	81
MVL, EEM	6500	B6*	54	45	59	76

4.6.3. Case C: Mix of Solar and Wind

Table 4.15: Description of case C. Conv.Gen: Conventional Generation, Import/Export: Interconnections, P2x Dem. = Electrolyser Demand. Gen. - Dem = The amount of national generation minus the amount of regional demand. The active power surplus is used to balance the grid losses. All values are for Active Power (P) in (GW).

Case Type	Solar (GW)	Wind (GW)	Conv. Gen. (GW)	Regional Demand (GW)	P2x. Dem. (GW)	Import (-)/ Export (+) (GW)	Gen. - Dem. (GW)	Active Power Surplus (GW)
C0	4,5	16,7	0,0	21,0	0,0	0,0	0,2	0,2
C1-7	12,9	18,6	0,0	21,0	10,0	0,0	10,5	0,5

In this case a mix of solar and wind powered generation is considered. The most ideal location of the Electrolyser is either in Eemshaven and Borssele (case C5) or in Maasvlakte and Eemshaven (case C6) according to initial power flows, as only these two cases show no component loadings above 70%. The results for these cases for the contingency analysis are shown in figure E.12. For a more detailed discussion see appendix E.



(a) Geographical Diagram for Contingency Analysis for Electrolysers at Eemshaven and Borssele - Scenario C5

(b) Geographical Diagram for Contingency Analysis for Electrolysers at Eemshaven and Maasvlakte - Scenario C6

Figure 4.11: Contingency Analysis Results in Geographical Diagram for Scenarios C5 and C6

Case C is especially interesting for optimal power flow analysis as solar and some selected wind generators can participate in the redispatch. For the initial power flow wind generation was dispatched at 100 % while solar generation was dispatched at 52%, general demand was set to 21GW and electrolyser demand at 10GW. In general, the loading of all the wind farms are decreased while the dispatch of the solar generation is increased for regions with a high demand, especially in Noord-Holland (NH), Zuid-Holland (ZH), Limburg (L) and Brabant (B). In Groningen & Drenthe (GD) , Friesland (F), as well as in Gelderland,Flevoland & Overijssel (GFU) the amount of solar generation is lowered for all locations of the electrolyser. For some regions such as Zeeland (Z), whether the amount of solar generation dispatched is increased or decreased relies on whether there is an electrolyser located at Maastvlakte.

4.6.4. Case D: Average Winter VRES

Table 4.16: Description of case D. Conv.Gen: Conventional Generation, Import/Export: Interconnections, P2x Dem. = Electrolyser Demand. Gen. - Dem = The amount of national generation minus the amount of regional demand. The active power surplus is used to balance the grid losses. All values are for Active Power (P) in (GW).

Case Type	Solar (GW)	Wind (GW)	Conv. Gen. (GW)	Regional Demand (GW)	P2x. Dem. (GW)	Import (-)/ Export (+) (GW)	Gen. - Dem. (GW)	Active Power Surplus (GW)
D1-7	3,7	14,9	0,0	16,0	2,5	0,0	2,6	0,1

For the initial power flows, none of the scenarios show any high loaded (above 70%) components. Power Flows show similarities with Case C,as there is a high dispatch of wind and low dispatch of solar. For these scenarios both solar and wind generation can be redispatched for optimal power flow studies. For all cases the total amount of solar production is increased and the total amount of offshore wind generation is decreased to lower the loadings of different components in the network, bringing generation closer to demand. The results show a decrease in dispatch of solar generation for Northern regions Groningen & Drenthe and Friesland and an increase in dispatch of solar generation in Southern regions. This is because there is more generation in the Northern regions than demand and in the South vice versa. Even when an electrolyser is located in EEM380 (case D2) the dispatch of solar in these to regions does not exceed 12% while other regions show an increase in dispatch. As in previous scenarios the regions with the highest new dispatch of solar generation are Limburg, Noord-Holland, Brabant and Zuid-Holland.

Considering contingency analysis, there is only one scenario that shows loadings of over 70% on the national ring, scenario D2 where there is only a single electrolyser located at Eemshaven with a demand of 2.6 GW. In that case connections between ZH-GFU and NH-GFU are loaded to 75%, illustrated by the blue circles in figure 4.12. For all contingency analysis cases high loadings of transformers from EHV to HV areas can be seen for Noord-Holland, Gelderland,Flevoland & Overijssel, Brabant and Limburg in case of failure of one of the other transformers connected to the same busbar, illustrated by the red circles in figure 4.12 for scenario D2.

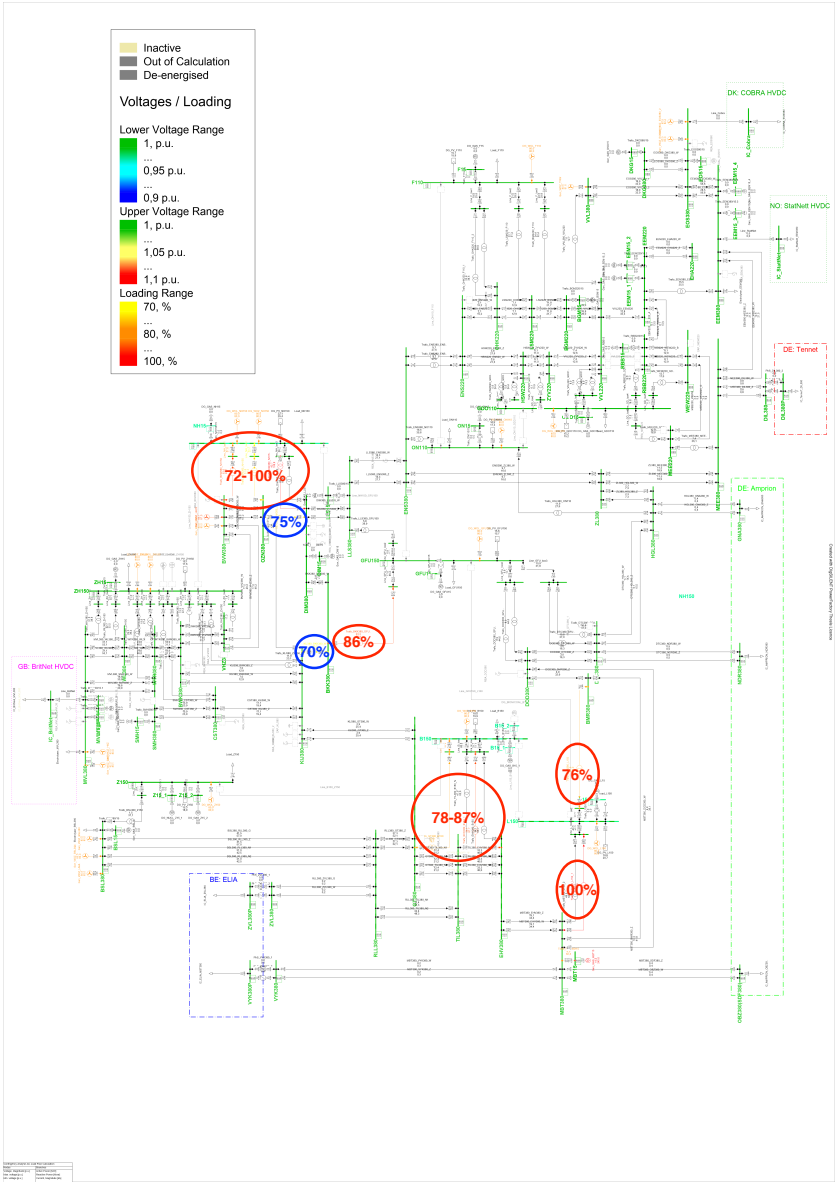


Figure 4.12: Single Line Diagram for Contingency Analysis for electrolyser at EEM380 - Scenario D2. The elements loaded above 70% of their apparent power on the national ring are circled in blue, the transformers loaded above 70% are circled in red

4.6.5. Case E: Average Summer VRES

Table 4.17: Description of case E. Conv.Gen: Conventional Generation, Import/Export: Interconnections, P2x Dem. = Electrolyser Demand. Gen. - Dem = The amount of national generation minus the amount of regional demand. The active power surplus is used to balance the grid losses. All values are for Active Power (P) in (GW).

Case Type	Solar (GW)	Wind (GW)	Conv. Gen. (GW)	Regional Demand (GW)	P2x. Dem. (GW)	Import (-)/ Export (+) (GW)	Gen. - Dem. (GW)	Active Power Surplus (GW)
E1-7	14,9	5,6	0,0	16,0	4,2	0,0	4,4	0,2

It is interesting to compare this Case to Case B1-7 (Case B1-7: only solar production of 18.6 GW, a regional demand of 12GW and electrolyser demand of 6.5 GW, see section E.2). For Case E, less power is exported from the 110/150 kV regions to the 220/380 kV regions due to a lower electrolyser demand, higher regional demand and a lower total electricity production from solar (as there is also wind generation). This leads to less overloading of transformers between the EHV and HV grid for the initial power flows.

Suprisingly, the scenario with a single electrolyser located at Eemshaven (scenario E2) now shows better results for the initial power flow, where no component is loaded above 70% of its apparent power. This result is a large contrast to other cases where a single electrolyser at Eemshaven, was not the most ideal option as initial power flows would show overloaded transformers and undervoltages in the region of Groningen & Drenthe (such as Case B, see section 4.6.2).

Overall, the best scenarios were scenario 2,5 and 6. Contingency Analysis shows no overloading of the components, except for one connection to Eemshaven in scenario E2. All these cases have in common that there is at least 50% of the electrolyser demand located in Eemshaven. For a more detailed discussion on the results of this case, see appendix chapter E section E.4.

Regional Power Flow results are shown for the best scenarios in figures 4.13,4.14 and 4.15. It can be seen that the flow direction from the North to the South can be reversed if there is an electrolyser demand of 4.4GW at Eemshaven. Also the power flow direction between Zeeland and Brabant is reversed if there is a 2.2GW demand electrolyser demand in Maasvlakte. For cases of high wind generation the dominant flow direction between Zeeland and Brabant would already be west to east due to the high production of offshore wind at Borssele.

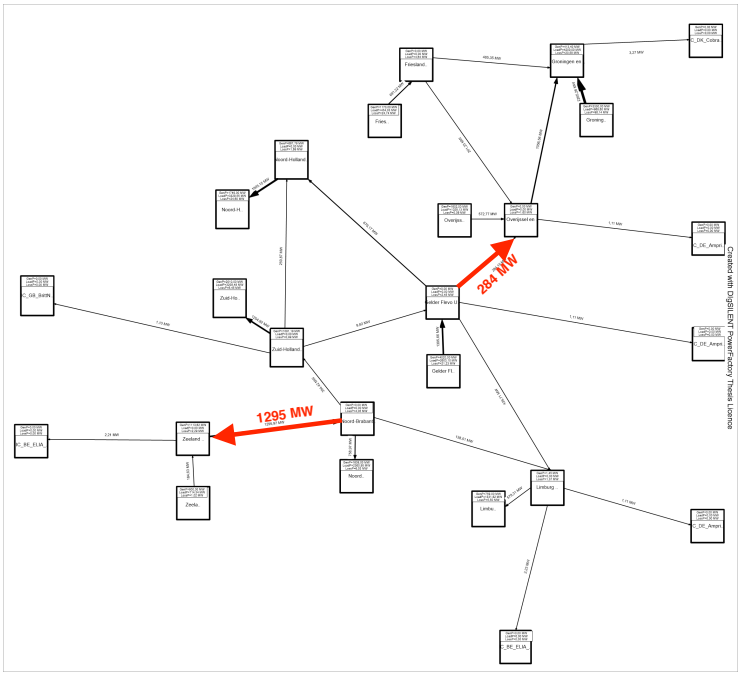


Figure 4.13: Regional Power Flows for an Electrolyser at Eemshaven - Scenario E2

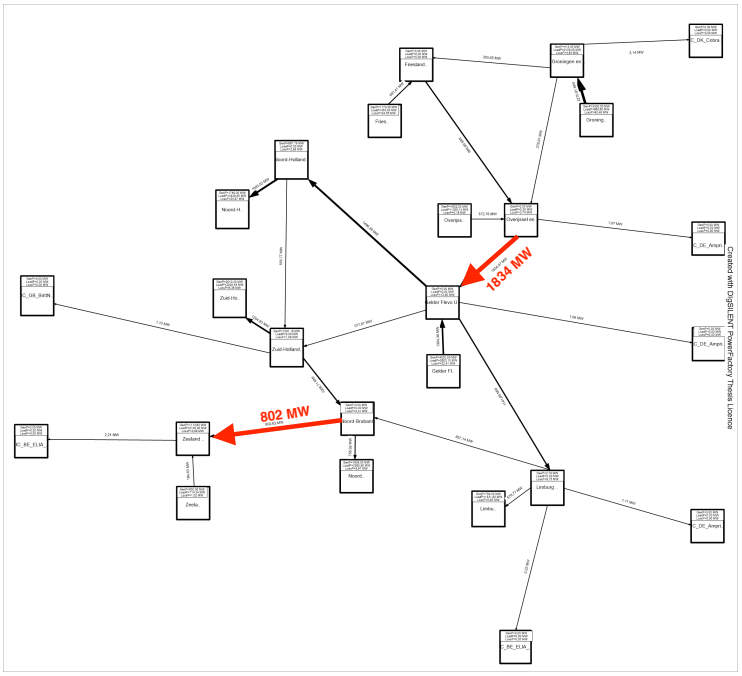


Figure 4.14: Regional Power Flows for Electrolysers at Eemshaven and Borssele - Scenario E5

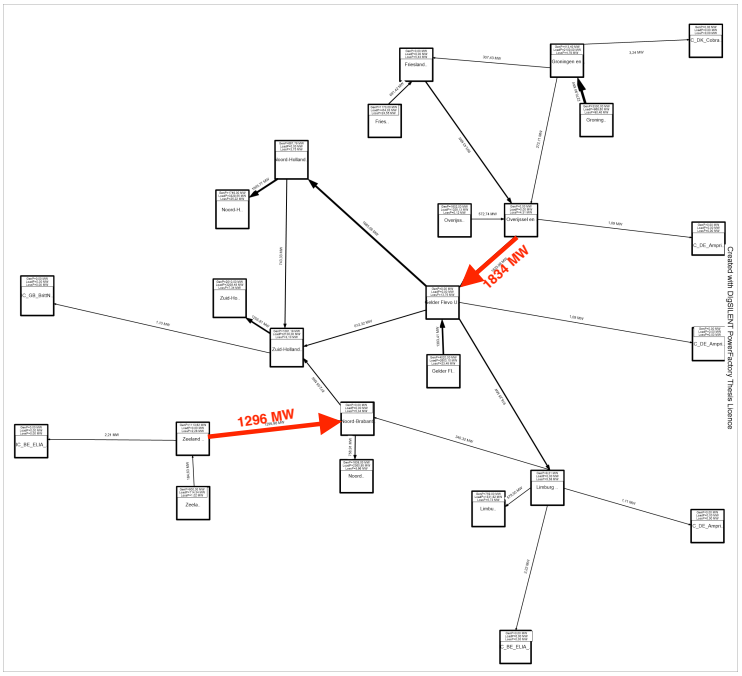


Figure 4.15: Regional Power Flows for Electrolysers at Eemshaven and Maasvlakte - Scenario E6

4.6.6. Case F: No VRES, Only Conventional Generation, Low Demand

Table 4.18: Description of case F. Conv.Gen: Conventional Generation, Import/Export: Interconnections, P2x Dem. = Electrolyser Demand. Gen. - Dem = The amount of national generation minus the amount of regional demand. The active power surplus is used to balance the grid losses. All values are for Active Power (P) in (GW).

Case Type	Solar (GW)	Wind (GW)	Conv. Gen. (GW)	Regional Demand (GW)	P2x. Dem. (GW)	Import (-)/ Export (+) (GW)	Gen. - Dem. (GW)	Active Power Surplus (GW)
F1	0,0	0,0	12,7	12,0	0,0	0,0	0,7	0,7

In case F no VRES production is considered and a demand of 12GW is met only by means of conventional back up generation. The initial power flow shows maximum transfers of around 1100 MW between different regions. The contingency analysis shows a high loading for one transformer between the EHV and HV part of Noord-Holland but no other critical elements, shown in figure 4.16. The optimal power flow shows a decline in generation dispatched in the north of the Netherlands as well as generally lower transfers of power between different EHV regions. More details on the increase or decrease in loading per generator as well as power flows between regions is given in appendix E section E.5.

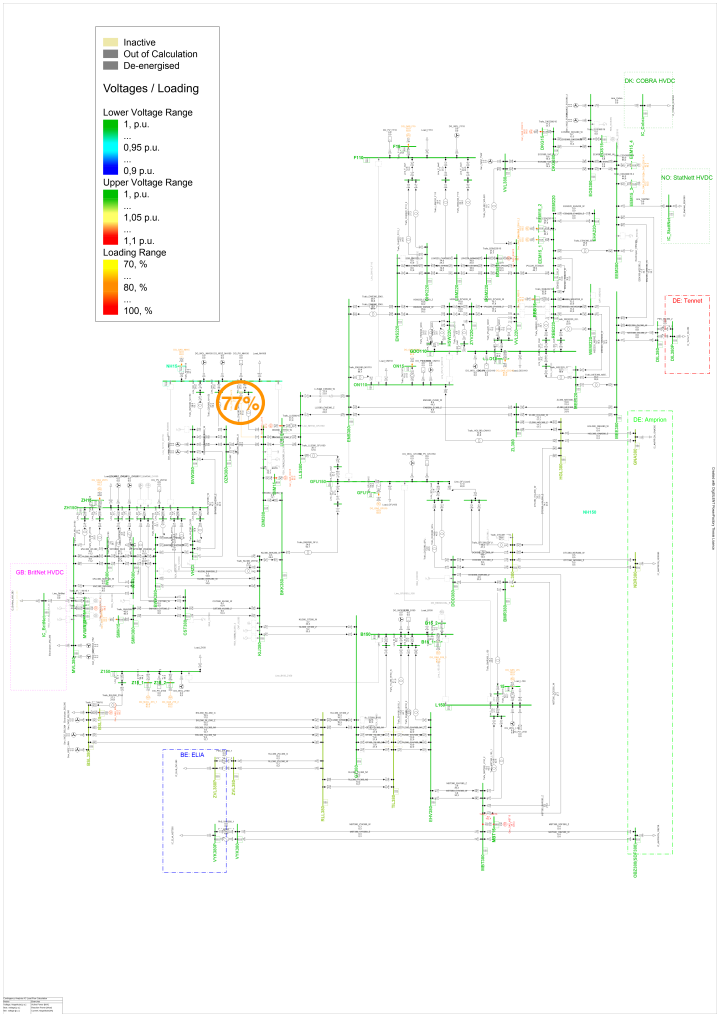


Figure 4.16: Single Line Diagram for Contingency Analysis of 12 GW national demand and only conventional electricity generation - Scenario F1

4.6.7. Case G: No VRES, Conventional Generation and Interconnections, High Demand

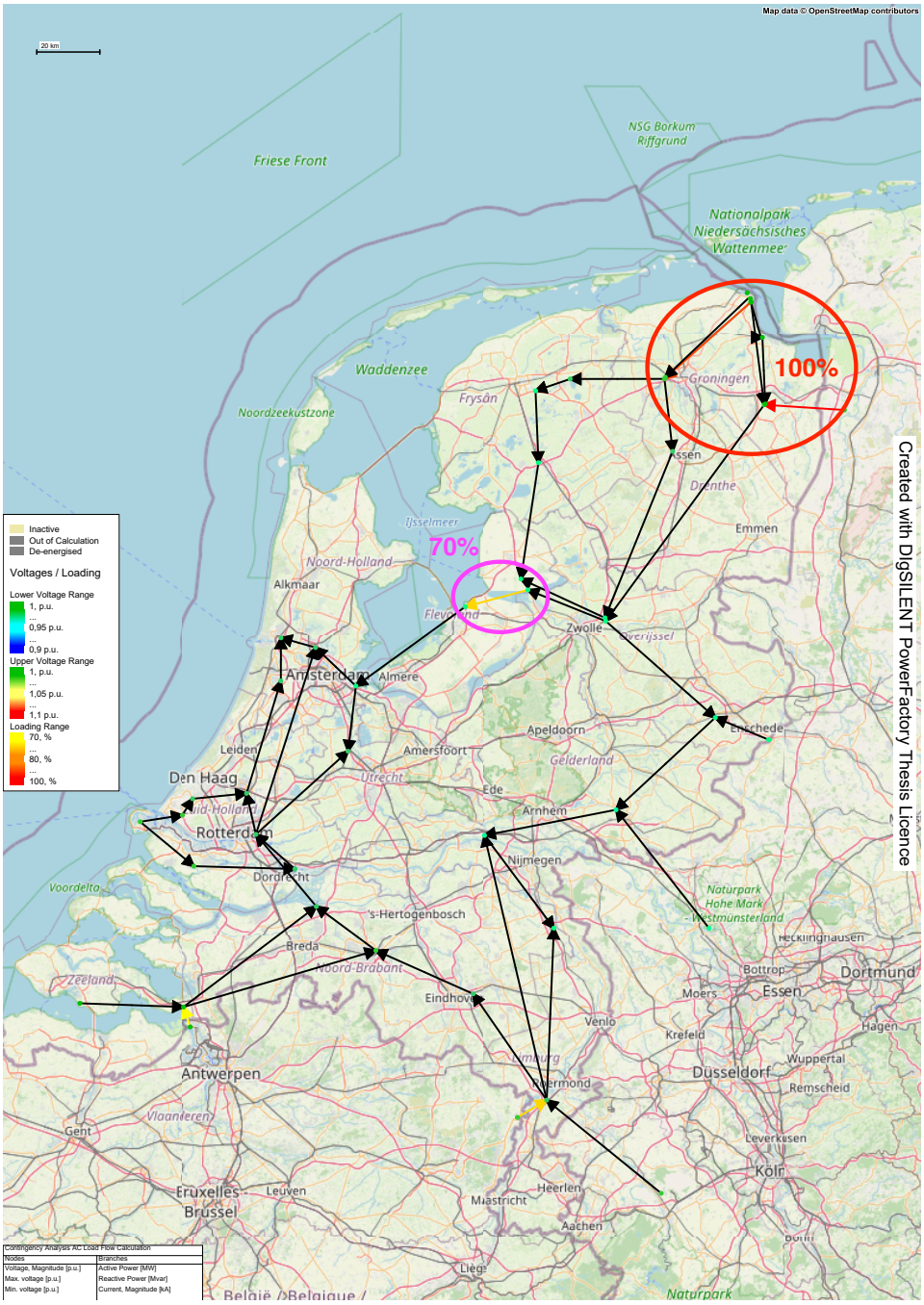
Table 4.19: Description of case G. Conv.Gen: Conventional Generation, Import/Export: Interconnections, P2x Dem. = Electrolyser Demand. Gen. - Dem = The amount of national generation minus the amount of regional demand. The active power surplus is used to balance the grid losses. All values are for Active Power (P) in (GW).

Case Type	Solar (GW)	Wind (GW)	Conv. Gen. (GW)	Regional Demand (GW)	P2x. Dem. (GW)	Import (-)/ Export (+) (GW)	Gen. - Dem. (GW)	Active Power Surplus (GW)
G1	0,0	0,0	21,4	21,0	0,0	-10,8	-10,6	0,2

This case investigates what happens when there is no VRES production and a peak demand of 21GW. The initial power flows were unrealistic due to loadings of transformers (100%) leading to undervoltages in Noord-Holland and Friesland. The reason for this is high regional demand in these areas and low regional generation.

An adjusted dispatch is set, where the amount of conventional generation at HV busbars is increased and the amount of interconnection capacity used is lowered from 100% to 70% of the total available capacity. Besides this, the demand within Noord-Holland is lowered.

In this case the initial power flow shows no highly loaded components. Now optimal power flow as well as contingency analysis is possible. For the Optimal Power Flow, a shift of the dispatch of the conventional generation in the North of the Netherlands to the South is observed due to the large amount of installed capacity of conventional generation in the North of the Netherlands and relatively low demand compared to the south. Contingency Analysis shows many overloaded transformers and potential risks of undervoltages, see also appendix E section E.5. Only one transmission line on the national ring is loaded to 70%, circled in pink in figure 4.17a. Besides this, two connections at Eemshaven show loadings of 100 % due to the high amount of active power bein imported from the North, shown in red.



(a) Geographical Diagram of Contingency Analysis for Peak Demand and no VRES production or electrolyser demand, using conventional generation and interconnections - Adjusted Scenario G1*

4.6.8. Transit Flow Cases: High VRES, added transit flows

Table 4.20: Description of cases with added transit flows. Conv.Gen: Conventional Generation, Import/Export: Interconnections, P2x Dem. = Electrolyser Demand. Gen. - Dem = The amount of national generation minus the amount of regional demand. The active power surplus is used to balance the grid losses. All values are for Active Power (P) in (GW).

Case Type	Solar (GW)	Wind (GW)	Conv. Gen. (GW)	Regional Demand (GW)	P2x. Dem. (GW)	Import (-)/ Export (+) (GW)	Gen. - Dem. (GW)	Active Power Surplus (GW)
X1-7	9,4	16,7	0,0	16,0	10,0	0,0	10,1	0,1
NZ1-7	9,4	16,7	0,0	16,0	10,0	0,0	10,1	0,1
WE1-7	9,4	16,7	0,0	16,0	10,0	0,0	10,1	0,1
ALL1-7	9,4	16,7	0,0	16,0	10,0	0,0	10,1	0,1
ZN1-7	9,4	16,7	0,0	16,0	10,0	0,0	10,1	0,1
EW1-7	9,4	16,7	0,0	16,0	10,0	0,0	10,1	0,1
ALLR1-7	9,4	16,7	0,0	16,0	10,0	0,0	10,1	0,1

These cases were added to see how the addition of electrolysers could potentially help alleviate the transmission system in case of large transit flows. Currently, the Dutch Transmission System often has to facilitate large power flows from Germany through the Dutch EHV network to the West of Belgium (even going on to France) [51] [52]. This can lead to critical parts of the national ring being overloaded [51]. In the future it is expected that the amount of cross-border power flows will only increase. According to the development plans, it is likely that large exports of electricity will occur from Great Britain and the Nordics to the Continent. This is mainly due to the expected increase in offshore wind capacities in these countries. As the generation portfolio of more central continental countries is less focused on offshore wind and more on nuclear (France), solar or gas-powered generation (other central European countries), the expected direction will be from North to South and more inland [51].

For none of the investigated transit flow cases, having only a single electrolyser is the best option. Even when transit flows from North to South are introduced for a scenario with 90% offshore wind and 38% solar generation, having 10 GW of electrolyser demand in the North of the Netherlands will lead to a large reversion of the power flow direction from the South to the North of the Netherlands (normally from North to South), as can be seen in figure 4.18.

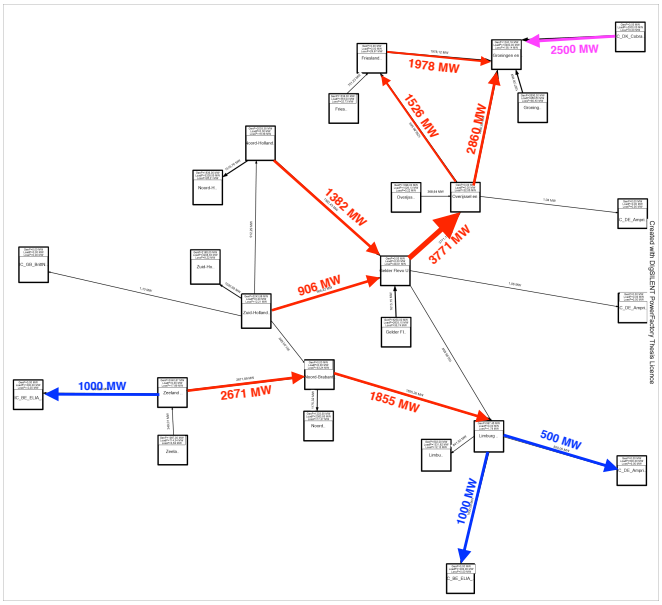


Figure 4.18: Regional Power Flows for when a single electrolyser with 10 GW demand is located at Eemshaven for a transit flow from North to South - Scenario NZ2

Also, undervoltages of 0.9 p.u. are visible in the region of Groningen & Drenthe, as can be seen in figure 4.19.

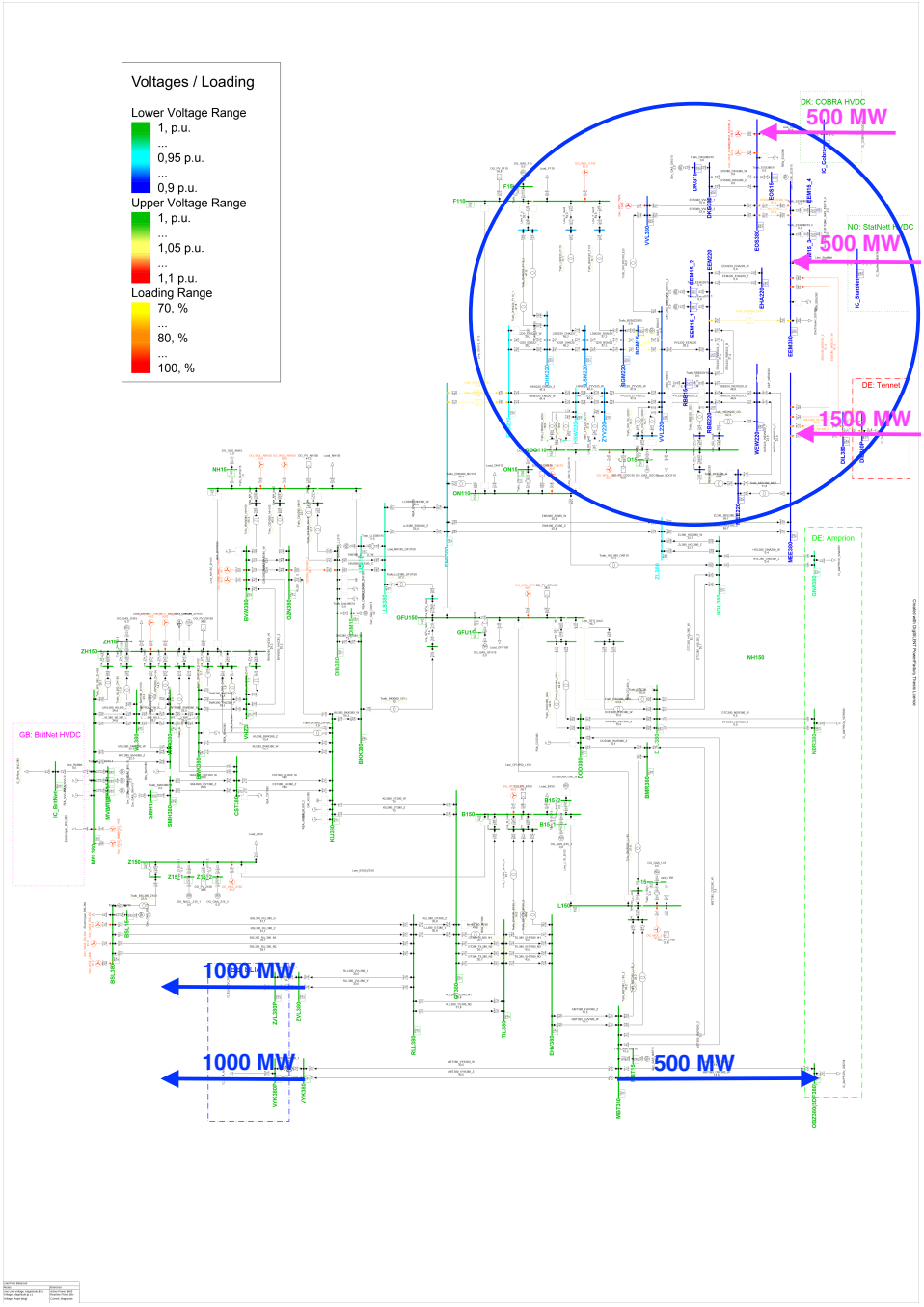
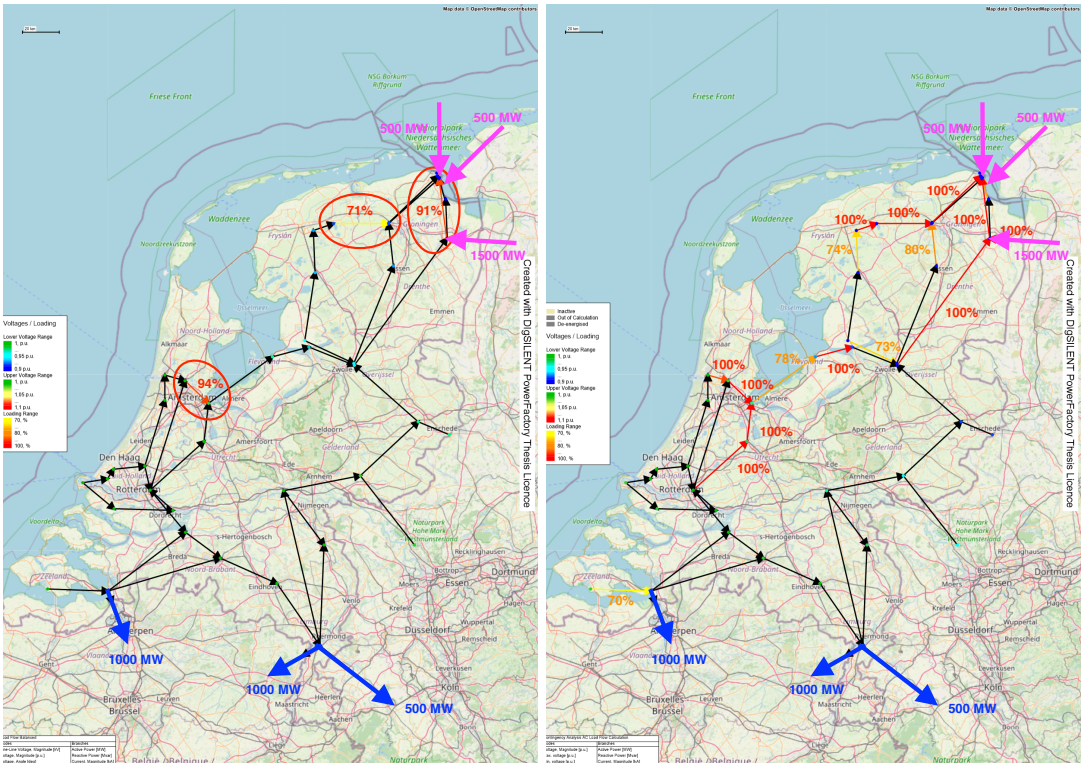


Figure 4.19: Single Line Diagram for Power Flow Analysis for Single Electrolyser with 10GW demand at Eemshaven for a Transit Flow from North to South - Scenario NZ2. Undervoltages in the Area of Groningen & Drenthe are circled in blue

The results for the initial power flow show high loaded components on the national ring, see figure 4.20a. Contingency Analysis shows that these power flows shows many potential overloaded components (indicated by 100% loading), shown in figure 4.20b. Based on this analysis the conclusion is drawn that having 10 GW Electrolyser demand in Eemshaven is too much, even if there are large transit flows from North to South.



(a) Geographical Diagram for Power Flow Analysis for Single Electrolyser with 10GW demand at Eemshaven for a Transit Flow from North to South - Scenario NZ2

(b) Geographical Diagram for Contingency Analysis for Single Electrolyser with 10GW demand at Eemshaven for a Transit Flow from North to South - Scenario NZ2

Figure 4.20: Geographical diagram showing results for when a single electrolyser with 10 GW demand is located at Eemshaven for a transit flow from North to South, on the left for the initial power flow, on the right for the contingency analysis

When combining the most dominant (likely to occur) transit flows from North to South as well as from West to East, the most ideal scenario is when there is 5 GW of electrolyser demand in Eemshaven and 5 GW in Maasvlakte. For the initial power flow of this scenario, no grid components are loaded above 50%, except for the interconnection lines which are loaded up to 90%. The power flows now show some power flowing from North to South, though this is limited to 1900 MW, shown in figure 4.21.

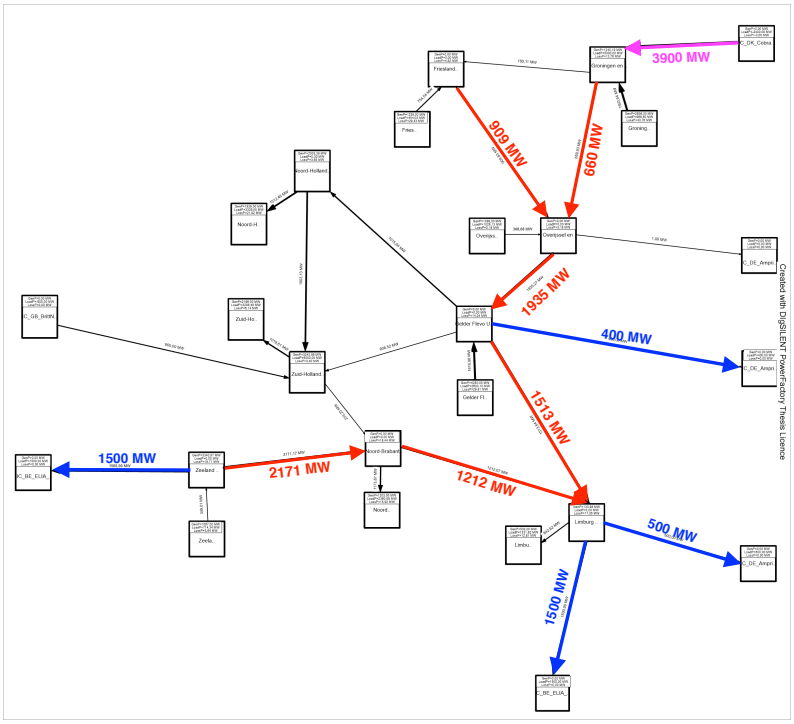


Figure 4.21: Regional Power Flows for when an electrolyser demand of 5 GW at Eemshaven and 5 GW at Maasvlakte, for a transit flow from North to South and West to East - Scenario ALL6

The results for the contingency analysis is given in figure 4.22. From this figure it can be be seen that the main risk is the overloading (indicated by 100% loading) of a transmission line in Noord-Holland (the connection BVW-VHZ). All other components on the national ring show loadings of a maximum of 77%.

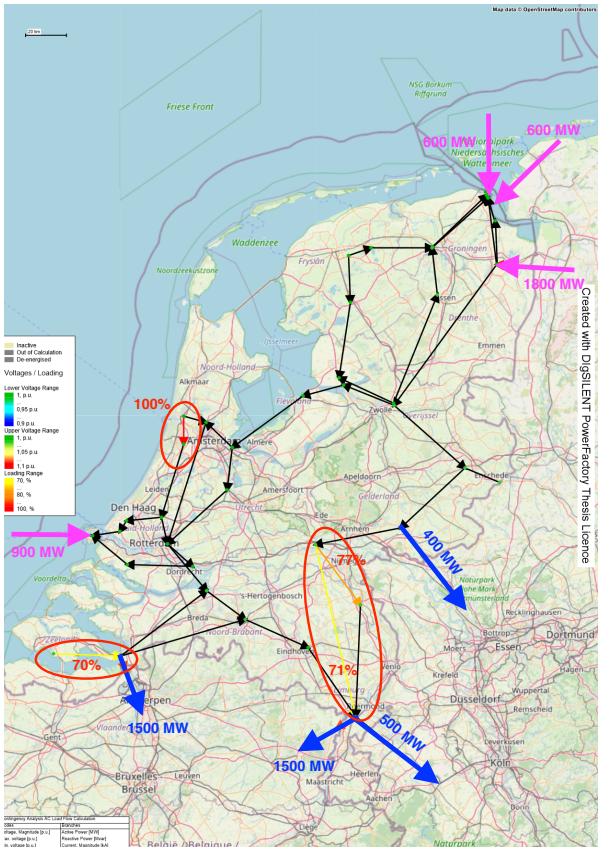


Figure 4.22: Geographical Diagram of Contingency Analysis for 10 GW electrolyser demand, of which 5 GW at Eemshaven and 5 GW at Maasvlakte for transit flows from North to South and West to East - Scenario ALL6

For scenarios in which these transit flows are reversed, coming from the South and East and leaving in the North and West, the most ideal scenario is where the electrolyser demand is equally divided between Maasvlakte and Borssele (5 GW each) and there is no electrolyser demand in Eemshaven, scenario ALLR7. This result will not be further discussed as these transit flows are not likely to occur very often, as mentioned in the introduction of this case.

4.7. Further Investigation of Optimal Distribution

Based on insights from the case study, additional scenarios were investigated for a division of installed capacity of the electrolysers of 6 GW in Eemshaven, 3 GW in Maasvlakte and 1 GW in Borssele, shown in table 4.21.

Table 4.21: Distribution of Electrolyser Capacity for further investigation

Electrolyser Location	Busbar in PowerFactory	Installed Capacity (GW)
Eemshaven	EEM380	6
Maasvlakte	MVL380	3
Borssele	BSL380	1

For this electrolyser distribution, 2 cases will be investigated. For this study, the definition of ”case” and ”scenario” are slightly adjusted. A ”case” will now only consider the amount of VRES production (so no longer the amount of demand and imports or exports). The demand is defined in three different ”demand variations” and the imports and exports are defined in ”cross-border variations”. Combining these cases, demand variations and cross-border variations leads to in total 18 different ”scenarios”.

One case has a high supply of wind powered generation and one case has a high supply of solar powered generation. In both the cases the electricity supply is coming for 100 % from VRES powered generation and adds up to 21,2 GW production. The amount of active power production for each technology is given in table 4.22. The 0.2 GW (160 MW) imbalance between generation and demand is used to compensate grid losses.

Table 4.22: Description of 2 investigated cases of VRES production for the proposed distribution, units are active power *P* in MW.

Case Name	Solar (%)	Wind (%)	Solar (GW)	Wind (GW)	Total Gen (GW)
Windy	18,0	90,0	4,5	16,7	21,2
Sunny	63,0	30,0	15,6	5,6	21,2

For both cases, windy and sunny, 9 scenarios are investigated, listed below in table 4.23. These scenarios all have a total demand of 21 GW, however they differ in how much of this demand is regional demand and how much is electrolyser demand. For this three demand variations are created, **High Regional Demand (H)**, **Medium Regional Demand (M)** and **Low Regional Demand (L)**. Each demand variation has 3 cross-border variations:

1. **Balanced (B):** The system is balanced nationally and there are no transit flows
2. **Transit (T):** There are transit flows, but an equal amount of power is imported as is exported
3. **Import (I):** The electrolysers import as much of the transit flow coming in from the North as is possible (between 1-3.9 GW depending on the scenario). For the scenario with a low demand, the electrolyser is already demanding 9 GW therefore only 1 GW extra is imported.

In total this leads to: 2 cases (windy,sunny) x 3 demand variations (high,med,low) x 3 cross-border variations (balanced, transit,import) = 18 scenarios investigated. For each scenario, the total electrolyser demand is distributed among the different electrolysers according to their installed capacities (so for example for a 9 GW demand, 5.4 GW demand in Eemshaven, 0.9 GW in Borssele and 2.7 GW in Eemshaven).

Table 4.23: List of Scenarios for the further investigation of a distribution for the electrolysers among Eemshaven, Maasvlakte and Borssele of 6,3 and 1 GW respectively

Scenario Name	Description	Regional Demand (GW)	P2x Demand (GW)	Transit Flow (GW)	Import (GW)
HB	High Reg. Demand - Balanced	21	0	0	0
HT	High Reg. Demand - Transit	21	0	3.9	0
HI	High Reg. Demand - Import	21	3.9	0	3.9
MB	Medium Reg. Demand - Balanced	15	6	0	0
MT	Medium Reg. Demand - Transit	15	6	3.9	0
MI	Medium Reg. Demand- Import	15	9.9	0	3.9
LB	Low Reg. Demand - Balanced	12	9	0	0
LT	Low Reg. Demand - Transit	12	9	3.9	0
LI	Low Reg. Demand - Import	12	10	2.9	1

The amount of cross-border flow for each of these variations is given in table E.5. In figure 4.23 the location of these connections is illustrated.

Table 4.24: Cross-border power flows considered for each of the variations in MW

Connection Name	Country	Unit	Max Capacity	Balanced (HB,MB,LB)	Transit Flow (HT,MT,LT)	High Import (HI,MI)	Low Import (LI)
IC_AMPRION_GNA380	Germany	MW	750	0	0	0	0
IC_AMPRION_NDR380	Germany	MW	1500	0	400	0	400
IC_AMPRION_OBZ380(SDF380)	Germany	MW	750	0	500	0	500
IC_BritNed_MVL380	United Kingdom	MW	1000	0	-900	-900	-900
IC_COBRA_EOS380	Denmark	MW	700	0	-600	-600	-600
IC_ELIA_MBT380	Belgium	MW	1700	0	1500	0	1000
IC_ELIA_ZVL380	Belgium	MW	1700	0	1500	0	1000
IC_StatNett_EEM380	Norway	MW	700	0	-600	-600	-600
IC_TenneT_DIL380	Germany	MW	2000	0	-1800	-1800	-1800

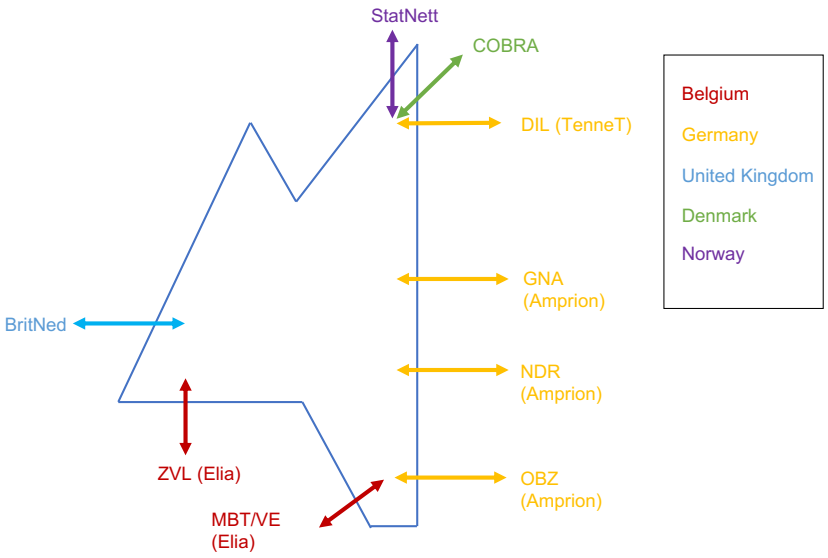


Figure 4.23: Illustration of cross-border electrical interconnections

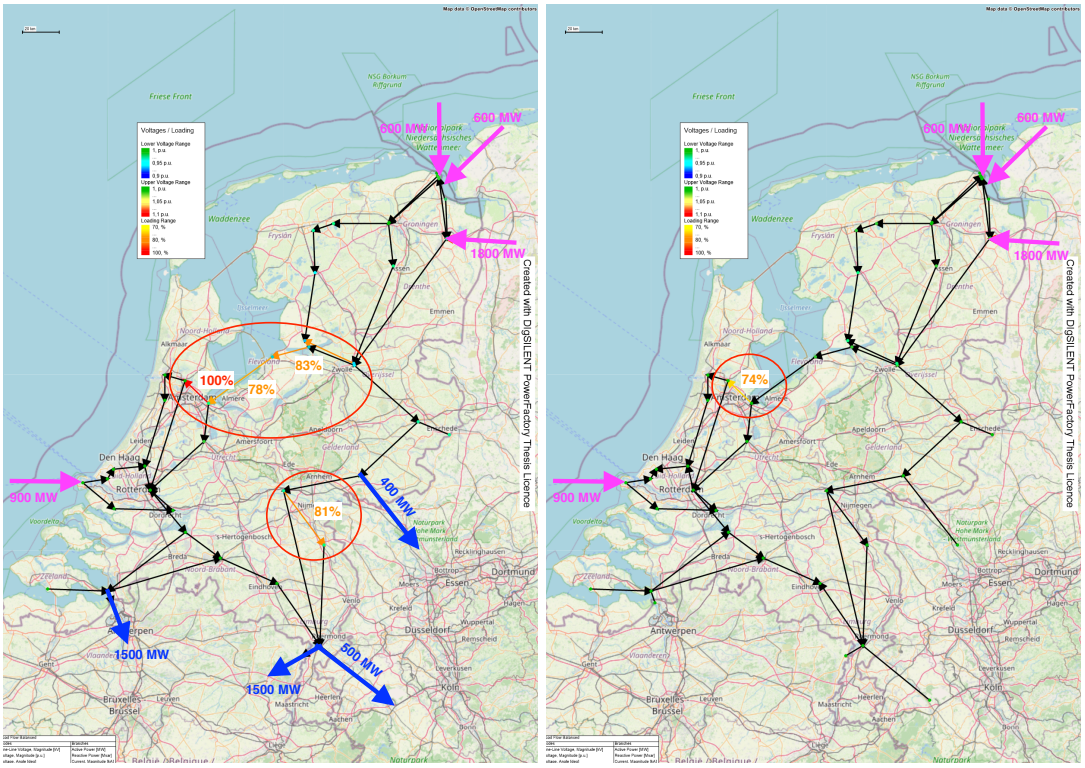
4.8. Insights from study of 6-3-1 Distribution

In this section the main results and insights will be presented for a 6-3-1 distribution of the electrolyser capacity among Eemshaven, Maasvlakte & Borssele. All scenarios show the same total demand of 21 GW, though for loop flow and import scenarios, an added transit flow of 3.9 GW will need to be accommodated by the Dutch Transmission System. In the following sections, different scenarios are compared to show the benefit of adding electrolysers to the Dutch transmission system (for a 6-3-1 distribution between Eemshaven, Maasvlakte and Borssele). For more discussion of the results of each scenario, see appendix E.7.

The initial power flow results show that only in two scenarios components are loaded above 70%. This is in scenario Sunny-HT and Sunny-HI, an overview of these two scenarios is given in table 4.25. The results for the initial power flows are shown in figure 4.24. For scenario Sunny-HT, different components on the national ring in the areas of Gelderland, Flevoland & Utrecht, Noord-Holland and Brabant are loaded between 78-100%. For scenario Sunny-HI, the only highly loaded component is the connection OZN-DIM in Noord-Holland which is loaded to 74%.

Table 4.25: Overview of scenarios that showed components loaded above 70% for the initial power flows

Scenario Name	Scenario Description	Reg. Dem. (GW)	P2x Dem. (GW)	Transit Flow (GW)	Import (GW)	Wind (GW)	Solar (GW)
Sunny - HT	Medium Reg. Demand - Transit	21	0	3.9	0	5.6	15.6
Sunny - HI	Medium Reg. Demand- Import	15	3.9	0	3.9	5.6	15.6



(a) Geographical Diagram for Power Flow Analysis for Scenario with 5.6 GW wind, 15.6 GW solar, 21 GW regional demand, 0 GW electrolyser demand and 3.9 GW Transit Flow - Scenario Sunny-HT

(b) Geographical Diagram for Power Flow Analysis for Scenario with 5.6 GW wind, 15.6 GW solar, 21 GW regional demand, 3.9 GW Electrolyser Demand coming from Import and 0 GW Transit Flow - Scenario Sunny-HI

Figure 4.24: Geographical Diagram for Power Flow Analysis for Scenario Sunny-HT (21 GW demand and 3.9 GW transit flow) and Sunny-HI (21 GW demand, 3.9 GW import for electrolyser demand)

Comparison 1: Transit Flow turns into Import

It is interesting to compare the two scenarios that showed high loaded components for the initial power flows, Sunny-HT and Sunny-HI. This is because for the first scenario there is a transit flow of 3.9 GW while in the second case, the transit flow is turned into an import for the electrolysers (so there is no longer any export from the NL). The initial power flows of the two cases show that if, hypothetically, a transit flow could be changed into an import for the electrolysers, there will be less highly loaded components, shown in figure 4.24. No other scenarios showed component loadings on the national ring of above 70% for the initial power flows.

Comparison 2: Electrolyser Demand without Transit Flow vs with Transit Flow

In table 4.26 a description is given of the scenarios that will be used in this comparison. The scenarios differ in the total amount of grid loading. In the scenarios of Windy-MB and Sunny-MB there are no transit flows while in the scenarios of Windy-MT and Sunny-MT there is an added 3.9 GW of transit flow leading to a higher loading on the national grid. This Comparison was made to see what would happen in a situation where there is already electrolyser demand in the Netherlands of 6 GW and transit flows occur.

Table 4.26: Overview of Scenarios referred to in Comparison 2

Scenario Name	Scenario Description	Reg. Dem. (GW)	P2x Dem. (GW)	Transit Flow (GW)	Import (GW)	Wind (GW)	Solar (GW)
Windy - MB	Medium Reg. Demand - Balanced	15	6	0	0	16.7	4.5
Windy - MT	Medium Reg. Demand - Transit	15	6	3.9	0	16.7	4.5
Sunny - MB	Medium Reg. Demand - Balanced	15	6	0	0	5.6	15.6
Sunny - MT	Medium Reg. Demand - Transit	15	6	3.9	0	5.6	15.6

The results show that due to the eletrolyser demand the power flow direction for connections between the North and the South in the initial situation (without transit flows) is reversed compared to situations in which there is no electrolyser demand (see also case A0 and B0 in section E.1 and E.2 of the appendix). When transit flows are introduced the flow direction is reversed again to the initial direction. However, because the balanced case showed a flow from south to North, the total amount of power flowing from North to South for the Transit Flow Case is now much lower as compared to when there is no electrolyser demand. An example of this is given in figure 4.25 and figure 4.26 for Case Windy-MB and Windy-MT, in which there is 16.7 GW wind, 4.5 GW solar production, 15 GW regional demand and 6 GW electrolyser demand. Figure 4.25 shows the scenario where the electrolyser demand leads to a power flow from South to North of 1209 MW (due to 3.6 GW electrolyser demand in Eemshaven). Figure 4.26 shows the scenario when a transit flow leads to the reversal of this power flow direction, now from North to South of 1706 MW.

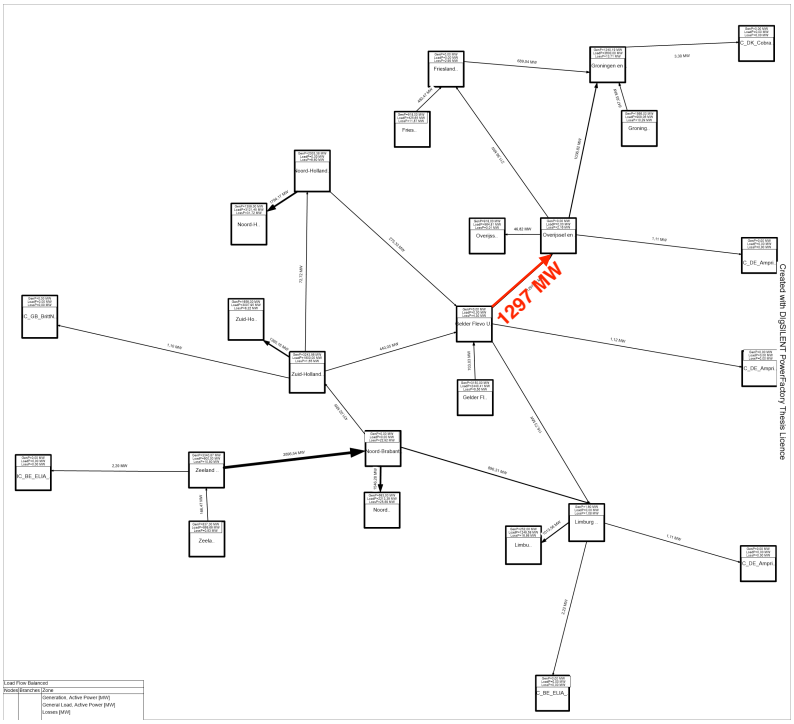


Figure 4.25: Regional Power Flow Diagram for Power Flow Analysis for Scenario with 16.7 GW wind, 4.5 GW solar, 15 GW regional demand and 6 GW electrolyser demand, no transit flow - Scenario Windy-MB

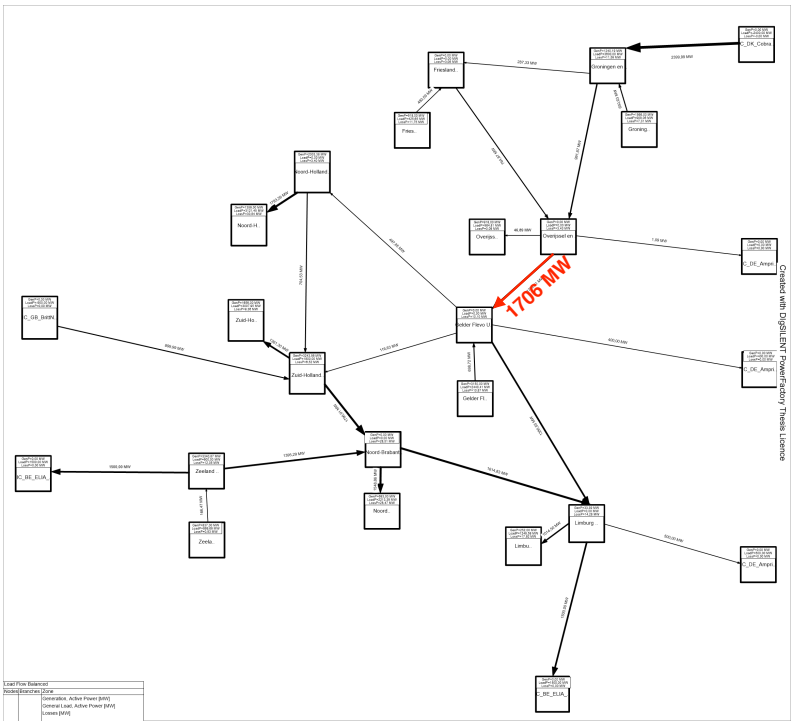


Figure 4.26: Regional Power Flow Diagram for Power Flow Analysis for Scenario with 16.7 GW wind, 4.5 GW solar, 15 GW regional demand and 6 GW electrolyser demand, 3.9 GW transit flow - Scenario Windy-MT

An overview of the Power Flow for North to South direction and vice versa (the maximum exchange between regions of Overijssel en Noord-Oostpolder (ON) and Gelderland, Flevoland & Utrecht (GFU)) for each of the scenarios is given in table 4.27. The bold cases show how extra electrolyser demand can reverse the power flow direction on this connection. By creating a base case of ”negative” flow,

when transit flows are introduced in the ”positive” direction, the transmission lines become less highly loaded compared to the base case with ”positive” flow.

Table 4.27: Windy Case: 16,7 GW wind and 4,5 GW solar. In the last two columns the maximum amount of active power flowing in North to South direction (connections GD-ON, F-ON and ON-GFU) and vice versa is given.

Scenario Name	Reg. Dem. (GW)	P2x Dem. (GW)	Transit Flow (GW)	Import (GW)	North-South (GW)	South-North (GW)
Windy-HB	21	0	0	0	1.4	-
Windy-HT	21	0	3.9	0	4.3	-
Windy-HI	21	3.9	0	3.9	2.0	-
Windy-MB	15	**6**	0	0	-	**1.3**
Windy-MT	15	6	3.9	0	1.7	-
Windy-MI	15	9.9	0	3.9	-	0.6
Windy-LB	12	**9**	0	0	-	**2.7**
Windy-LT	12	9	3.9	0	0.4	
Windy-LI	12	10	0	1		0.2

The same results are given for the Sunny Case in table 4.28. In these scenarios there is a larger amount of power flowing from North to South due to the large installed capacity of solar in the North of the Netherlands. Therefore the maximum transport of active power on the connection from North to South (ON to GFU) is higher than for the windy cases (a max of 6.3 GW vs a max of 4.3 GW in N-S direction in case of regional peak demand, transit flows and no electrolyser demand, scenario Windy-HT and sunny-HT). When adding a high electrolyser demand of 9 GW in the scenario Sunny-LB (for a low regional demand of 12 GW), the power flow direction is also reversed, see table 4.28.

Table 4.28: Sunny Case: 5.6 GW wind and 15.6 GW solar. In the last two columns the maximum amount of active power flowing in North to South direction (connections GD-ON, F-ON and ON-GFU) and vice versa is given.

Scenario Name	Reg. Dem. (GW)	P2x Dem. (GW)	Transit Flow (GW)	Import (GW)	North-South (GW)	South-North (GW)
Sunny-HB	21	0	0	0	3.4	
Sunny-HT	21	0	3.9	0	6.3	
Sunny-HI	21	3.9	0	3.9	4.1	
Sunny-MB	15	6	0	0	0.7	
Sunny-MT	15	6	3.9	0	3.7	
Sunny-MI	15	9.9	0	3.9	1.4	
Sunny-LB	12	**9**	0	0		**0.6**
Sunny-LT	12	9	3.9	0	2.4	
Sunny-LI	12	10	0	1	1.8	

Comparison 3: Transit Flow without Electrolyser Demand vs with Electrolyser Demand

This comparison is added to show how electrolyser demand could help to mitigate risks for n-1 security in case of transit flows. For this comparison, results from the contingency analysis of scenarios Windy-HT and Windy-MT will be used, in contrast to the previous two comparisons where results from the initial power flows were used.

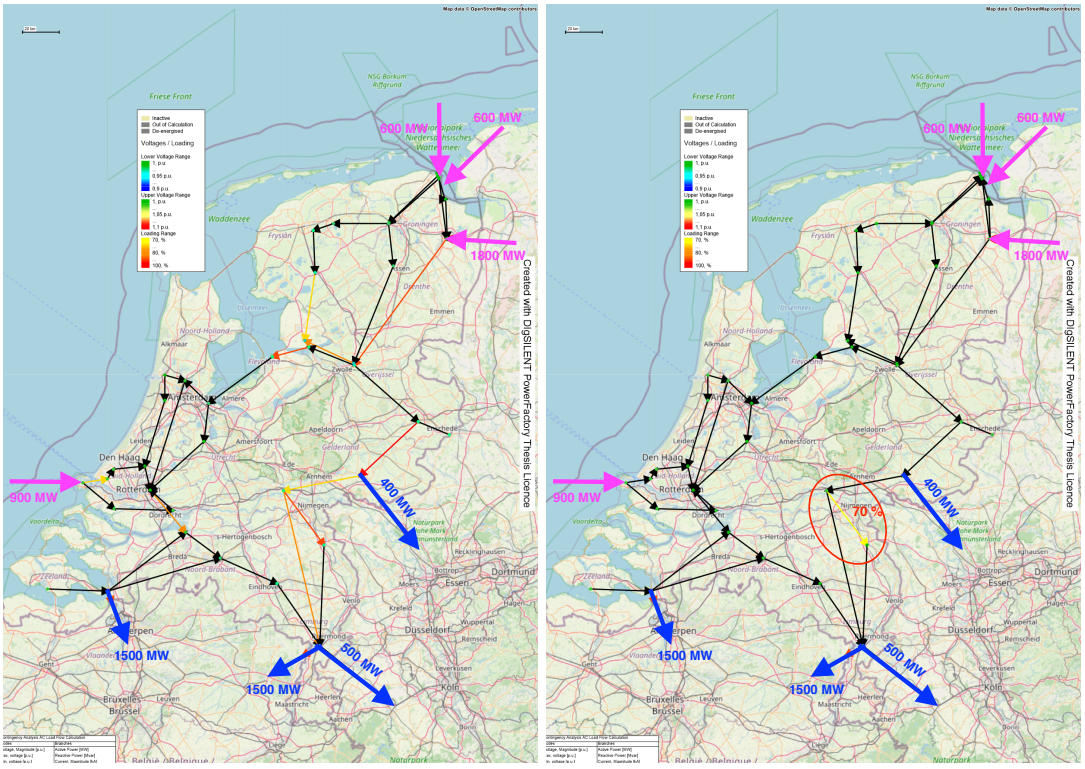
For this comparison, scenarios Windy-HT and Windy-MT are used, see table 4.29, The two scenarios differ in the amount of regional demand. However, the total grid loading is equal in both cases (21 GW demand + 3.9 GW transit). To add electrolyser demand to an existing scenario with transit flows, either the total amount of generation needs to increase or the regional demand has to be lowered to be able to accommodate the electrolyser demand. In these scenarios it was chosen to keep the total loading on the grid the same in both cases, to allow for a fair comparison of the loading of components on the national ring.

Table 4.29: Overview of Scenarios referred to in Comparison 3

Scenario Name	Scenario Description	Reg. Dem. (GW)	P2x Dem. (GW)	Transit Flow (GW)	Import (GW)	Wind (GW)	Solar (GW)
Windy-HT	High Reg. Demand - Transit	21	0	3.9	0	16.7	4.5
Windy-MT	Medium Reg. Demand - Transit	15	6	3.9	0	16.7	4.5

From figure 4.27 it can be seen that for a scenario with 15 GW regional demand and 6 GW electrolyser demand (scenario Windy-MT), contingency analysis shows reduced potential overloading of compo-

nents on the national ring as compared to a case of 21 GW regional demand and 0 GW electrolyser demand (scenario Windy-HT). In the case where these is 6 GW of electrolyser demand, only one component between DOD-BMR is loaded to 70%, seen in figure 4.27b. In the case of no electrolysers demand there are much more components identified as being loaded above 70%, seen in figure 4.27a. This illustrates how added electrolyser demand could help to safeguard n-1 security on the national ring by mitigating the potential high loading of components (for a total grid loading of 24.9 GW: 21 GW demand and 3.9 GW transit flow).



(a) Geographical Diagram for Contingency Analysis for Scenario with 16.7 GW wind, 4.5 GW solar, 21 GW regional demand and 0 GW electrolyser demand - Scenario Windy-HT

(b) Geographical Diagram for Contingency Analysis for Scenario with 16.7 GW wind, 4.5 GW solar, 15 GW regional demand and 6 GW electrolyser demand - Scenario Windy-MT

Figure 4.27: Geographical Diagram for Contingency Analysis for Scenario Windy-HT and Windy-MT

4.9. Overall Summary of Case Study Results

For cases with high offshore wind generation, the most ideal distribution (of the considered distributions) would be to equally divide the 10 GW of installed capacity among the three locations of Eemshaven, Maasvlakte and Borssele. This would lead to relatively low flows of power between EHV regions, the largest begin from Noord-Holland to Zuid-Holland. When dominant transit flows from North to South and West to East are added, the most ideal case becomes having one electrolyser at Eemshaven and one in Maasvlakte each of 5 GW.

When scenarios with high solar generation are considered, the best cases have at least 5 GW of electrolyser capacity located in Eemshaven. The reason for this is that for scenarios with high solar generation, a large power flow from the North to the South of the Netherlands is visible. This leads to high loadings on the national EHV ring which can be mitigated by introducing an electrolyser in the North of the Netherlands at Eemshaven. Optimal Power Flows for these cases show the re-dispatching of generation to more Southern and Western Areas for all electrolyser locations. For cases with high solar generation, many transformers between EHV and HV areas are identified as critical due a lack of total installed capacity, in Groningen & Drenthe especially, leading to undervoltages.

When transit flows are directed from South to North or from East to West, electrolyser demand could make congestion issues worse. The reason for this is that the added electrolyser demand will only increase power flows in the direction of these transit flows (South to North and East to West) in these scenarios, increasing the loading of transmission lines on the national ring. Therefore it is vital that incentives to help with alleviating congestion are introduced for electrolyser operators.

Based on insights from the case study, further investigation into a distribution of 6 GW installed capacity at Eemshaven, 3 GW at Maasvlakte and 1 GW at Borssele was done. The results show that using these installed capacities a ”negative” flow can be introduced in the direction of the electrolyser demand for base scenarios with no transit flows. This can help to alleviate congestion issues for cases in which there is high VRES generation (especially for solar generation) or when there are transit flows from North to South or West to East.

If there has to be a choice between the location of Maasvlakte or Borssele for the introduction of an electrolyser, less congestion issues arise for Maasvlakte. However, if both locations can be considered, introducing a smaller electrolyser at Borssele would help to steer the power flow between Noord-Brabant and Zeeland during times of large generation from offshore wind.

Installing 10 GW of capacity at a single location would be too much considering the installed capacities and developments taken into account for scenario KA2030 from KCD2020 [2], as all scenarios with only single locations for 10 GW of electrolyser capacity show increased congestion issues. In all investigated cases it is better to divide the installed capacity among the North and the South of the Netherlands.

5

Conclusion and Discussion

This chapter discusses the main findings of this thesis. The topics discussed are scenarios for the future of the Dutch Transmission Network, the creation of a synthetic model of the Dutch EHV network, a study into the impact of future additions of VRES and electrolysers, and a discussion about the used criteria for security of supply. Finally, recommendations for future work are given.

5.1. Scenarios for the future

Within power system planning the uncertainties taken into account by different countries vary. In this thesis many different reports with created scenarios for the Dutch future energy system were considered. Different studies with scenarios for 2030 and 2050 were compared, based on the following qualitative criteria: the considered range for installed capacities of VRES and increase in demand, the comprehensiveness of the study, the type of created scenarios (explorative or also target based), the involvement of other stakeholders, and consideration of emerging technologies. When creating scenarios, the difficulty is to not narrow the field to be considered while still making realistic assumptions. Social, economical as well as technological developments can all lead to very different futures. For the transmission network to safeguard security of supply, it is essential that not just the wishful but also the most critical scenarios are investigated. This way insights can be provided into where new developments are needed.

For the Netherlands, the largest uncertainties (which are considered in the created scenarios) are the future level of electrification and the amount of de-central or central variable renewable energy supply (VRES). The level of electrification depends on whether we will stay a molecular oriented country or move to a higher level of electrification. However, electricity demand could also tremendously increase if we choose to produce these molecules (green hydrogen) ourselves. The amount of installed wind generation can be estimated quite easily for 2030 due to the long lead time of projects. However, for solar generation these scenarios assume relatively conservative numbers. This might lead to underestimating the importance of introducing regional flexibility into the system (for the long and short term).

Using these insights, scenarios were created which can be used to test the created Dutch EHV Network model for 2030. To create a minimum but representative set of future scenarios, the most extreme situations (for the Dutch EHV network) that are deemed plausible should be considered, together with a scenario based on set future targets. If this approach is followed, chances are that the future will unfold somewhere in the spectrum between these scenarios.

When creating scenarios to be used for testing the future Dutch Transmission System, transparency of current data and expected future regional developments is vital. This concerns data such as: current and expected future grid topology (e.g. new transmission lines or substations), component parameters (e.g. generator settings, operational voltages and transformer capacities) and the development of regional generation and demand. When this data is not available, it is still possible to make a realistic model of an EHV network based on other examples, but the model becomes less representative for the

real Dutch Transmission Network. Publicly available information for possible regional developments of generation capacity as well as expected future topology [2] [13] were used to create a model for 2030.

5.2. Creating a Synthetic Model of the Dutch EHV Network

By creating this model of the Dutch EHV network a small step in the direction of more available test models for researchers of transmission network planning is taken [5]. However, when creating a model for a large system such as the Dutch EHV Transmission System, many different parameters need to be introduced. As this model was built using only publicly available data many assumptions were made that can have a large influence on the different power flows. For the synthetic model of the Dutch EHV network that was created in PowerFactory, the main assumptions that needed to be made (due to lack of data) were for settings and component parameters of generators and transformers. Creating a base model was complicated, as different sources needed to be combined to imitate historical dispatches that could be used to test the model.

The model provides a base layer which can be used to make a more representative digital twin of the Dutch Transmission System. It is useful as a tool to gain insights about future developments such as, in this case study, the additions of VRES and potential measures for system flexibility. When drawing conclusions on real life situations it is important to consider the more basic and intuitive findings such as the amount of export, imports or installed capacities of regions.

5.3. Study of impact of future additions of VRES and electrolysers

For steady state performance of the EHV network the introduction of VRES poses a challenge. For large centralised projects such as offshore wind, an increase in power flows between extra high voltage regions can be expected if alternative solutions are not considered. If decentralised projects such as local solar generation grow, it will be vital to introduce flexibility measures at a local level.

According to the model, the current Dutch EHV Network does not have enough installed transformer capacity to accommodate large flows of solar generation going from high voltage (110/150kV) to extra high voltage (220/2380kV) areas for the KA2030 scenario created by Tennet (if no other local flexibility or curtailment of solar generation is considered) [2]. If generation and demand are brought closer together, a reduced amount of investment into the Dutch EHV network will be needed and there will be an increased security of supply.

For each of the cases, it is investigated which location would be best for the addition of an electrolyser: Maasvlakte, Borssele, Eemshaven or a combination of the above. Results show that having both electrolysers in the North of the Netherlands as in the South of the Netherlands could help to alleviate congestion issues. The reason for this is that the added demand of the electrolysers can help to steer the flow of power. This will be highly relevant in cases of dominant transit flows from North to South, cases of high solar generation (as there is a large amount of installed capacity in the North of the Netherlands) or cases of high offshore wind generation. By creating a ”negative” flow in the opposing direction due to electrolyser demand, a larger transmission capacity is available for the transmission lines to transport electricity in these cases, see an illustration in figure 5.1. For new transmission lines approximately 2635 MVA is available in either direction [33]. Therefore, if ”negative” flow is introduced (pink arrows representing electrolyser demand in figure), 5270 MVA could become available for transit flows (yellow arrows).

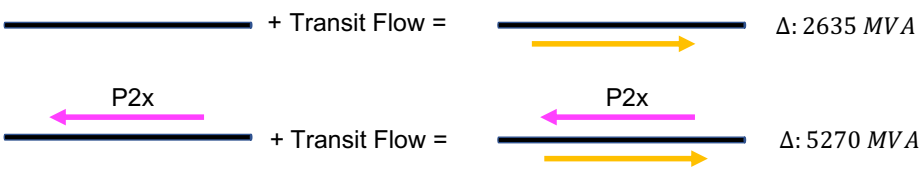
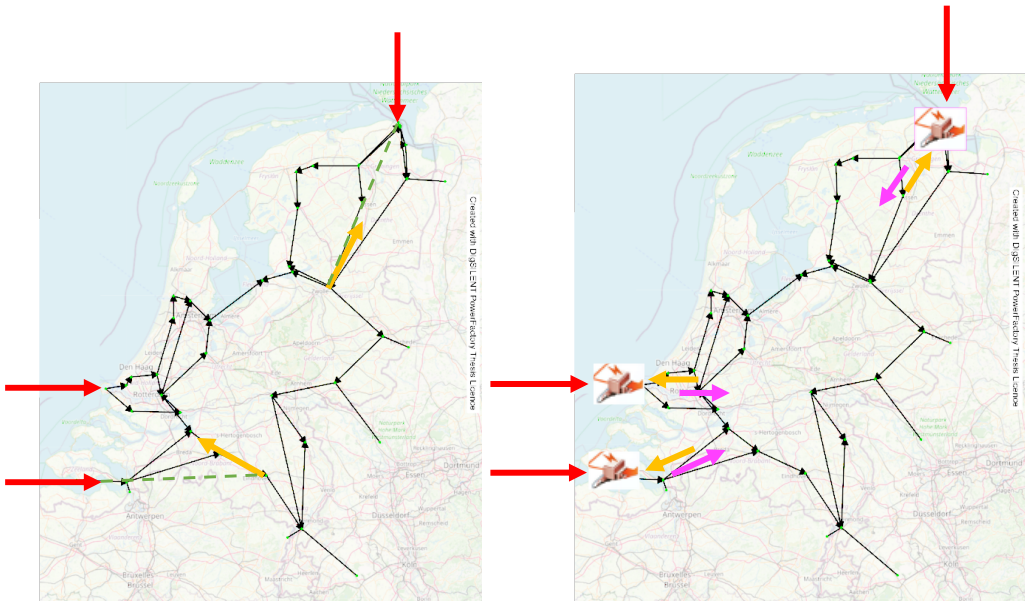


Figure 5.1: Illustration of introducing a negative flow due to electrolyser demand (pink arrow) to create a larger transmission capacity available for situations of high VRES or transit flows (yellow arrow).

Recently, there has been a discussion to connect future offshore wind using DC connections to more inland locations to alleviate congestion [41]. Introducing electrolyser demand at the locations of Eemshaven, Maasvlakte and Borssele could also help to alleviate congestion without having to invest in these transmission lines, illustrated in figure 5.2. The electrolysers provide more flexibility than DC lines in the sense that the demand of the electrolysers can be increased or decreased depending on the situation. This can help to steer the loading of the transmission lines. For example, if there are no transit flows, the national ring is able to transport more of the offshore electricity generation inland, as discussed in case A of the case study, section 4.6.1. In this case the electrolyser demand could be lowered.



(a) Illustration of situation in which DC lines are used to introduce "negative" flow, see green lines

(b) Illustration of situation in which Electrolysers are used to introduce "negative" flow

Figure 5.2: Figures illustrating the potential benefit of introducing electrolysers at Eemshaven, Maasvlakte and Borssele opposed to connecting offshore wind farms further inland using DC connections.

The proposal is to install a large share of the installed capacity in Eemshaven and in Maasvalkte (e.g. 6 GW in Eemshaven and 3 GW in Maasvalkte). In Borssele, electrolyser demand is also needed to for congestion management, however according to the studied scenarios, lower capacities of 1-2 GW will suffice. This distribution will allow for the management of many situations of high VRES infeed as well as transit flows without the need for operational measures.

Providing the correct incentives to be able to steer the electrolyser demand for different situations is key. An added electricity demand from an electrolyser could also increase the congestion issues in the network, for example if there is a very high demand in the North combined with a transit flow occurring from South to North or if the electrolyser demand is much higher than the production of offshore wind energy. Besides this, it is also important to consider other factors such as the most ideal connection to the methane or hydrogen network as well as other economical or social concerns.

5.4. Netdesign and criteria for assesment of security of supply

For future scenarios of high installed capacities of VRES, maintaining the same grid criteria such as n-1 security for all EHV connections and n-2 security for the important connections in the national ring will be very costly [13]. It is important to focus on what this criteria is trying to asses, namely security of supply. Based on insights from this thesis, a proposal would be to adjust the criteria. The new criteria should asses whether each region is able to meet their (essential) electricity demand in all future scenarios. For example, if a transmission lines fails for a connection in Groningen & Drenthe due to large infeed of offshore wind or transit flows, this is not an issue as long as all the regions in the Netherlands are still

able to meet their electricity demand, for example by using flexible backup in 110/150kV regions. To increase security of supply for the future, the focus should be on bringing generation close to demand and increasing the flexibility of the system. A first step would be to match the amount VRES production to the regional demand as well as incorporating demand response and flexible back-up generation in each region.

By taking proactive steps for net design, considering the future addition of VRES into the transmission network, costly situations such as operational measures for congestion management can be reduced. Proactive means planning ahead for locations where generation (or extra demand) is needed in the transmission system and to provide the correct incentives (to all stakeholders) to realise this.

5.5. Future Work

For future transmission planning, an integrated approach is necessary [13]. Creating a more high level holisitic model of an integrated system of the gas, electricity, and heat network would be a great basis for further research. Furthermore, research into the economical and social aspects of the future scenarios could provide insight into the most likely and favorable potential direction. It would be interesting to improve the model of the Dutch EHV network such that it can be used for dynamic simulations [1]. Regarding the simulations done, the base work has been done to perform simulations for other scenarios of 2030, as well as investigate other sensitivities such as different demand profiles, operational voltages of generators, or specific scenarios for imports and exports to neighbouring countries. Furthermore, it could be considered to adjust the existing cases for a netto import or export of electricity by adjusting the loading of electrolysers. For 2050 scenarios, extra controls will need to be implemented to be able to run simulations (such as demand response and VRES curtailment) due to the extreme amounts of installed capacities for some scenarios compared to the status quo.

[1] In this case first alternative approaches for removing different parallel flows should be investigated, for example by creating more pockets with demand scaled according to transformer size. Also, by creating extra seperate busbars for onshore wind and solar generation, active participation of both generators for reactive power control as well as for optimal power flow of the entire system during peak demand could be investigated. Besides this, a different approach for reactive power compenstation could be considered by inserting STATCOMS at specific locations. Investigating the optimal locations for reactive power compensation would then also be interesting [54].

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A

Installed Capacity and Demand

A.1. The Base Model

The base model is used to simulate scenarios for 2017-2020. The generation capacity and demand are modelled according to KCD2017 for 2018 [31]. The model has been adjusted however to include all the generators currently listed by ENTSOE transparency platform to be able to perform simulations for 2019 and 2020 [36].

A.1.1. Base Model: Overview of Installed Generation Capacity

In table A.1 the total amount of Generation and Demand that was used in the base model for each of the different regions is given. In the second part of the table, the ratio of total generation to the peak demand is given as well as the ratio of the conventional (synchronous) generation to the peak demand. This is done to get a feeling for the amount of excess/lack of capacity that each region has to supply itself in times of peak demand. The reason to distinguish the total from the conventional generation, is because the static (renewable) generation in the base model is either Solar PV or Wind which is not controllable.

Table A.1: Base Model: Total Amount of Generation and Demand

Totals		**F**	**GD**	**ON**	**GFU**	**Z**	**B**	**L**	**NH**	**ZH**	***Totals***
220/380kV Gen Cap	MW	144	5519	0	426	1622	0	1304	435	3071	*12521*
110/150kV Gen Cap	MW	630	1220	940	2838	1741	2905	963	3686	4282	*19205*
Total Gen Cap	**MW**	**774**	**6739**	**940**	**3264**	**3363**	**2905**	**2267**	**4121**	**7353**	***31726***
Synchr. Gen. Cap.	MW	214	5239	200	1929	2054	2189	1909	3343	6456	*23533*
Peak Demand	MW	590	1460	1258	3251	625	3550	1650	3333	4355	*20072*
Total Gen. Cap./Demand	-	1,31	4,62	0,75	1,00	5,38	0,82	1,37	1,24	1,69	-
Synchr. Gen. Cap./Demand	-	0,36	3,59	0,16	0,59	3,29	0,62	1,16	1,00	1,48	-

Figure A.1 shows the amount of conventional (thermal) generation compared to the peak demand of each region. Groningen and Drenthe (GD) cleary has an excess of capacity to meet its own demand, while other regions such as Brabant (B), Overijssel en Noordoostpolder (ON), Gelderland, Flevoland and Utrecht (GFU) show deficits. The demand is modelled according to the distribution of the peak demand which will be further elaborated on in section A.1.4. This leads to significant flows of power between the regions mentioned above.

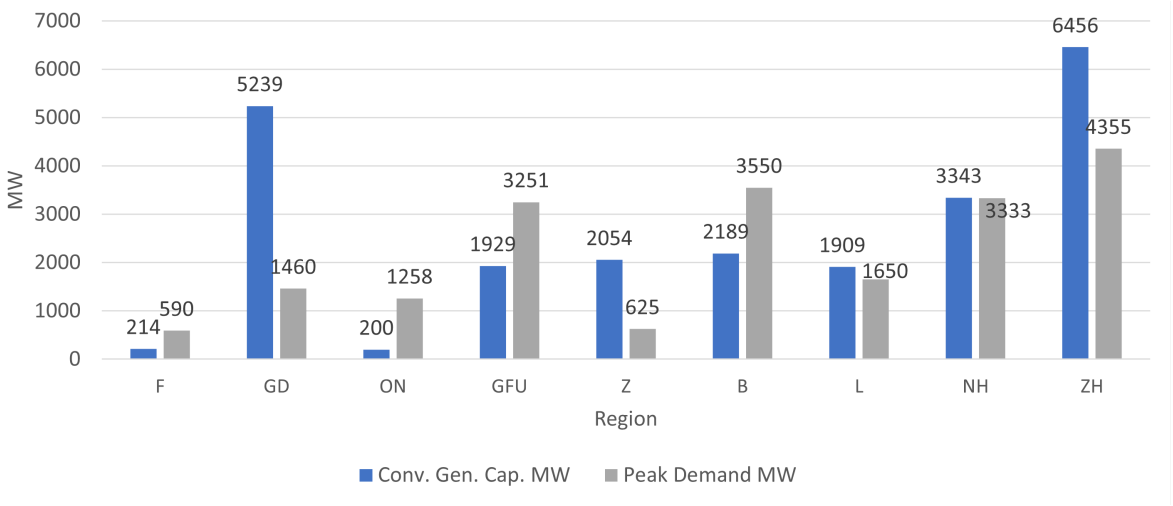


Figure A.1: Conventional Geneartion and Peak Demand per region for the base model

It can also easily be seen from figure A.2 that the amount of generation is not evently distributed among the HV and EHV areas of the network. In Groningen and Drenthe (GD) the amount of generation connected to the 220/380kV part of the network is much higher than for example in Gelderland, Flevoland and Utrecht (GFU).

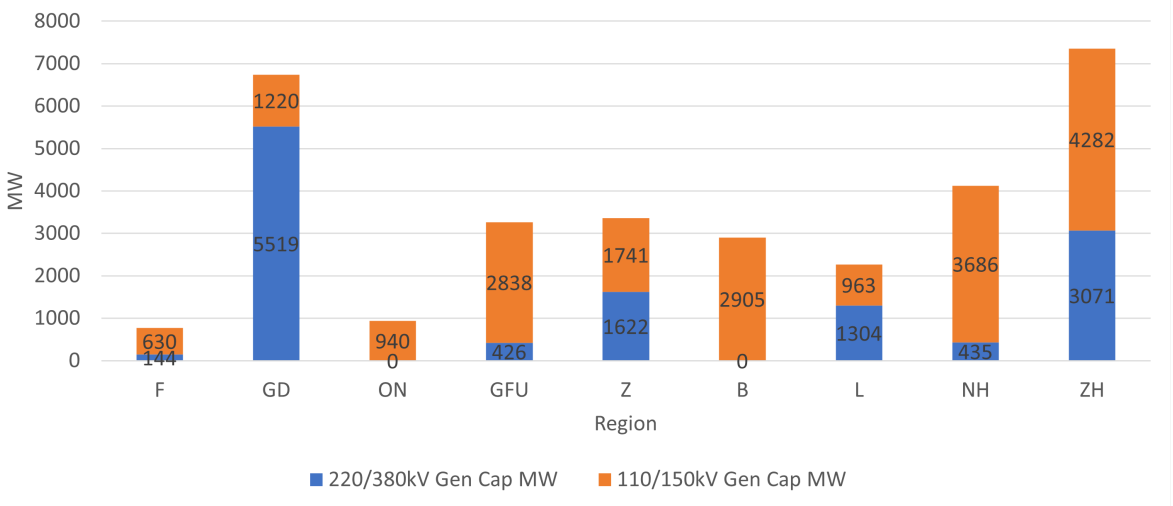


Figure A.2: Total Generation Capacity per region for the Base Model

A.1.2. Base Model: Generation at 380/220kV

This section discusses the location an nominal capacity of the different generators connected to 220/380kV busbars.

Location and Nominal Capacity

The location and capacity of the generators connected to the EHV network was modelled by cross-referencing public information about active generators [55],[37] with the location and size of generators indicated on different grid maps [49], [56]. For some of the synchronous generators, there are parallel units installed, which is indicated in table A.2 under ”Par. No. Of Gen”.

Table A.2: Synchronous Generators at 220/380kV Connections for the base model

Name in PowerFactory	Generators	Modelled as	Terminal	Zone in PowerFactory	Grid Connection Level (kV)	Pnom (MW)	Snom (MVA)	Par. No. Of Gen	Total Capacity (MW)
Gen_COAL_EOS15	Eemshaven A/B (2x790MW)	COAL	EOS380	Groningen en Drenthe	380	790,0	877,8	2,0	1755,6
Gen_COAL_MVL15_1	Maasvlakte3 (1070MW)	COAL	MVL3	Zuid-Holland	380	1070,0	1188,9	1,0	1188,9
Gen_COAL_MVL15_3	NLROTTETH (riverstone) (731MW)	COAL	MVL380	Zuid-Holland	380	731,0	812,2	1,0	812,2
Gen_GAS_BGM15	Bergum 10/20 (2x72MW)	GAS	BGM220	Friesland	220	72,0	80,0	2,0	160,0
Gen_GAS_BSL15	Sloe10/20 (2x435MW)	GAS	BSL380	Zeeland	380	435,2	483,6	2,0	967,1
Gen_GAS_DIM15	Diemen 34 (435MW)	GAS	DIM380	Noord-Holland	380	435,0	483,3	1,0	483,3
Gen_GAS_DKG15	Eemshaven10/20/30 (3x470MW)	GAS	DKG380	Groningen en Drenthe	380	470,0	522,2	3,0	1566,7
Gen_GAS_EEM15_1	Eems5 (361MW)	GAS	EEM220	Groningen en Drenthe	220	361,0	401,1	1,0	401,1
Gen_GAS_EEM15_2	Eems3/4 (359W)	GAS	EEM220	Groningen en Drenthe	220	359,0	398,9	2,0	797,8
Gen_GAS_EEM15_3	Eems6 (359MW)	GAS	EEM380	Groningen en Drenthe	380	359,0	398,9	1,0	398,9
Gen_GAS_EEM15_4	Eems7 (360MW)	GAS	EEM380	Groningen en Drenthe	380	360,0	400,0	1,0	400,0
Gen_GAS_LLS15	Flevo4 (426MW)	GAS	LLS380	Gelder, Flevo en Utrecht	380	426,0	473,3	1,0	473,3
Gen_GAS_MBT15	Claus C (1304 MW)	GAS	MBT380	Limburg	380	1304,0	1448,9	1,0	1448,9
Gen_GAS_MVL15_2	Unit10/Unit20 (Enecogen) (2x422MW)	GAS	MVL380	Zuid-Holland 380kV	380	422,0	468,9	2,0	937,8
Gen_GAS_RBB15	Eems20 (131MW)	GAS	RBB380	Groningen en Drenthe	220	131,0	145,6	1,0	145,6
Gen_GAS_SMH15	Maasstroom CV (426MW)	GAS	SMH380	Zuid-Holland	380	426,0	473,3	1,0	473,3

Table A.3: Static Generators at 220/380 kV for the base model

Name	Year added	Description	Plant Catgory	Terminal	Zone	Grid Connection Voltage (kV)	Pnom (MW)
Gen_WOZ_EOS380_1	2017	Gemini	Wind Offshore	EOS380	Groningen en Drenthe	380	300
Gen_WOZ_EOS380_2	2017	Gemini	Wind Offshore	EOS380	Groningen en Drenthe	380	300
Gen_WOZ_BSL380	2019	Borssele I & II	Wind Offshore	BSL380	Zeeland	380	752

220/380kV Generation per Region

In table A.4 the total Generation Capacity for the EHV (220/380kV) area’s of the network are summarized per region. As can be seen in table A.4 the total amount of generation capacity connected to 220/380kV busbars in the model is around 12500 MW, of which approximately 7800 MW are gasplants and 3400 MW are coalplants. From table A.4 it can be seen that a significant amount of the generation is located in the region of Groningen en Drenthe. Also, it can be seen that there is no generation currently in the 220/380kV areas of Overijssel/Noordoostpolder and Noord-Brabant.

Table A.4: Overview of Generation Capacity at 220/380kV for the base model

Type	Unit	F	GD	ON	GFU	Z	B	L	NH	ZH	Tot.
WOL	MW	0	0	0	0	0	0	0	0	0	*0*
WOZ	MW	0	600	0	0	752	0	0	0	0	*1352*
ZON PV	MW	0	0	0	0	0	0	0	0	0	*0*
GAS	MW	144	3339	0	426	870	0	1304	435	1270	*7788*
NUCL	MW	0	0	0	0	0	0	0	0	0	*0*
COAL (/BIOMASS)	MW	0	1580	0	0	0	0	0	0	1801	*3381*
Tot. HV Gen. Cap per zone	**MW**	**144**	**5519**	**0**	**426**	**1622**	**0**	**1304**	**435**	**3071**	***12521***

A.1.3. Base Model: Generation at 110/150kV

In the model, the 110/150kV parts of the network and their lower voltage connections are represented by one separate busbar. At this bus the total amount of conventional generation is aggregated and represented by 1 synchronous generator, with the exception of nuclear and coal plants which are represented as separate generators. Renewable generation is sorted into 3 categories for the current model: Solar (PV), Onshore Wind (WOL) and Offshore Wind (WOZ). For each of these categories one generator is created and connected directly to the 110/150 bus. An example is shown in figure A.3

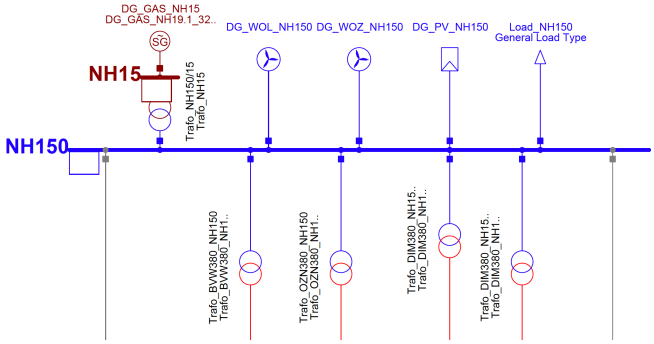


Figure A.3: Example of the 150kV busbar for Noord-Holland

Location and Nominal Capacity

In table A.5 a list is given of the different synchronous and static generators connected to HV (110/150kV) areas. These numbers were taken from KCD2017 [31] and adjusted with data from the ENTSOE transparency platform [37], checking the capacity as well as whether the generators mentioned in KCD2017 were really mothballed or still active.

Table A.5: Synchronous Generators at 110/150kV for the base model

Name	Generators	Modelled as	Terminal	Zone in PowerFactory	Grid Connection Level (kV)	Prated (MW)	Par. No. Of Gen	Prated Total (MW)
DG_GAS_F15	WKK (70)	WKK (70)	F110	Friesland	110	70,0	1,0	70,0
DG_GAS_GDO15	Delesto2* (343MW) blackstart, WKK (320)	WKK (320)	GDO110	Groningen en Drenthe	110	320,0	1,0	320,0
DG_GAS_GFU15	Flevo 5 (415MW), Lage Weide 6 (247MW), Merwedekanaal 11*** en 12 (103,227 MW), WKK (511)	GAS (992), WKK (511)	GFU150	Gelder Flevo en Utrecht	110	1503,0	1,0	1503,0
DG_GAS_ON15	WKK (220)	WKK (200)	ON110	Overijssel en Noordoostpolder	110	200,0	1,0	200,0
DG_BIOM/COAL_B15_2	Amer-9 of 91 (620MW)	GAS(620)	B150	Noord-Brabant	150	620,0	1,0	620,0
DG_GAS_B15_1	Moerdijk 1,2 (343,426MW), Afval (100), WKK (700)	GAS (769), AFVAL (100), WKK (700)	B150	Noord-Brabant	150	1569,0	1,0	1569,0
DG_GAS_L15	Swentibold1 (245MW), Claus CCC4**(495), WKK (360)	GAS (245), WKK (360)	L150	Limburg	150	605,0	1,0	605,0
DG_GAS_NH15	Hemweg 8,9 (650,440MW) Ijmond (144MW), Velsen 24/25 (725MW), Diemen 33 (249MW), WKK (700)	GAS (2208), WKK (700)	NH150	Noord-Holland	150	2908,0	1,0	2908,0
DG_GAS_Z15_2	Elsta1 (440MW), WKK (250)	GAS (440), WKK (250)	Z150	Zeeland	150	690,0	1,0	690,0
DG_GAS_ZH15	EDH (97MW), Pergen1/2 (2x125MW), Rijmond REC (810MW), Roca (1,2),3 (49,220MW), Leiden 12(81MW), WKK (1800)	GAS(1585), WKK (1800)	ZH150	Zuid-Holland	150	3385,0	1,0	3385,0
DG_NUCL_Z15_1	Borssele30 (494MW)	NUCL	Z150	Zeeland	150	494,0	1,0	494,0

Table A.6: Static Generators at 110/150 kV for the base model

Name	Plant Catgory	Terminal	Zone	Grid Connection Voltage (kV)	Pnom (MW)
DG_PV_F110	Photovoltaic	F110	Friesland	110	210
DG_WOL_F110	Wind Onshore	F110	Friesland	110	350
DG_PV_GDO110	Photovoltaic	GDO110	Groningen en Drenthe	110	340
DG_WOL_GDO110	Wind Onshore	GDO110	Groningen en Drenthe	110	560
DG_PV_ON110	Photovoltaic	ON110	Overijssel en Noordoostpolder	110	290
DG_WOL_ON110	Wind Onshore	ON110	Overijssel en Noordoostpolder	110	450
DG_PV_GFU150	Photovoltaic	GFU150	Gelder Flevo en Utrecht	150	289
DG_WOL_GFU150	Wind Onshore	GFU150	Gelder Flevo en Utrecht	150	1046
DG_PV_L150	Photovoltaic	L150	Limburg	150	288
DG_WOL_L150	Wind Onshore	L150	Limburg	150	70
DG_PV_B150	Photovoltaic	B150	Noord-Brabant	150	476
DG_WOL_B150	Wind Onshore	B150	Noord-Brabant	150	240
DG_PV_NH150	Photovoltaic	NH150	Noord-Holland	150	200
DG_WOL_NH150	Wind Onshore	NH150	Noord-Holland	150	400
DG_WOZ_NH150	Wind Offshore	NH150	Noord-Holland	150	300
DG_PV_Z150	Photovoltaic	Z150	Zeeland	150	71
DG_WOL_Z150	Wind Onshore	Z150	Zeeland	150	486
DG_PV_ZH150	Photovoltaic	ZH150	Zuid-Holland	150	178
DG_WOL_ZH150	Wind Onshore	ZH150	Zuid-Holland	150	693
DG_WOZ_ZH150	Wind Offshore	ZH150	Zuid-Holland	150	150

110/150kV Generation per Region

In table A.7 the total Generation Capacity for 110/150kV area's are summarized per region for the base model.

Table A.7: Overview of Generation Capacity at 110/150kV for the base model

Type	Unit	F	GD	ON	GFU	Z	B	L	NH	ZH	*Totals*
WOL	MW	350	560	450	1046	486	240	70	350	590	*4142*
WOZ	MW	0	0	0	0	0	0	0	228	129	*357*
ZON PV	MW	210	340	290	289	71	476	288	200	178	*2342*
GAS	MW	0	0	0	992	440	869	245	2208	1585	*6339*
WKK en overig	MW	70	320	200	511	250	700	360	700	1800	*4911*
NUCL	MW	0	0	0	0	494	0	0	0	0	*494*
COAL (/BIOMASS)	MW	0	0	0	0	0	620	0	0	0	*620*
Tot. HV Gen. Cap.	**MW**	**630**	**1220**	**940**	**2838**	**1741**	**2905**	**963**	**3686**	**4282**	***19205***

A.1.4. Base Model: Demand

For the demand, it is currently assumed that all the national power consumption is located at the HV busbars representing each region (110/150kV). The demand is modelled per region by adding a single aggregate load at each of the HV buses, see also figure A.3.

On the ENTSOE transparency platform only the total load for the whole of NL is available. Therefore, a distribution key was created according to the peak demands mentioned in KCD2017 [38], shown in table A.8.

Table A.8: Peak Demand for the base model [31]

	Unit	F	GD	ON	GFU	Z	B	L	NH	ZH	*Totals*
Peak Demand	MW	590	1460	1258	3251	625	3550	1650	3333	4355	*20072*
Distribution	%	2,9	7,3	6,3	16,2	3,1	17,7	8,2	16,6	21,7	*100*

This approach was validated by comparing the peak demand to the annual electricity consumption per region. The annual electricity consumption was taken from ”klimaatmonitor.nl” which uses statistics from CBS [39]. In table A.9 the peak demand and average annual electricity consumption are expressed as % of the national total. It can be seen that both approaches lead to approximately the same distribution. A sensitivity could be introduced to further investigate the impact of this distribution in simulations of future scenarios.

Table A.9: Distribution of national demand according to peak and average electricity consumption in 2019

	F110	ON110	GD110	GFU150	Z150	B150	L150	NH150	ZH150
Peak Demand (%)	2,94	6,27	7,27	16,20	3,11	17,69	8,22	16,61	21,70
Average Electricity Consumption (%)	3,01	5,72	8,77	17,09	2,93	16,18	8,56	18,19	19,55
Difference (%)	0,07	-0,55	1,49	0,90	-0,18	-1,51	0,34	1,59	-2,15

A.1.5. Base Model: Interconnections

For the base model the interconnection capacities given KCD2017 are used [19]. For each country the amount of transfer capacity to and from the Netherlands is specified. The capacities for some of different connections to Belgium and Germany were unclear, therefore an even distribution was assumed among the unknown connections. In table B.2 the assumptions regarding the amount of maximum capacity per connection are specified used for the model.

Table A.10: Interconnection Capacities for the Base Model

Connection Names	Country	Cap. per Country 2018	Pmax (MW) 2018
IC_ELIA_MBT380	Belgium	1400	700
IC_ELIA_ZVL380	Belgium		700
IC_COBRA_EOS380	Denmark	700	700
IC_AMPRION_GNA380	Germany Z	3950*	650
IC_AMPRION_NDR380	Germany Z		650
IC_AMPRION_OBZ380(SDF380)	Germany Z		650
IC_TenneT_DIL380	Germany N		2000
IC_StatNett_EEM380	Norway	700	700
IC_BritNed_MVL380	UK	1000	1000
Total Exchange		*7750*	*7750*

*The cross-zonal capacity for Germany is divided equally among North Connection (2000MW) and the Southern Connections (3*650MW) to Germany for the base scenario as was done in an older report prepared for the European Commission when investigating loopflows[57].

A.2. The 2030 Model

For the 2030 Model the amount of generation and demand was determined according to numbers and graphs found in KCD2020 [2]. For the case study only the numbers from the scenario KA20 will be considered. However, in this section the numbers for the other scenarios are also discussed as these could be used for other future simulations.

A.2.1. 2030: Installed Generation Capacity

As can be seen in figure A.4 the total amount of conventional generation declines in all scenarios, whilst the (peak) demand increases. In figure A.5 the division of the generation among HV and EHV areas of the model is shown.

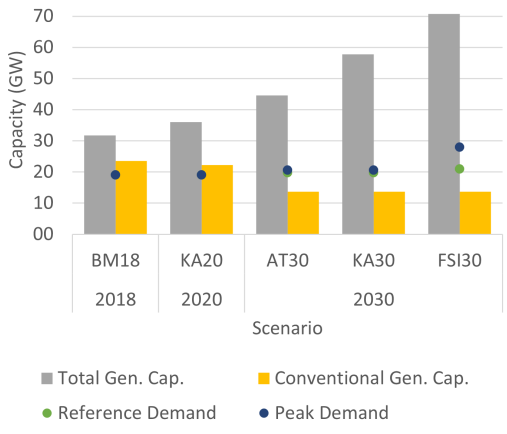


Figure A.4: Total (Conventional) Generation Capacity per Scenario and corresponding Demand

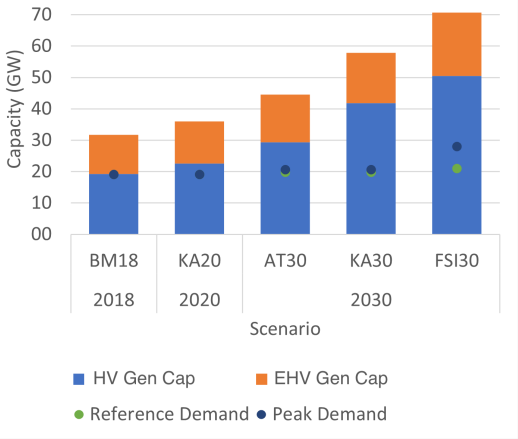


Figure A.5: Total LV and HV Generation Capacity per Scenario and corresponding Demand

In table A.11 the total amount of generation and demand for each of the different considered scenarios is given. In the last part of the table, figures are given showing the ratio of total generation to the peak demand and the ratio of the conventional (synchronous) generation to the peak demand.

Table A.11: Total Generation and Demand for the different scenarios for 2030

	Unit	**BM18**	**KA20**	**AT30**	**KA30**	**FSI30**
LV Gen. Cap.	GW	19,2	22,5	29,4	41,9	50,5
HV Gen. Cap.	GW	12,5	13,5	15,2	15,9	20,2
Total Gen. Cap.	**GW**	**31,7**	**36,0**	**44,6**	**57,8**	**70,7**
Conventional Gen. Cap.	*GW*	*23,5*	*22,2*	*13,7*	*13,7*	*13,7*
Reference Demand	GW	19,1	19,1	19,8	19,8	21,0
Peak Demand	GW	19,1	19,1	20,6	20,6	28,0
Gen/Peak Demand	-	1,66	1,89	2,17	2,81	2,53
Conv Gen/Peak Demand	-	1,23	1,16	0,67	0,67	0,49

In the following sections, the specific developments in the EHV and HV areas of the model will be discussed.

A.2.2. 2030: Generation at 220/380kV

The modelling of the amount of Generation for 2030 at 220/380kV will be according to the scenarios listed in KCD2020 [2]. The total amount of generation connected to 220/380kV parts of the network is given in table A.12 for each of the scenarios for 2030.

Table A.12: Total Generation for different scenarios at 220/380kV

	Unit	BM18	KA20	AT30	KA30	FSI30
WOL	GW	0	0	0	0	0
WOZ	GW	1,35	2,08	10,25	10,95	14,25
ZON PV	GW	0	0	0	0	0
GAS	GW	7,79	8,04	5,00	5,00	4,60
WKK (/OTHER)	GW	0	0	0	0	0
NUCL	GW	0	0	0	0	0
COAL (/BIOMASS)	GW	3,38	3,38	0	0	1,40
Tot. HV Gen. Cap.	*GW*	12,52	13,50	15,25	15,95	20,25

As can be seen from figure A.2 there will only be offshore wind, gas and coal connected to the 380/220kV busbars in the model. This means that other types of generation will be connected at 110/150kV levels. According to KVD2020 however, there should also be some Solar PV and onshore wind connected to the 220/380kV areas in some of the scenarios, as can be seen in figure A.6 [2]. Also, for the FSI scenario there should be some demand within HV areas of the network [2].



Figure A.6: 220/380kV Generation Capacity from KCD2020 [2]

The locations however where all these developments occur are not mentioned or speculated on. The allocation/decline in conventional generation is approached by proportionally lowering the installed capacity of each generator. In real life situations this would not be realistic. For future research this should be considered, however for this study it is less of an issue as the case study will focus mainly on a situation with a surplus of VRES. The developments and locations in offshore wind are discussed further in section B.2.2

A.2.3. 2030: Generation at 110/150kV

KCD2020 has defined regional outcomes for each of the scenarios for 2030 [2]. This was used to model the amount of generation for the each of the 110/150kV regions. By following these developments for the different 2030 scenarios, the most realistic representation of the change per region can be achieved. In figure A.7 the total amount of generation per scenario at 110/150kV is shown. These numbers are based on the following assumptions:

- The offshore wind that is already connected to the 110/150kV parts of the network will remain connected there but all new offshore wind will be connected to 220/380kV.
- All of the onshore wind will be connected to 110/150kV areas
- The only coal/biomass plant Amer 9 in Brabant, will be taken out of production by 2030. This means there will be no biomass or coal based generation at the lower voltage parts of the network.

- The nuclear plant will remain connected to the lower voltage part of the network in Zeeland and will remain operational.
- All of the WKK installations will be located at the 110/150kV.
- There will still also be gas plants operating in lower voltage areas (defined on the basis of regional development)

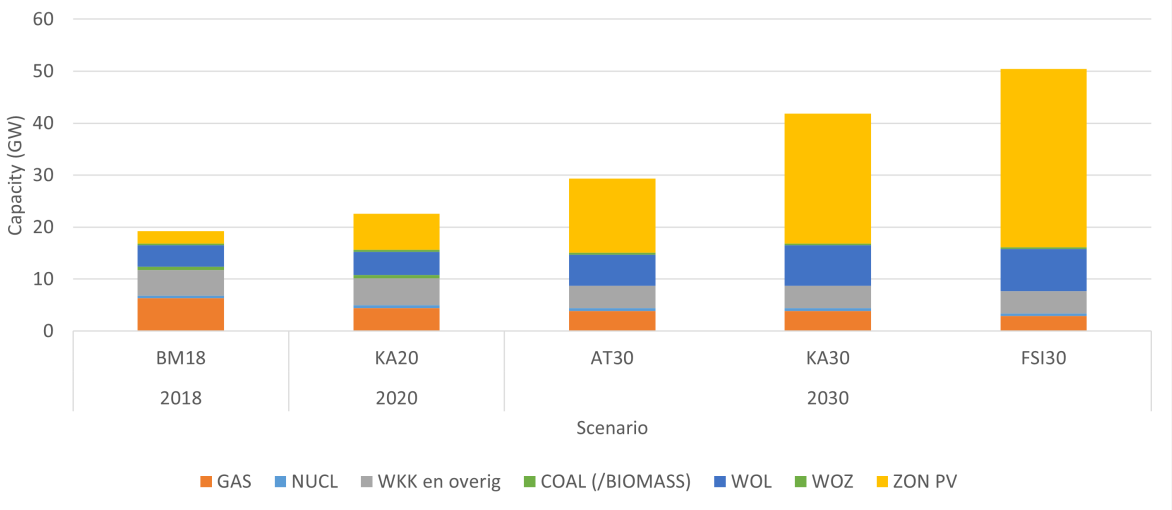


Figure A.7: Total Generation Capacity at 110/150kV for different 2030 Scenarios

Table A.13: Total Generation for different scenarios at 110/150kV

	Unit	BM18	KA20	AT30	KA30	FSI30
WOL	GW	4,14	4,50	6,00	7,80	8,10
WOZ	GW	0,36	0,35	0,35	0,35	0,35
ZON PV	GW	2,34	6,90	14,30	25,00	34,30
GAS	GW	6,34	4,46	3,90	3,90	2,90
WKK en overig	GW	4,91	5,21	4,31	4,31	4,31
NUCL	GW	0,49	0,49	0,49	0,49	0,49
COAL (/BIOMASS)	GW	0,62	0,62	0,00	0,00	0,00
Tot. LV Gen. Cap.	GW	*19,21*	*22,53*	*29,35*	*41,85*	*50,45*

Installed Generation Capacity for KA30 Scenario used for Case Study

In table A.17 the total amount of installed capacity for each of the defined regions within the PowerFactory model is given for the KA30 Scenario. In table A.14 and A.15 the total amount of generation at 220/380KV and 110/150kV level for each of region is given.

Table A.14: Total Installed Generation Capacity at 220/380kV level for the 2030 Model

Type	**Unit**	**F**	**GD**	**ON**	**GFU**	**Z**	**B**	**L**	**NH**	**ZH**	***Totals***
Onshore Wind	MW	0	0	0	0	0	0	0	0	0	*0*
Offshore Wind	MW	0	1378	0	0	3712	0	0	2226	3604	*10920*
Solar	MW	0	0	0	0	0	0	0	0	0	*0*
Gas	MW	85	1972	0	252	514	0	770	257	750	*4600*
Wkk	MW	0	0	0	0	0	0	0	0	0	*0*
Nuclear	MW	0	0	0	0	0	0	0	0	0	*0*
Coal	MW	0	0	0	0	0	0	0	0	0	*0*
Total	**MW**	**85**	**3350**	**0**	**252**	**4226**	**0**	**770**	**2483**	**4354**	***15520***

Table A.15: Total Installed Generation Capacity at 110/150kV level for the 2030 Model

Type	**Unit**	**F**	**GD**	**ON**	**GFU**	**Z**	**B**	**L**	**NH**	**ZH**	***Totals***
Onshore Wind	MW	700	700	540	2400	700	260	30	800	1150	*7280*
Offshore Wind	MW	0	0	0	0	0	0	0	230	150	*380*
Solar	MW	1600	5200	2400	5500	1150	2550	1250	2400	2700	*24750*
Gas	MW	0	500	80	850	380	390	450	650	1000	*4300*
Wkk	MW	70	250	260	400	150	620	280	700	1700	*4430*
Nuclear	MW	0	0	0	0	494	0	0	0	0	*494*
Coal	MW	0	0	0	0	0	0	0	0	0	*0*
Total	**MW**	**2370**	**6650**	**3280**	**9150**	**2874**	**3820**	**2010**	**4780**	**6700**	***41634***

Table A.16: Total Generation and Demand for each region for the 2030 model

	Unit	**F**	**GD**	**ON**	**GFU**	**Z**	**B**	**L**	**NH**	**ZH**	**Totals**
220/380kV Gen Cap	MW	85	3350	0	252	4226	0	770	2483	4354	15520
110/150kV Gen Cap	MW	2370	6650	3280	9150	2874	3820	2010	4780	6700	41634
Tot.Gen. Cap.	**MW**	**2455**	**10000**	**3280**	**9402**	**7100**	**3820**	**2780**	**7263**	**11054**	**57154**

Table A.17: Total amount of installed generation capacity for each technology per region for the 2030 model

Type	**Unit**	**F**	**GD**	**ON**	**GFU**	**Z**	**B**	**L**	**NH**	**ZH**	**Totals**
Onshore Wind	MW	700	700	540	2400	700	260	30	800	1150	7280
Offshore Wind	MW	0	1378	0	0	3712	0	0	2456	3754	11300
Solar	MW	1600	5200	2400	5500	1150	2550	1250	2400	2700	24750
Gas, Wkk and Other	MW	155	2722	340	1502	1044	1010	1500	1607	3450	13330
Nuclear	MW	0	0	0	0	494	0	0	0	0	494
Tot.Gen. Cap.	*MW*	*2455*	*10000*	*3280*	*9402*	*7100*	*3820*	*2780*	*7263*	*11054*	*57154*

A.2.4. 2030: Demand

The distribution of the demand for each of the 110/150kV areas is modelled according to the peak demands listed in KCD2020 per region [2], presented in table A.18. The approach for the distribution of the national demand follows the same approach as for the base model, see section A.1.4. Modelling of the ”extra demand” specifically at 220/380kV levels is neglected as there was no information available for this (and it is only relevant in the FSI30 scenario).

Table A.18: Peak Demand and share of total national assumed for each region for 2030

	Unit	**F**	**GD**	**ON**	**GFU**	**Z**	**B**	**L**	**NH**	**ZH**	**Totals**
Peak Demand	MW	750	1600	1700	4300	1180	3900	2200	5500	5300	-
Distribution	%	2,84	6,05	6,43	16,27	4,46	14,76	8,32	20,81	20,05	100

A.2.5. 2030: Interconnections

For the base model the details concerning interconnections are discussed in section A.1.5. For the 2030 model, there is an increase in capacity between Germany and the Netherlands due to a new connection between Doetinchem and Niederrhein (NDR380) as well as upgrades made to other parts of the Dutch Transmission Network. These developments are based on the numbers provided in KCD2017 [19]. As mentioned before, the capacities for some of different connections to Belgium and Germany were unclear, therefore an even distribution was assumed among the unknown connections.

Table A.19: Interconnection Capacities for base and 2030 model

Connection Names	Country	Cap. per Country 2018	Pmax (MW) 2018	Cap. per Country 2030	Pmax (MW) 2030
IC_ELIA_MBT380	Belgium	1400	700	3400	1700
IC_ELIA_ZVL380	Belgium	-	700	-	1700
IC_COBRA_EOS380	Denmark	700	700	700	700
IC_AMPRION_GNA380	Germany	3950*	650	5000*	750
IC_AMPRION_NDR380	Germany	-	650	-	1500
IC_AMPRION_OBZ380(SDF380)	Germany	-	650	-	750
IC_TenneT_DIL380	Germany	-	2000	-	2000
IC_StatNett_EEM380	Norway	700	700	700	700
IC_BritNed_MVL380	UK	1000	1000	1000	1000
Total Exchange		*7750*	*7750*	*10800*	*10800*

B

Topology per Region and Upgrades for 2030 Model

B.1. Overview

In this chapter, the different developments that lead to a change in network topology of the base model are discussed. The initial model is based on a single line diagram of 2019 with corresponding network data, hence only the developments that occur after this time horizon will be discussed. There are cases of upgrades to the existing system as well as addition or removal of certain network components.First, general developments are discussed after which different specific projects will be highlighted according to the corresponding region in which they are happening. For more details about the network components within the different regions, see appendix C.

Projects that are already incorporated into the single line diagram of 2019 and thus the base model (BM18):

1. Randstad 380kV Noordring (see section: Noord-Holland)
2. Doetinchen-Wesel 380kV (see section: Gelderland, Flevoland en Utrecht)

The most important new projects and developments that are added to the model are:

1. Noord-West 380kV (see section: Groningen & Drenthe)
2. Zuid-West 380kV (see section: Zeeland and Noord-Brabant)
3. Beter Benutten Bestaande 380kV

B.2. System wide upgrades

In the following sections, the project: BBB380, the integration of extra offshore wind capacity and additional interconnection capacity will be discussed.

B.2.1. Project BBB380: Beter Benutten Bestaande 380kV

According to KCD2020 different 380kV transmission lines will be upgraded to 2x2635 MVA. Some of these upgrades were already part of other projects whereas other proposals were still under investigation according to other parts of KCD2020. All of the transmission lines listed under this project have been incorporated into the 2030 Model. They have been adjusted to have the properties described in section 3.2.3 for new transmission lines. It concerns the following connections:

- Zwolle-Hengelo (ZL380-HGL380)
- Ens-Zwolle (ENS380-ZL380)
- Eindhoven-Maasbracht (EHV380-MBT380)
- Geertruidenberg-Krimpen (GT380-KIJ380)

- Lelystad-Ens(LLS380-ENS380)
- Diemen-Lelystad (DIM380-LLS380)

B.2.2. Offshore Wind

In table A.3 the Offshore Wind farms connected to the 220/380kV grid and the years in which they are added to the model are shown. This was modelled according to KCD2020 and government publications for offshore wind [40] [41]. For 2019 this means that windfarm Gemini as well as Borssele I and II are connected to the HV network. For the 2020 scenarios Borssele II, IV and also Two Towers (Kavel V) are added to the offshore wind generation capacity. For 2025 Hollandse Kust Noord, -Zuid, -West are added. For 2030 Ijmuiden Ver Alpha, Beta and Ten Noorden van de Waddeneilanden are added for the reference scenario (the KA Scenario from KCD2020 [2]). At time of the case study, the most suitable location for the connection was not yet clear [40], therefore the new substation of VVL380 was selected. However, for future simulations, EEM380 should be considered as this has now been selected as the most suitable location [58]. This has been adjusted in the final model. For the other scenarios such as FSI30, offshore wind capacity needs to be expanded, however again it was not investigated which location is then most suitable or whether the capacity should be divided among existing farms for simulations.

Table B.1: List of New Offshore Wind connections at 220/380 kV

Name	Year added	Description	Plant Catgory	Terminal	Zone	Grid Connection Voltage (kV)	Pnom (MW)
Gen_WOZ_EOS380_1	2017	Gemini	Wind Offshore	EOS380	Groningen en Drenthe 380/220kV	380	300
Gen_WOZ_EOS380_2	2017	Gemini	Wind Offshore	EOS380	Groningen en Drenthe 380/220kV	380	300
Gen_WOZ_BSL380	2019	Borssele I & II	Wind Offshore	BSL380	Zeeland 380kV	380	752
Gen_WOZ_BSL3&4	2020	Borssele III, IV & V	Wind Offshore	BSL380	Zeeland 380kV	380	750
Gen_WOZ_MVL380_N1	2022	Hollandse Kust Zuid	Wind Offshore	MVL380	Zuid-Holland 380kV	380	1400
Gen_WOZ_HKN	2023	Hollandse Kust Noord	Wind Offshore	BVW380	Noord-Holland 380kV	380	700
Gen_WOZ_HKW	2025	Hollandse Kust West	Wind Offshore	BVW380	Noord-Holland 380kV	380	1400
Gen_WOZ_TNW	2027	Ten Noorden van de Waddeneilanden	Wind Offshore	BGM380/VVL380 /EEM380 [1]	Groningen en Drenthe 380/220kV or Friesland 380kV	380	700
Gen_WOZ_IJMA	2028	Ijmuiden Ver Alpha	Wind Offshore	BSL380	Zeeland 380kV	380	2000
Gen_WOZ_IJMB	2029	Ijmuiden Ver Beta	Wind Offshore	MVL380	Zuid-Holland 380kV	380	2000

2

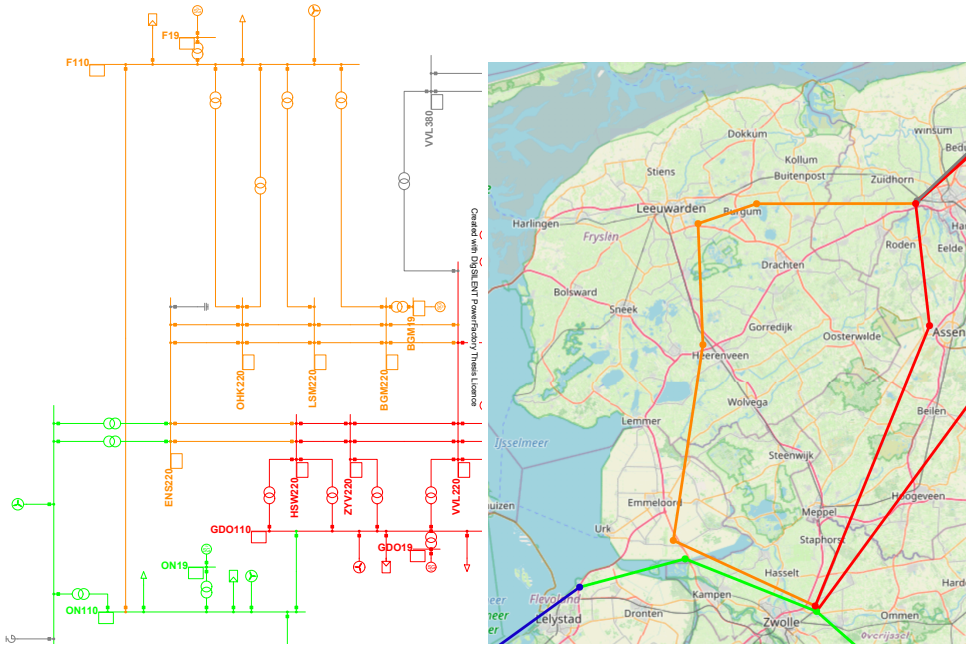
B.2.3. Increase in Interconnection Capacity

The different developments for the increase in interconnector capacity is discussed in section A.2.5 but are repeated here as these numbers will have a large impact on the different power flows that are possible within the Dutch transmission network. As mentioned before, for the 2030 model there is an increase in capacity between Germany and the Netherlands due to a new connection between Doetinchem and Niederrhein (NDR380) as well as upgrades made to other parts of the Dutch Transmission Network.The capacities for some of different connections to Belgium and Germany were unclear, therefore an even distribution was assumed among the unknown connections. How these capacities for 2050 will develop has not yet been investigated. Another development mentioned is the North Sea Power Hub in KCD2017 [59], however numbers for these capacities have also not yet been investigated.

Table B.2: Interconnection Capacities for base and 2030 model

Connection Names	Country	Cap. per Country 2018	Pmax (MW) 2018	Cap. per Country 2030	Pmax (MW) 2030
IC_ELIA_MBT380	Belgium	1400	700	3400	1700
IC_ELIA_ZVL380	Belgium	-	700	-	1700
IC_COBRA_EOS380	Denmark	700	700	700	700
IC_AMPRION_GNA380	Germany	3950*	650	5000*	750
IC_AMPRION_NDR380	Germany	-	650	-	1500
IC_AMPRION_OBZ380(SDF380)	Germany	-	650	-	750
IC_TenneT_DIL380	Germany	-	2000	-	2000
IC_StatNett_EEM380	Norway	700	700	700	700
IC_BritNed_MVL380	UK	1000	1000	1000	1000
Total Exchange		*7750*	*7750*	*10800*	*10800*

B.3. Friesland



(a) Friesland Single Line Diagram **(b)** Friesland Simplified Geographic

Figure B.1: Friesland in PowerFactory

Transformers in Louwsmeer, Oudhaske en Bergum

In KCD2017 there is mention of adding an extra transformer to Louwsmeer (LSM220) as well as Oudhaske (OHK220) to connect the 220KV and the 110kV network. This would mean having 3 transformers each. Currently the model has been modelled assuming the amount and ratings illustrated by the netkaart of hoogspanningsnet.com [30] which can be seen in figure B.2. As listed in table B.3 this means 3 transformers connecting OHK220 to F110, and 2 tranformers connecting LSM220 to F110.

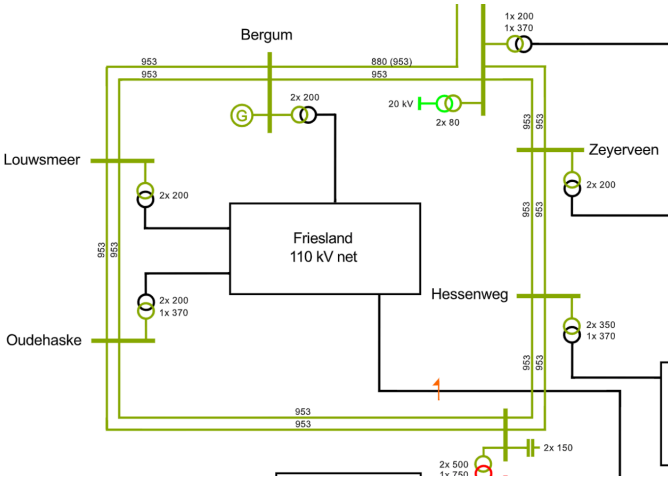


Figure B.2: Connection of LSM and OHK220 to F110 [30]

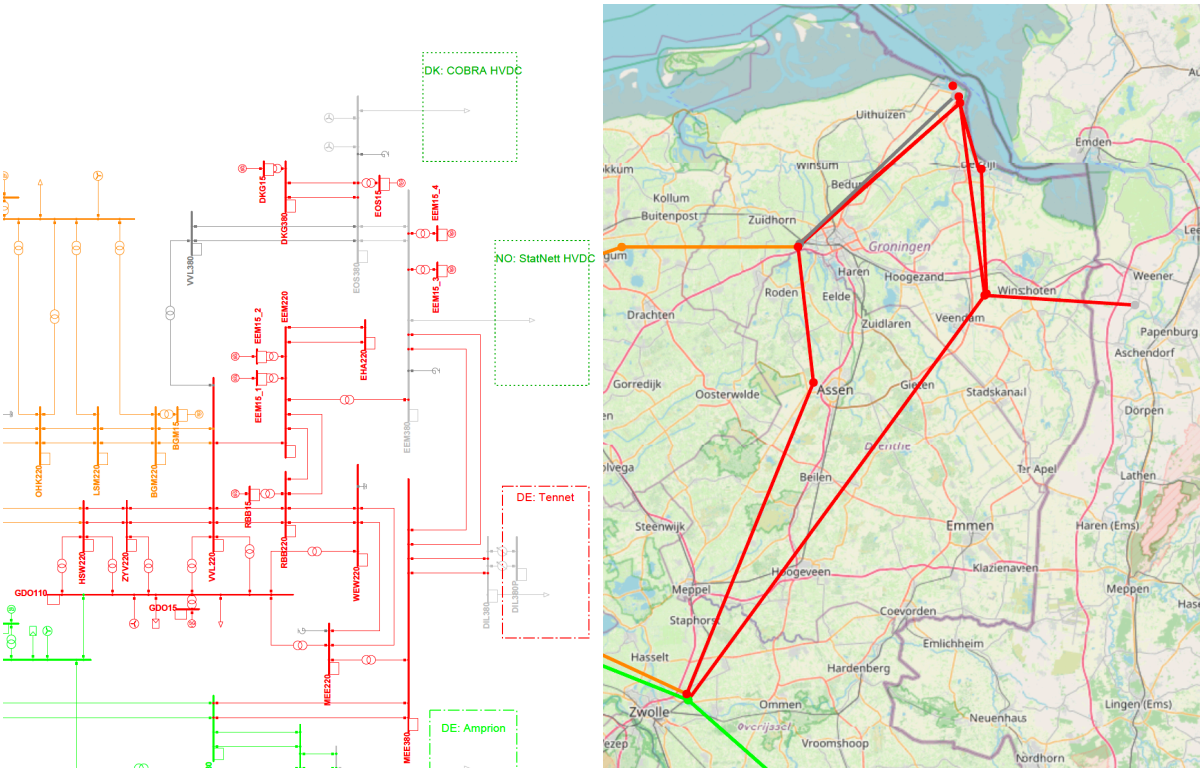
Table B.3: Adjusted/Assumptions Transformers in Friesland

Name	HV Terminal	LV Terminal	Zone	Parallel number of Trafos	S_total (MVA)	S_rated (MVA)	HV side (kV)	LV side (kV)
Trafo_LSM220_F110	LSM220	F110	Friesland 110	2	400	200	220	110
Trafo_OHK220_F110_1	OHK220	F110	Friesland 110	2	400	200	220	110
Trafo_OHK220_F110_2	OHK220	F110	Friesland 110	1	370	370	220	110

Connection to ON110

Currently, the connection of the lower voltage grid F110 to the ON110 grid is modelled as out of service, as according to KCD2017 this connection is only used in special situations [31].

B.4. Groningen en Drenthe



(a) Groningen en Drenthe Single Line Diagram

(b) Groningen en Drenthe Simplified Geographic Representation

Figure B.3: Groningen en Drenthe in PowerFactory

Project Noord-West 380 kV

In KCD2017 it is mentioned that there is need for expansion of transmission capacity between the North and the center of the Netherlands [31]. On the site of the government (as well as on a specific website of the project), the following possible plans are mentioned [60][61]:

- Building of VVL380 high voltage station
- Transmission line EOS380-VVL380: 2 circuits, (possible) upgrade to 4 circuits (2635MVA each)
- Transformers VVL380/VVL220: 5500 MVA total
- Transmission line VVL380-ENS380 (in future): data unsure

For this project, the inpassingsplan from 2017 was used to model the connection between EOS380 and VVL380 [62].The assumptions for the current model:

- 2023: Connection between EOS380 and VVL380: 2 transmission lines of 40km with max 4kA each (2635 MVA), see table B.5. It was mentioned that although initially it was thought that at least 4 circuits would be necessary, for the coming years 2 circuits are sufficient.

- 2023: Transformers VVL380/VVL220, 7 in total (750 MVA each), total capacity of 5250 MVA, see table B.4.
- 2025: Connection between VVL220 and RBB220: Out of Service, see table B.5.

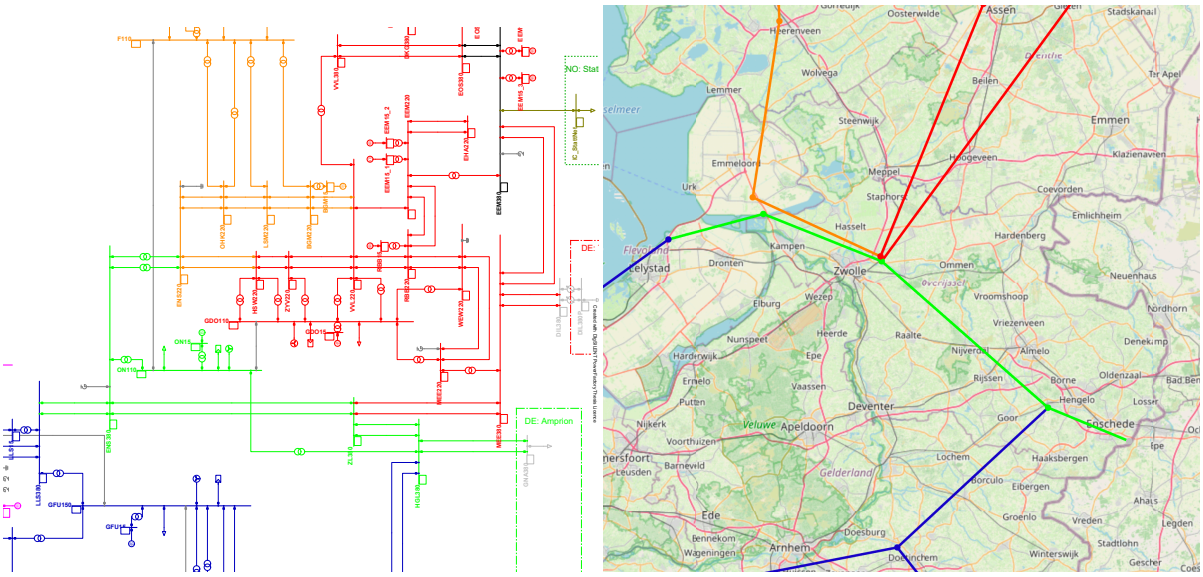
Table B.4: Adjusted Transformers in Groningen en Drenthe

Name	HV Terminal	LV Terminal	Zone	Parallel number of Trafos	S_total (MVA)	S_rated (MVA)	HV side (kV)	LV side (kV)
Trafo_VVL380_VVL220	VVL380	VVL220	Groningen en Drenthe 220/380kV	3 (4) becomes 7	3000	750	380	220

Table B.5: Added or Removed Transmission lines in Groningen en Drenthe

Name	Type in PowerFactory	Terminal i	Terminal j	Zone	Length (km)
EEM220_RBB220_A	Adj_Line_220kV_2.3kA	EEM220	RBB220	Groningen en Drenthe 220/380kV	0,04
EEM220_RBB220_B	Adj_Line_220kV_2.3kA	EEM220	RBB220	Groningen en Drenthe 220/380kV	0,04
EOS380_VVL380_1	Adj_Line_380kV_4kA	EOS380	VVL380	Groningen en Drenthe 220/380kV	40
EOS380_VVL380_2	Adj_Line_380kV_4kA	EOS380	VVL380	Groningen en Drenthe 220/380kV	40

B.5. Overijssel en Noordoostpolder

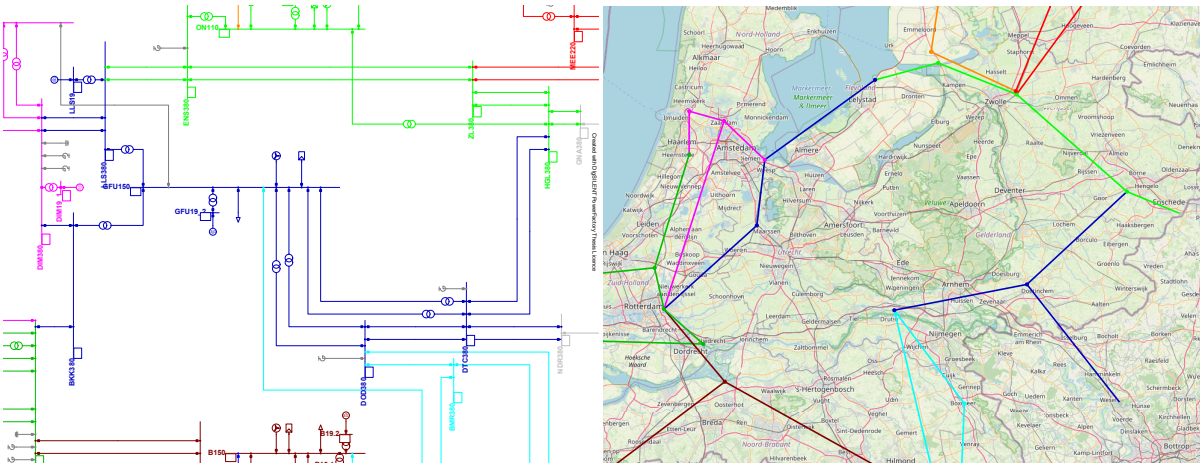


(a) ON Single Line Diagram

(b) ON Simplified Geographic Representation

Figure B.4: Overijssel en Noordoostpolder (ON) in PowerFactory

B.6. Gelderand, Flevoland en Utrecht



(a) GFU Single Line Diagram

(b) GFU Geographic 220/380kV

Figure B.5: Gelderland,Flevoland en Utrecht (GFU) in PowerFactory

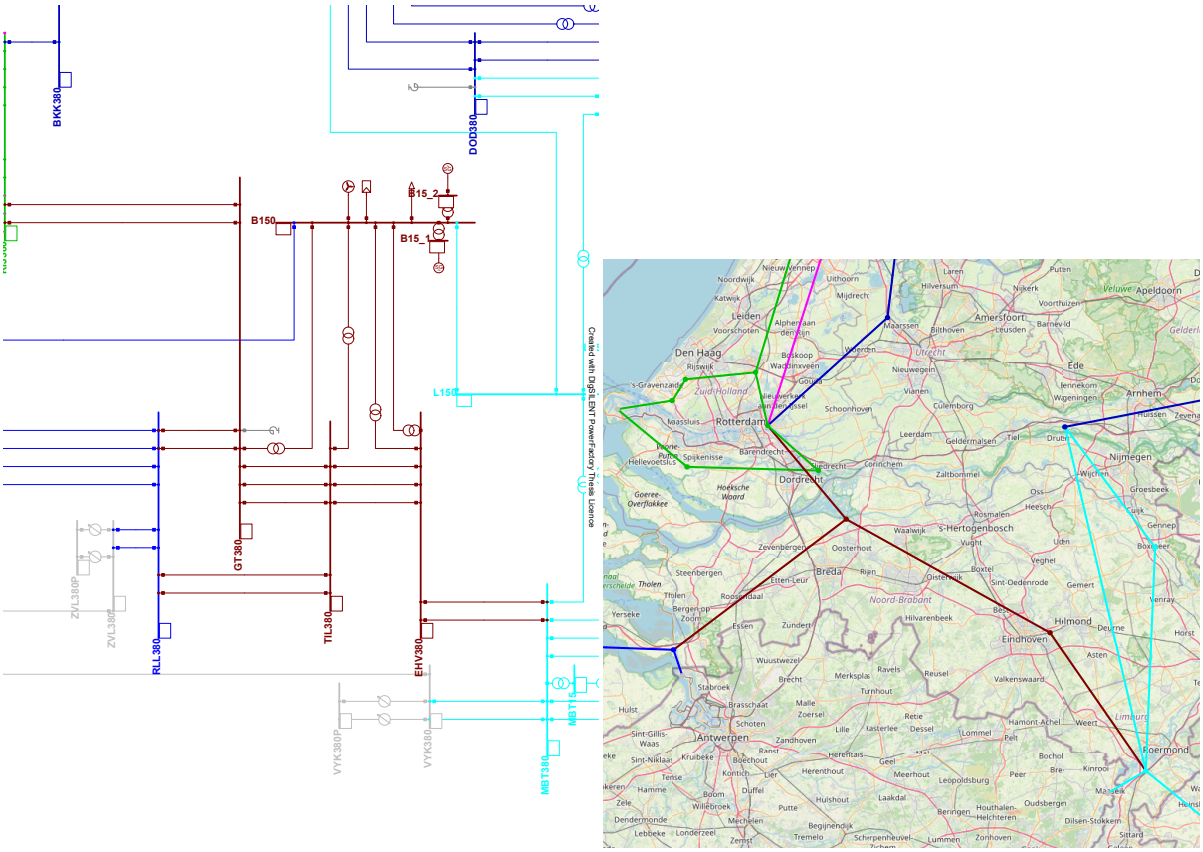
Tranformers at Station Lelystad

In KCD2017 the upgrade of the transformer between Lelystad 380kV and the 150kV grid is mentioned due to congestion issues in this part of the network. During Power Flow Analysis this part of the network is often the most critical. There is mentioned in KCD2017 that there are also two phase-shift transformers operating in the lower voltage part of the network to releive this problem. These phase-shifters are currently not yet modelled, due to lack of information. For the 2030 model the amount of transformers, their location and their installed capacity is listed below in table B.6. ”Number of Trafos” indicates the total amount of these transformers that were installed at the specific connection (if 2, the transformer is installed in parallel).

Table B.6: Amount of Transformers installed between LLS380, BKK380 and the 150kV part of GFU

Name	HV-Side	LV-Side	Number of Trafos	S (MVA)	Stot (MVA)
Trafo_BKK380_GFU150	BKK380	GFU150	1	500	500
Trafo_LLS380_GFU150	LLS380	GFU150	2	500	1000

B.7. Noord-Brabant



(a) Noord-Brabant Single Line Diagram for 2025 **(b)** Noord-Brabant Geographic 220/380kV

Figure B.6: Noord-Brabant (B) in PowerFactory

Project Zuid-West 380kV-Oost

According to KCD2017 as well as a special website for the project [63] and [31] a 380kV connection will be created bewteen RLL380 (Rilland) and TIL380 (Tilburg). The final topology of the project was taken from a supplementary document investigating the potential to have partial underground cabling [64] and is shown in figure B.7.

Currently the following components are added to the EHV network:

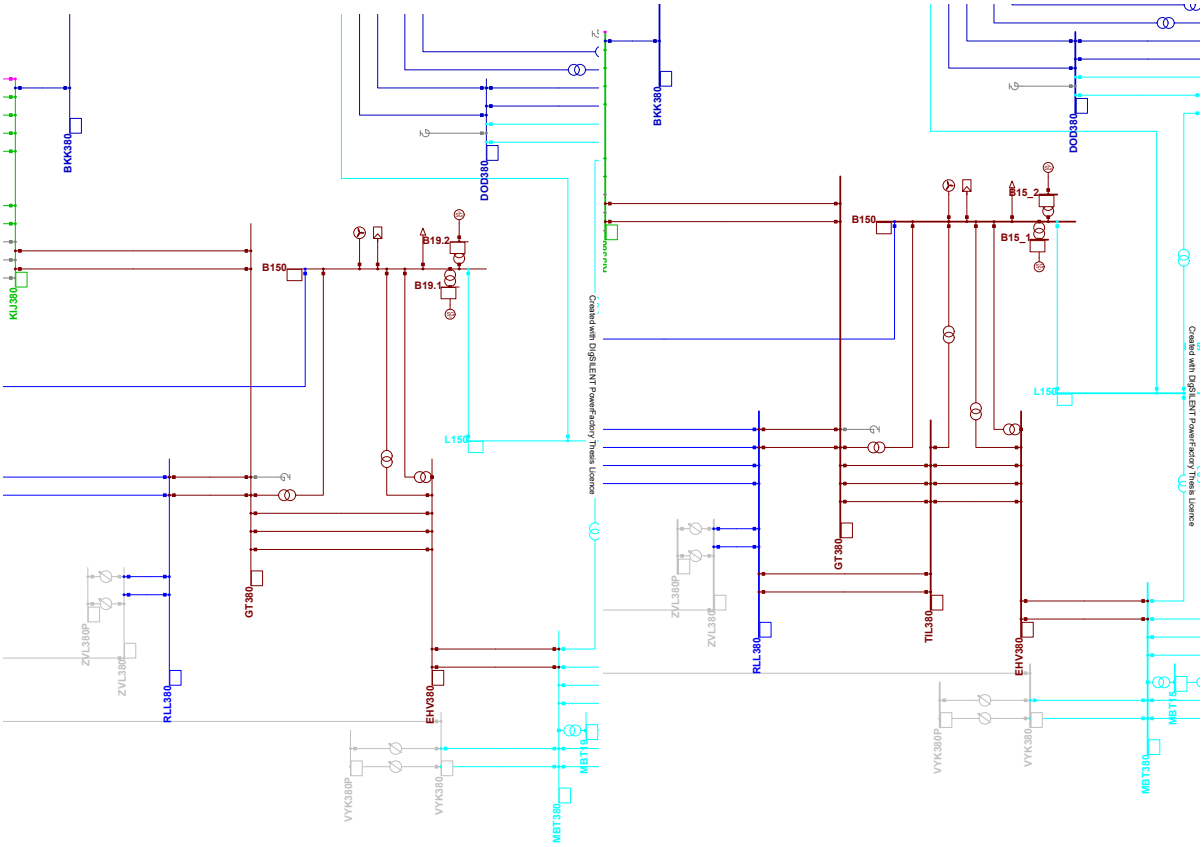
- 2024: Transmission Lines TIL380-RLL380: 2x2635MVA (4kA,380kV)

Table B.7: New Transmission lines in Noord-Brabant

Name	Type in PowerFactory	Terminal i	Terminal j	Zone	Length (km)
RLL380_TIL380_N1	Line_380kV_4kA_future	RLL380	TIL380	Noord-Brabant 380kV	60
RLL380_TIL380_N2	Line_380kV_3kA_future	RLL380	TIL380	Noord-Brabant 380kV	60

- 2024: Transformers TIL380/B150: 3x500MVA (1500MVA total)

The initial connection between GT380 and EHV380 was 64 km. When the station TIL380 is introduced this connection will be split into two parts. The new connections GT380-TIL380 are assumed to be 30 km long (3 transmission lines) and TIL380-EHV380 (also 3 lines) is assumed to be 35 km long. All these lines are still assumed to keep their old line ratings of 1645 MVA (2,5kA,380kV) each. These could however be upgraded to higher ratings.

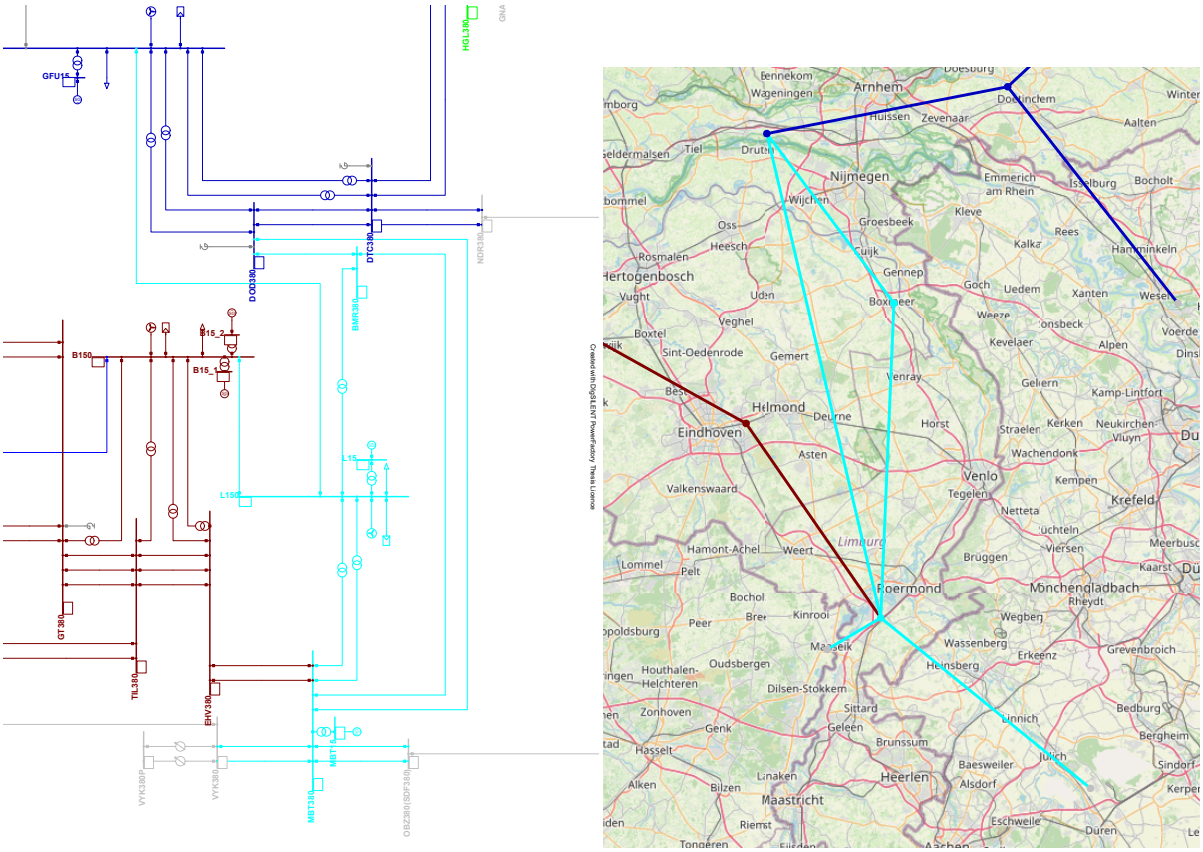


(a) Noord-Brabant Old Topology

(b) Noord-Brabant New Topology

Figure B.7: The old and new topology after introduction of project Zuid-West 380kV Oost in PowerFactory

B.8. Limburg

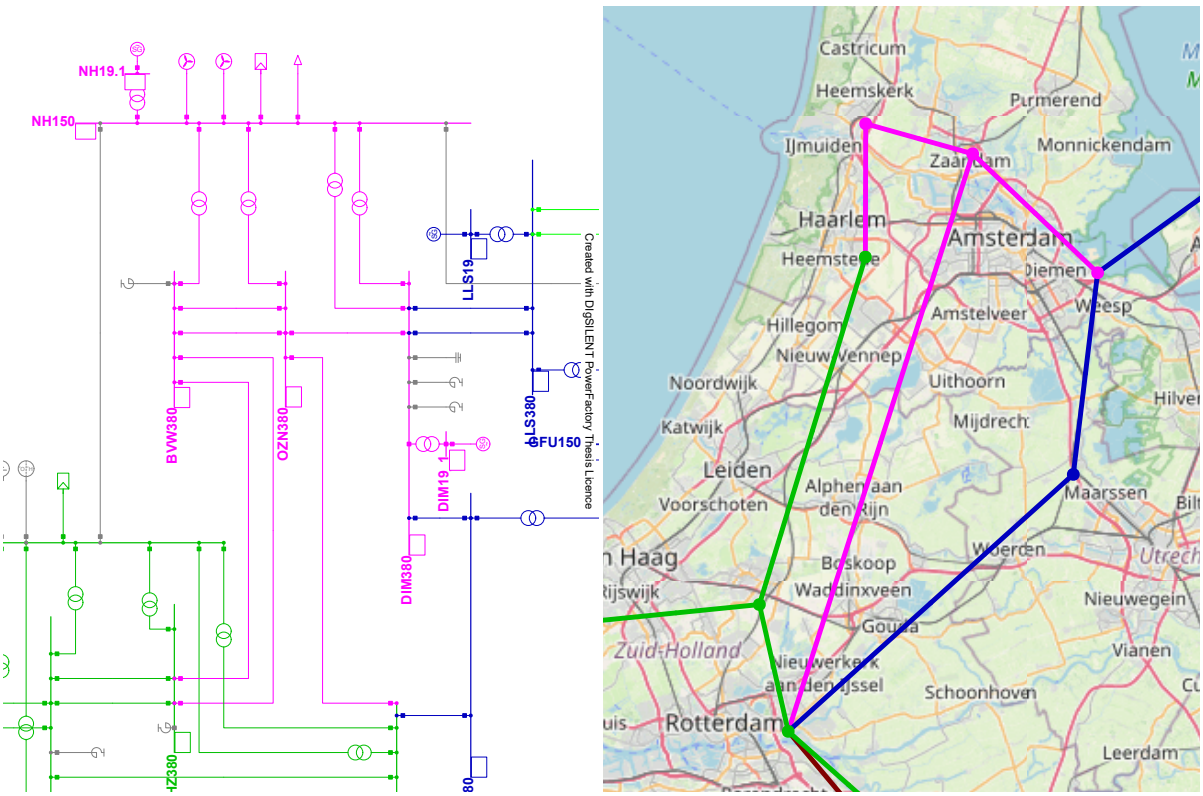


(a) Limburg Single Line Diagram

(b) Limburg Geographic 220/380kV

Figure B.8: Limburg (L) in PowerFactory

B.9. Noord-Holland

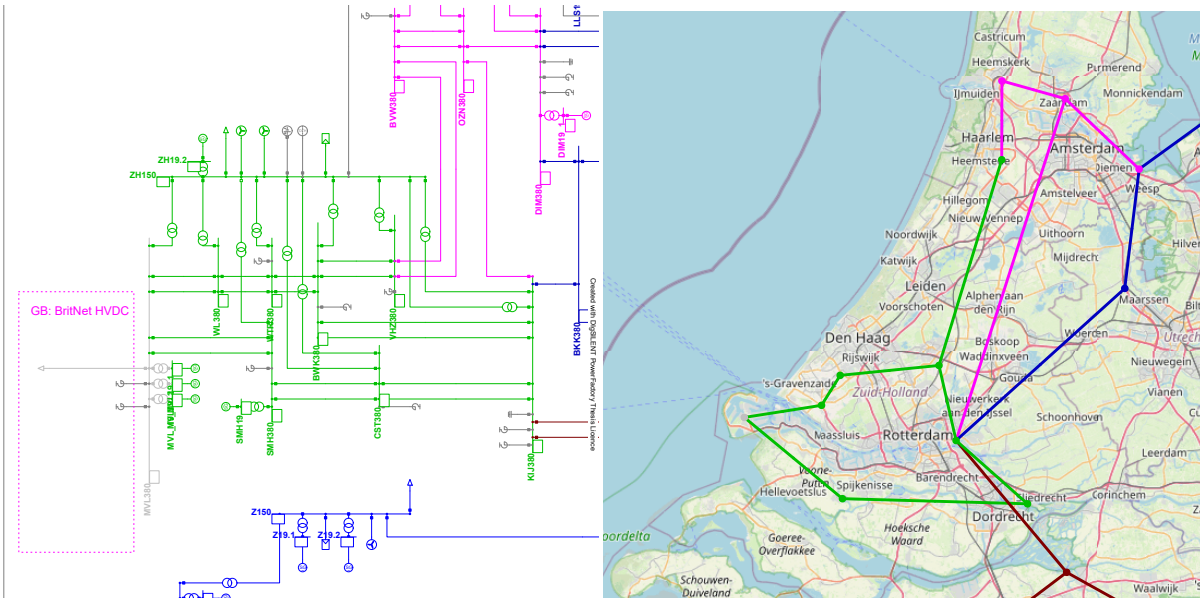


(a) Noord-Holland Single Line Diagram

(b) Noord-Holland Geographic 220/380kV

Figure B.9: Noord-Holland (NH) in PowerFactory

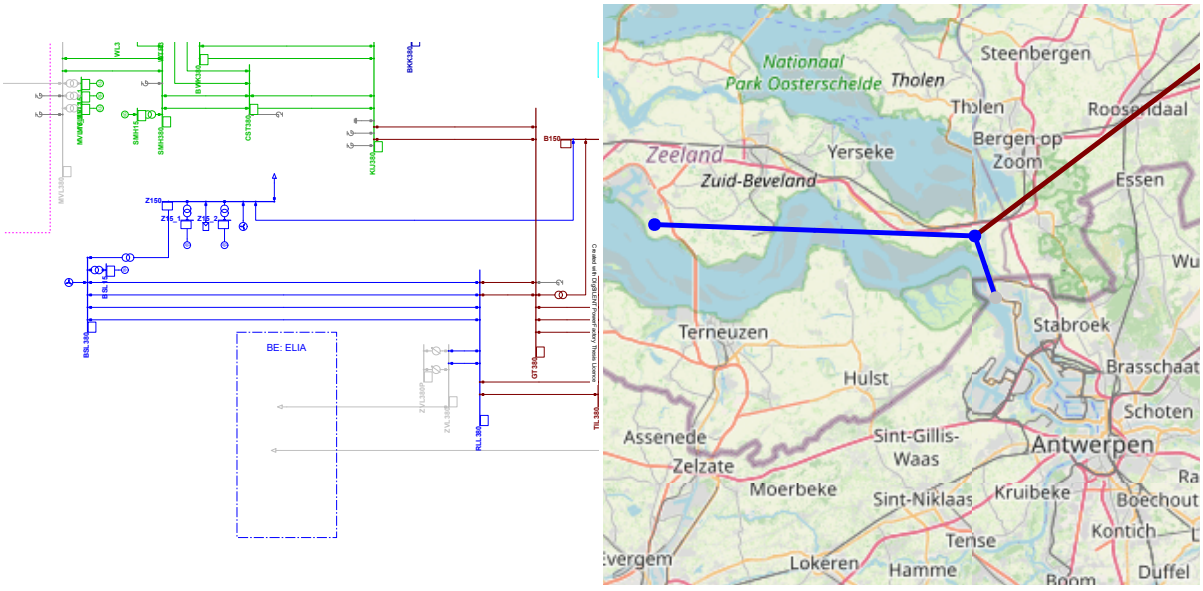
B.10. Zuid-Holland



(a) Noord-Holland Single Line Diagram **(b)** Noord-Holland Geographic 220/380kV

Figure B.10: Zuid-Holland (NH) in PowerFactory

B.11. Zeeland



(a) Zeeland Single Line Diagram **(b)** Zeeland Geographic 220/380kV

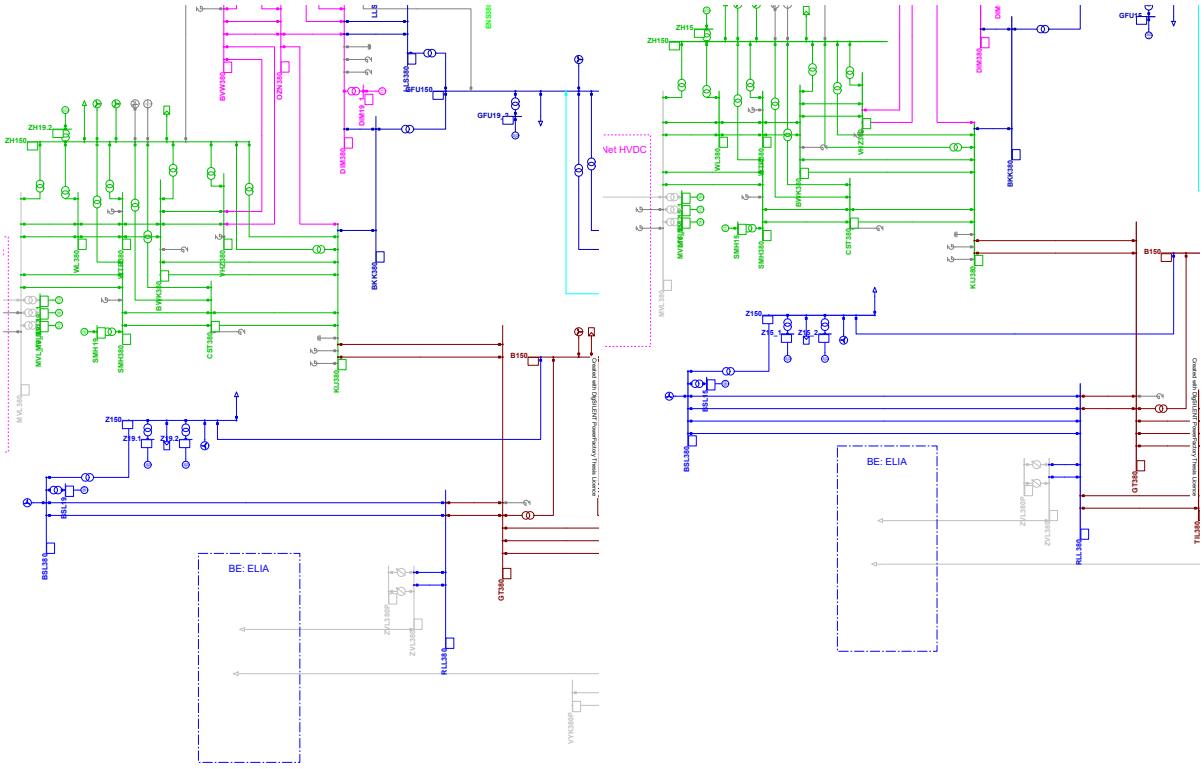
Figure B.11: Zeeland (Z) in PowerFactory

Project Zuid-West 380kV-West

According to KCD2017 as well as a special website for the project [31] [65], a new/upgraded 380kV connection will be created bewteen RIL380(Rilland) and BSL380(Borrsele). Currently the following components are added to the EHV network according to the inpassingsplan [66]:

- 2022: Addition of Transmission Lines RIL380-BSL380: 2x2635MVA (4kA,380kV) (were already

2 lines in place)



(a) Zeeland Old Topology **(b)** Zeeland New Topology

Figure B.12: The old and new topology after introduction of project Zuid-West 380kV West in PowerFactory

The two 380kV transmission lines that are already present between BSL380 and RIL380 are not upgraded to a higher rating in the current model as can be seen in table B.8.

Table B.8: Transmission Lines between Rilland and Borssele 380kV for the 2030/2050 Model

Name	Type in Powerfactory	Terminal i	Terminal j	Zone	Length	Irated
BSL380_RLL380_G	Line_380kV_2-3kA_002415R	RLL380	BSL380	Zeeland 380kV	38,9	2,5
BSL380_RLL380_Z	Line_380kV_2-3kA_002415R	RLL380	BSL380	Zeeland 380kV	38,9	2,5
BSL380_RLL380_N1	Line_380kV_4kA_future	BSL380	RLL380	Zeeland 380kV	38,9	4
BSL380_RLL380_N2	Line_380kV_4kA_future	BSL380	RLL380	Zeeland 380kV	38,9	4

C

Modelling of system components

C.1. Components: Assumptions

In this chapter underlying assumptions for the modelling of different system components is discussed.

C.1.1. Terminals

- *Operational Voltage:* All the terminals are modelled to operate at exactly 15/110/150/220 or 380kV.

C.1.2. Generators

- *PV/PQ Controls:* For the initial simulations, all the synchronous generators are modelled to be able to control the voltage (PV) in PowerFactory. The static generators are PQ controlled. For the case study this depends on the case and is discussed in chapter 4.
- *Nominal Operating Voltage:* For all the generators the assumption is made that they operate at 15kV. This was chosen as there was information available for step-up transformers in the steady state analysis of the Nordic Test System for this voltage [32].
- *Capability Curves* The active power capabilty curves of the generators are defined within the ”type” in PowerFactory by means of the different parameters, as given in the load flow parameters section of table 3.1. An example of this is given in figure C.1 by the blue line. As mentioned before in section 3.2.3, all the generators of the same ”type” are assumed to have the same parameters and therefore the same sort of capability curve. For static generators the operating curve is different, as can be seen in figure C.2.

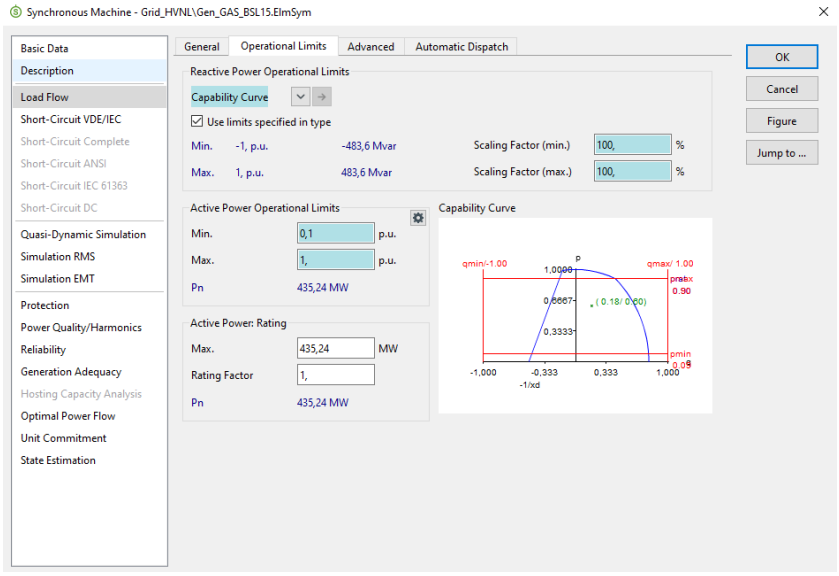


Figure C.1: Example of Operational Limits for a synchronous generator

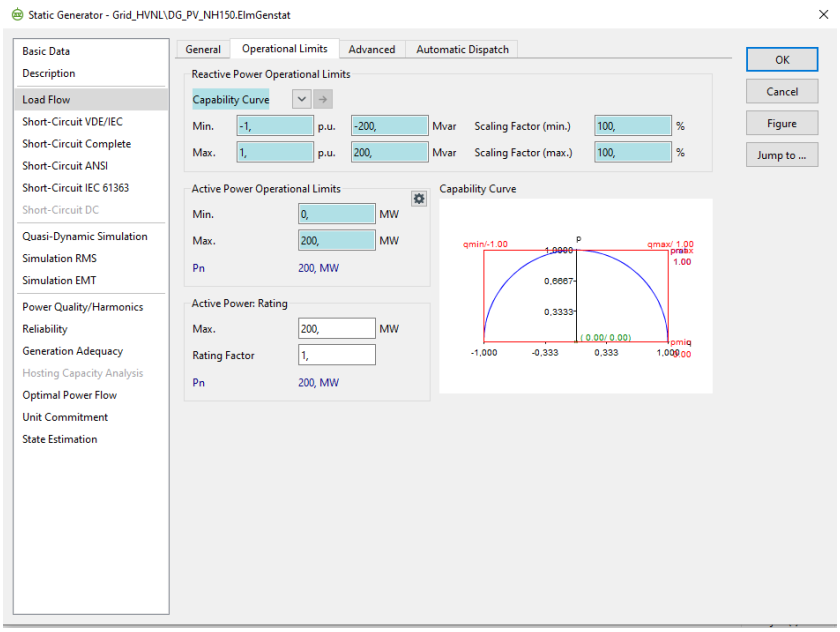


Figure C.2: Example of Operational Limits for a static generator

- *Active Power limits:* For the initial model the operational active power limits for synchronous generators are assumed to be Pmin = 0.1*Pnom and Pmax = Pnom as can be seen in figure C.1 by the red lines. For the 2030 model however, the limits are set to Pmin = 0 and Pmax = Pnom. The nominal power factor of the generators is chosen to be 0.9 like in the Nordic Test System [32]. Therefore the generator is limited to operating below its maximum capacity as shown in figure C.1. For the static generators Pmin = 0 and Pmax = Pnom. Pnom is the nominal capacity for each generator as discussed in section A.1.3.

  This minimum active power limit is chosen lower than is typical for synchronous generators [67]. This is because some generators were aggregated (at lower voltage busbars for example) and therefore a higher minimum output level would be unrealistic.
- *Reactive Power Limits:* The generator limits for reactive power are defined as +- 1 p.u.. In the Nordic test system the reactive power limits are defined by the Overexcitation limited model (and

stator current limits for negative reactive power as there is no underexcitation model) but such controllers have not yet been introduced for this model [32]. Capability curves can be introduced for reactive power, taking examples from [68]. This however, has not been done yet for the current model.

- *Initial Generator Dispatch Voltages & Phase angle:* The voltage of all the generators has been set to 1 (p.u.) as an initial starting point. In different test systems for transmission networks such as the Nordic Test System however, these values often range between 0.99 to 1.06 (p.u.) [32]. The initial phase angle of the different generators has therefore automatically been set to 0 (deg). Again, in the Nordic Test System these values can range between -81 to +4 (deg) [32].
- *Slack generator:* Within the model in PowerFactory the largest generator located at Maasbracht (MBT380) is assumed to provide the mismatch between the scheduled generation and load-/losses.

C.1.3. Transmission Lines

- *Rated Current:* For the current model, the rated currents are modelled using the summer values as these are the most critical. However, this could be adjusted to the slightly winter values.

Adjusted Values

Some lines were adjusted as their parameters seemed unlikely (for overhead transmission lines). These adjusted lines are listed explicitly below in table C.1 to values that of other transmission lines already in the model with the same (voltage and current) ratings. It could however be possible that some of these odd lines are partially underground but for the created model all transmission lines are modelled as overhead lines (OHL).

Table C.1: Adjusted Parameters for certain Transmission Lines

Name	Type in PowerFactory	R' (Ohm/km)	X' (Ohm/km)	C' (uF/km)	R' (Ohm/km)	X' (Ohm/km)	C' (uS/km)	Length (km)	Parameters taken from
		New Parameters			Old Parameters				
EEM220_EHA220_W	Adj_Line_220kV_2.3kA	0,0247	0,286	0,013	0,0806	0,112	0,462	0,93	RBB220-VVL220
EEM220_EHA220_Z	Adj_Line_220kV_2.3kA	0,0247	0,286	0,013	0,0806	0,112	0,462	0,93	RBB220-VVL220
EEM220_RBB220_A	Adj_Line_220kV_2.3kA	0,0247	0,286	0,013	0,0500	0,700	0,400	0,04	RBB220-VVL220*
EEM220_RBB220_B	Adj_Line_220kV_2.3kA	0,0247	0,286	0,013	0,0500	0,700	0,400	0,04	RBB220-VVL220*
BKK380_DIM380_W	Adj_Line_380kV_2.5kA	0,0254	0,274	0,013	0,0237	0,274	0,041	37,52	ZL380-HG380
KIJ380_BKK380_W	Adj_Line_380kV_2.5kA	0,0254	0,274	0,013	0,0235	0,274	0,041	20,01	ZL380-HG380
MBT380_OBZ380_W	Adj_Line_380kV_2.6kA	0,0254	0,274	0,013	0,1147	1,072	0,058	10,5	ZL380-HG380
MBT380_SDF380_Z	Adj_Line_380kV_2.6kA	0,0254	0,274	0,013	0,0474	0,465	0,025	10,5	ZL380-HG380
DTC380_NDR380_W	Adj_Line_380kV_4kA	0,0139	0,2292	0,014	0,0188	0,333	0,062	22,18	EEM380-EOS380
DTC380_NDR380_Z	Adj_Line_380kV_4kA	0,0139	0,2292	0,014	0,0188	0,333	0,062	22,18	EEM380-EOS380
MVL380_WL380_W	Adj_Line_380kV_4kA	0,0139	0,229	0,014	0,0146	0,589	0,035	20,432	EEM380-EOS380
MVL380_WL380_Z	Adj_Line_380kV_4kA	0,0139	0,229	0,014	0,0146	0,589	0,035	20,432	EEM380-EOS380
WTR380_BWK380_W	Adj_Line_380kV_4kA	0,0139	0,229	0,014	0,0080	0,166	0,234	22	EEM380-EOS380
WTR380_BWK380_Z	Adj_Line_380kV_4kA	0,0139	0,229	0,014	0,0080	0,166	0,234	22	EEM380-EOS380

- *110/150kV Lines:* That a length of 50km with these ratings is reasonable for this purpose of interconnecting the low voltage area's.

C.1.4. Transformers

Table C.2: Parameters of Grid Transformers Used

Name	S_{rated} (MVA)	U_{HV} (kV)	U_{LV} (kV)	uk (%)	P_{copper} (kW)	Ratio X/R	$x1$ (p.u.)	$r1$ (p.u.)	Int. Delta Winding	Ph.Shift (*30 deg)	$x0$ (p.u.)	$r0$ (p.u.)
Trafo 220/110 (200MVA)	200	220	110	8,4	400	42	0,084	0,002	0	0	0	0
Trafo 380/110 (350MVA)	350	380	110	8,4	700	42	0,084	0,002	0	0	0	0
Trafo 220/110 (350MVA)	350	220	110	8,4	700	42	0,084	0,002	0	0	0	0
Trafo 380/110 (370MVA)	370	380	110	8,4	740	42	0,084	0,002	0	0	0	0
Trafo 220/110 (370MVA)	370	220	110	8,4	740	42	0,084	0,002	0	0	0	0
Trafo 380/150 (450MVA)	450	380	150	8,4	900	42	0,084	0,002	0	0	0	0
Trafo 380/150 (500MVA)	500	380	150	8,4	1000	42	0,084	0,002	0	0	0	0
Trafo 380/200 (500MVA)	500	380	220	8,4	1000	42	0,084	0,002	0	0	0	0
Trafo 380/200 (750MVA)	750	380	220	8,4	1500	42	0,084	0,002	0	0	0	0

Table C.3: Parameters of Step up/down Transformers Used

Name	S_{rated} (MVA)	U_{HV} (kV)	U_{LV} (kV)	uk (%)	P_{copper} (kW)	Ratio X/R	$x1$ (p.u.)	$r1$ (p.u.)	Int. Delta Winding	Ph.Shift (*30 deg)	$x0$ (p.u.)	$r0$ (p.u.)
Step up 15/110kV	255	110	15	15,0	765	50	0,15	0,003	0	0	0,13	0
Step up 15/150kV	255	150	15	15,0	765	50	0,15	0,003	0	0	0,13	0
Step up 15/220kV	255	220	15	15,0	765	50	0,15	0,003	0	0	0,13	0
Step up 15/380kV	255	380	15	15,0	765	50	0,15	0,003	0	0	0,13	0

C.1.5. Reactor Coils and Capacitor Banks

According to the single line diagram from hoogspanningsnet there are various locations at which reactive power compensation is provided in the EHV network [30]. However, exactly what type of compensation this is was not clear. As can be seen in table C.4 most of the devices are assumed to be inductive. Currently all reactive power compensation is disabled.

Table C.4: Reactive Power Compensation

Name	Terminal	Zone	Nom.Volt. (kV)	Type in PowerFactory	Max. Step	Qmax (Mvar)
CAP_DIM380	DIM380	Noord-Holland 380kV	380	C	2	300
CAP_ENS220	ENS220	Friesland 380/220kV	220	C	2	300
CAP_KIJ380	KIJ380	Zuid-Holland 380kV	380	C	2	300
CAP_WEW220	WEW220	Groningen en Drenthe 220/380kV	220	C	1	150
REA_BVW380	BVW380	Noord-Holland 380kV	380	R-L	2	200
REA_BWK380	BWK380	Zuid-Holland 380kV	380	R-L	3	300
REA_CST380	CST380	Zuid-Holland 380kV	380	R-L	2	200
REA_DIM380_1	DIM380	Noord-Holland 380kV	380	R-L	2	100
REA_DIM380_2	DIM380	Noord-Holland 380kV	380	R-L	2	200
REA_DOD380	DOD380	Gelder Flevo Utrecht 380	380	R-L	2	200
REA_DTC380_1	DTC380	Gelder Flevo Utrecht 380	380	R-L	2	90
REA_EEM380	EEM380	IC_NO_StattNet_EEM	380	R-L	3	225
REA_ENS380	ENS380	Overijssel en Noordoostpolder 380kV	380	R-L	5	375
REA_EOS380	EOS380	IC_DK_Cobra_EOS/EOS Offshore	380	R-L	2	200
REA_GT380	GT380	Noord-Brabant 380kV	380	R-L	2	150
REA_KIJ380_1	KIJ380	Zuid-Holland 380kV	380	R-L	2	200
REA_KIJ380_2	KIJ380	Zuid-Holland 380kV	380	R-L	1	45
REA_MEE220	MEE220	Groningen en Drenthe 220/380kV	220	R-L	1	75
REA_MVL380_1	MVL380	IC_GB_BrittNet_MVL	380	R-L	1	50
REA_MVL380_2	MVL380	IC_GB_BrittNet_MVL	380	R-L	1	100
REA_SMH380	SMH380	Zuid-Holland 380kV	380	R-L	1	100
REA_VHZ380	VHZ380	Zuid-Holland 380kV	380	R-L	3	300
REA_WTR380	WTR380	Zuid-Holland 380kV	380	R-L	3	300

C.1.6. Phase Shifting Transformers

According to the grid map by hoogspanningsnet, the ratings of the phase shifters are either 1000 or 1400 MVA [30]. Currently all the phase shifters in the model have a circuit base power of 1000 MVA. The numbers for the voltage regulation (4,5%) and the maximum and minimum tap positions (+-5) were taken from the data sheet with the transmission lines [29]. The phase shifters have no reactance or resisitance. The rated voltage was set to 380kV, as it was assumed this should be set to the grid voltage. The rated current was changed until the total circuit base power was 1000 MVA.

Table C.5: Phase Shifting Transformers currently incorporated into the model

Name	S-Side	L-Side	Zone	Srated	Re	Xe	Rated voltage	Rated current	Min. Tap	Max. Tap	Voltage regulation range (+/-)	Add.V./tap
				MVA	Ohm	Ohm	kV	A			%	%
PhS_DIL380_1	DIL380	DIL380P	IC_DK_Cobra_EOS and EOS Offshore	1000	0	0	380	1520	-5	5	4,549	0,9098
PhS_DIL380_2	DIL380	DIL380P	IC_DK_Cobra_EOS and EOS Offshore	1000	0	0	380	1520	-5	5	4,549	0,9098
PhS_VYK380_1	VYK380P	VYK380	IC_BE_ELIA_VYK	1000	0	0	380	1520	-5	5	4,549	0,9098
PhS_VYK380_2	VYK380P	VYK380	IC_BE_ELIA_VYK	1000	0	0	380	1520	-5	5	4,549	0,9098
PhS_ZVL380_1	ZVL380P	ZVL380	IC_BE_ELIA_ZVL	1000	0	0	380	1520	-5	5	4,549	0,9098
PhS_ZVL380_2	ZVL380P	ZVL380	IC_BE_ELIA_ZVL	1000	0	0	380	1520	-5	5	4,549	0,9098

D

Initial Simulations

In this chapter the approach, results and discussion for the initial power flow, transfer capacity analysis (TCA) and optimal power flow (OPF) simulations is given.

D.1. Power Flow: Peak Demand Simulations

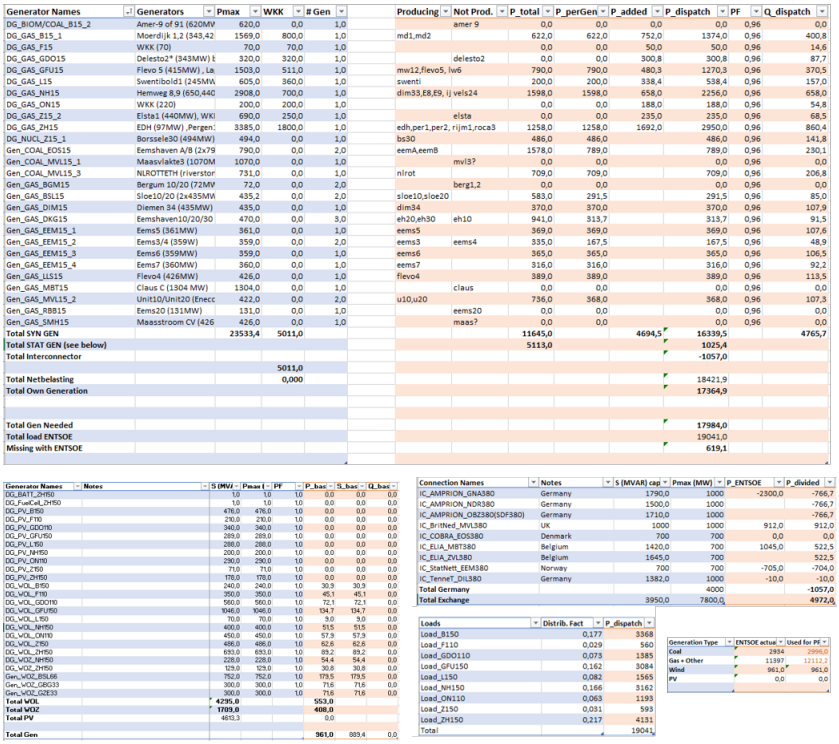
These simulations were done to see if the power flows within the system are representative for the real transmission network and to see if the same critical components and areas are identified as in KCD2017 and KCD2020 [31] [2].

D.1.1. Dispatch and Settings

Generation

To initially model the different peak demand scenarios, generation data was looked up on the ENTSOE Transparency Platform [36]. Here information could be found for specific generator dispatches, the amount of production according to fuel type (to determine the amount of renewable generation) and the cross-border flows for each hour. However, even when combining and cross-referencing different data, often around 25-30% of the needed generation capacity stayed unaccounted for. This could be due to the fact that not all of the generation capacity is controlled by Tennet or that perhaps not all the data is publicly available. The approach to distribute the missing generation was as follows:

1. Check if there was more coal production according to the fuel type production data than listed in the generator dispatches, the difference was distributed among the non operating coal plants.
2. Check the total amount of ”Gas” and ”other” production in the fuel type data sheet. If this number was higher than the current dispatch for gas plants, regard the remainder of the missing generation capacity as category ”WKK and other”.
3. Distribute the remaining amount of needed capacity proportionally according to their total capacities among the different WKK generators in lower voltage areas of the network.



Generator Names	Generators	Pmax	WKK	# Gen
DG_BIOM/COAL_B15_2	Amer-9 of 91 (620MV	620,0	0,0	1,0
DG_GAS_B15_1	Moerdijk 1,2 (343,42	1569,0	800,0	1,0
DG_GAS_F15	WKK (70)	70,0	70,0	1,0
DG_GAS_GDO15	Delesto2* (343MW) [	320,0	320,0	1,0
DG_GAS_GFU15	Flevo 5 (415MW) , La	1503,0	511,0	1,0
DG_GAS_L15	Sventibold1 (245MW	605,0	360,0	1,0
DG_GAS_NH15	Hemweg 8,9 (650,440	2908,0	700,0	1,0
DG_GAS_ON15	WKK (220)	200,0	200,0	1,0
DG_GAS_Z15_2	Elsta1 (440MW), WKI	690,0	250,0	1,0
DG_GAS_ZH15	EDH (97MW) ,Pergen:	3385,0	1800,0	1,0
DG_NUCL_Z15_1	Borssele30 (494MW)	494,0	0,0	1,0
Gen_COAL_EOS15	Eemshaven A/B (2x79	790,0	0,0	2,0
Gen_COAL_MVL15_1	Maasvlakte3 (1070M	1070,0	0,0	1,0
Gen_COAL_MVL15_3	NUROTTETH (riverstor	731,0	0,0	1,0
Gen_GAS_BGM15	Bergum 10/20 (72MW	72,0	0,0	2,0
Gen_GAS_BSL15	Sloe10/20 (2x435MW	435,2	0,0	2,0
Gen_GAS_DIM15	Diemen 34 (435MW)	435,0	0,0	1,0
Gen_GAS_DKG15	Eemshaven10/20/30	470,0	0,0	3,0
Gen_GAS_EEM15_1	Eems5 (361MW)	361,0	0,0	1,0
Gen_GAS_EEM15_2	Eems3/4 (359W)	359,0	0,0	2,0
Gen_GAS_EEM15_3	Eems6 (359MW)	359,0	0,0	1,0
Gen_GAS_EEM15_4	Eems7 (360MW)	360,0	0,0	1,0
Gen_GAS_LLS15	Flevo4 (426MW)	426,0	0,0	1,0
Gen_GAS_MBT15	Claus C (1304 MW)	1304,0	0,0	1,0
Gen_GAS_MVL15_2	Unit10/Unit20 (Enec	422,0	0,0	2,0
Gen_GAS_RBB15	Eems20 (131MW)	131,0	0,0	1,0
Gen_GAS_SMH15	Maasstroom CV (426	426,0	0,0	1,0
Total SYN GEN		**23533,4**	**5011,0**	
Total STAT GEN (see below)				
Total Interconnector				
			5011,0	
Total Netbelasting			**0,000**	
Total Own Generation				
Total Gen Needed				
Total load ENTSOE				
Missing with ENTSOE				

Producing	Not Prod.	P_total	P_perGen	P_added	P_dispatch	PF	Q_dispatch
	amer 9	0,0	0,0	0,0	0,0	0,96	0,0
md1,md2		622,0	622,0	752,0	1374,0	0,96	400,8
		0,0	0,0	50,0	50,0	0,96	14,6
	delesto2	0,0	0,0	300,8	300,8	0,96	87,7
mw12,flevo5, lw6		790,0	790,0	480,3	1270,3	0,96	370,5
swenti		200,0	200,0	338,4	538,4	0,96	157,0
dim33,E8,E9, lj	vels24	1598,0	1598,0	658,0	2256,0	0,96	658,0
		0,0	0,0	188,0	188,0	0,96	54,8
	elsta	0,0	0,0	235,0	235,0	0,96	68,5
edh,per1,per2,	rijm1,roca3	1258,0	1258,0	1692,0	2950,0	0,96	860,4
bs30		486,0	486,0		486,0	0,96	141,8
eemA,eemB		1578,0	789,0		789,0	0,96	230,1
	mvl3?	0,0	0,0		0,0	0,96	0,0
nlrot		709,0	709,0		709,0	0,96	206,8
	berg1,2	0,0	0,0		0,0	0,96	0,0
sloe10,sloe20		583,0	291,5		291,5	0,96	85,0
dim34		370,0	370,0		370,0	0,96	107,9
eh20,eh30	eh10	941,0	313,7		313,7	0,96	91,5
eems5		369,0	369,0		369,0	0,96	107,6
eems3	eems4	335,0	167,5		167,5	0,96	48,9
eems6		365,0	365,0		365,0	0,96	106,5
eems7		316,0	316,0		316,0	0,96	92,2
flevo4		389,0	389,0		389,0	0,96	113,5
	claus	0,0	0,0		0,0	0,96	0,0
u10,u20		736,0	368,0		368,0	0,96	107,3
	eems20	0,0	0,0		0,0	0,96	0,0
	maas?	0,0	0,0		0,0	0,96	0,0
		11645,0		**4694,5**	**16339,5**		**4765,7**
		5113,0			**1025,4**		
					-1057,0		
					18421,9		
					17364,9		
					17984,0		
					19041,0		
					619,1		

Generator Names	Notes	S (MV/	Pmax (	PF	P_bac	S_bac	Q_bac
DG_BATT_ZH150		1,0	1,0	1,0	0,0	0,0	0,0
DG_FuelCel_ZH150		1,0	1,0	1,0	0,0	0,0	0,0
DG_PV_B150		476,0	476,0	1,0	0,0	0,0	0,0
DG_PV_F110		270,0	270,0	1,0	0,0	0,0	0,0
DG_PV_GDO110		340,0	340,0	1,0	0,0	0,0	0,0
DG_PV_GFU150		289,0	289,0	1,0	0,0	0,0	0,0
DG_PV_L150		288,0	288,0	1,0	0,0	0,0	0,0
DG_PV_NH150		200,0	200,0	1,0	0,0	0,0	0,0
DG_PV_ON110		290,0	290,0	1,0	0,0	0,0	0,0
DG_PV_Z150		71,0	71,0	1,0	0,0	0,0	0,0
DG_PV_ZH150		178,0	178,0	1,0	0,0	0,0	0,0
DG_WOL_B150		240,0	240,0	1,0	30,9	30,9	0,0
DG_WOL_F150		350,0	350,0	1,0	45,1	45,1	0,0
DG_WOL_GDO110		560,0	560,0	1,0	72,1	72,1	0,0
DG_WOL_GFU150		1046,0	1046,0	1,0	134,7	134,7	0,0
DG_WOL_L150		70,0	70,0	1,0	9,0	9,0	0,0
DG_WOL_NH150		400,0	400,0	1,0	51,5	51,5	0,0
DG_WOL_ON110		450,0	450,0	1,0	57,9	57,9	0,0
DG_WOL_Z150		486,0	486,0	1,0	62,6	62,6	0,0
DG_WOL_ZH150		693,0	693,0	1,0	89,2	89,2	0,0
DG_WOZ_NH150		228,0	228,0	1,0	54,4	54,4	0,0
DG_WOZ_ZH150		129,0	129,0	1,0	30,8	30,8	0,0
Gen_WOZ_BSL66		752,0	752,0	1,0	179,5	179,5	0,0
Gen_WOZ_GBG33		300,0	300,0	1,0	71,6	71,6	0,0
Gen_WOZ_GZE33		300,0	300,0	1,0	71,6	71,6	0,0
Total WOL		**4295,0**			**553,0**		
Total WOZ		**1709,0**			**408,0**		
Total PV		4013,3			0,0		
Total Gen					**961,0**	889,4	0,0

Connection Names	Notes	S (MVAR) cap	Pmax (MW)	P_ENTSOE	P_divided
IC_AMPRION_GNA380	Germany	1790,0	1000	-2300,0	-766,7
IC_AMPRION_NDR380	Germany	1500,0	1000		-766,7
IC_AMPRION_OBZ380(SDF380)	Germany	1710,0	1000		-766,7
IC_BritNed_MVL380	UK	1000	1000	912,0	912,0
IC_COBRA_EOS380	Denmark	700	700	0,0	0,0
IC_ELIA_MBT380	Belgium	1420,0	700	1045,0	522,5
IC_ELIA_ZVL380	Belgium	1645,0	700		522,5
IC_StatNett_EEM380	Norway	700	700	-705,0	-704,0
IC_TenneT_DIL380	Germany	1382,0	1000	-10,0	-10,0
Total Germany			4000		**-1057,0**
Total Exchange		3950,0	7800,0		**4972,0**

Loads	Distrib. Fact	P_dispatch
Load_B150	0,177	3368
Load_F110	0,029	560
Load_GDO110	0,073	1385
Load_GFU150	0,162	3084
Load_L150	0,082	1565
Load_NH150	0,166	3162
Load_ON110	0,063	1193
Load_Z150	0,031	593
Load_ZH150	0,217	4131
Total		19041

Generation Type	ENTSOE actual	Used for PF
Coal	2934	2946,0
Gas + Other	11397	12112,2
Wind	961,0	961,0
PV	0,0	0,0

Figure D.1: Screenshot of Excel File used for Dispatches

Note: The reason to not just assign the remaining generation to other gas plants was that often these gas plants were listed with zero production on ENTSO-E. Whether this was really the case, or whether this data was unavailable due to other reasons is not known. In the table for production according to fuel type in the ENTSO-E platform, a lot of production is listed under ”other” and the total numbers might not be completely reliable.

Demand

As there was no data available on the specific demand per region the approach was to use a distribution key based on the peak demand of each region listed in KCD2017 [31] which was cross-referenced with yearly electricity consumption [39] as mentioned in section 3.2.4.

Interconnections

The cross-border flows of power are listed on the ENTSO-E platform according to bidding zone. Therefore there is not the possibility to distinguish the power flows for each of the different specific connections of NL-Germany and NL-Belgium. The approach here was to divide the listed amount of cross-border flow equally among the different connections (3 in Germany and 2 in Belgium) as mentioned in section A.1.5.

Settings

The initial power flows are modelled as AC Load Flows, balanced, positive sequence. The active and reactive power limits are considered, but there is no automatic tap adjustment of phase shifters, transformers or shunts. This was chosen to be able to see what the power flow would look like when there is no compensation active within the system.
The active power control is set to ”as dispatched” within powerfactory, and the balancing happens by the reference machine. The reference machine is set to the largest gas generator: Claus C, located at MBT380 in Zone: Limburg as discussed in section 3.2.3 under assumptions.

D.1.2. Power Flow Results

In the following sections the results for each of the different simulations will be discussed.

2017 Peak Demand Simulation

In figure D.2 a summary is given of the total generation, load, grid losses, line charging etc. of the powerflow for the 2017 Peak Demand simulation. The total amount of generation in this simulation is 18139 MW and the total demand at the 110/150kV busbars is 19041 MW. Because the interconnection to neighbouring countries are modelled as (negative) demands, the system summary shows a total demand of 17983 MW, reflecting an inflow from neighbouring countries of 1057 MW. The reactive power losses in the grid are around 1745 MW, which is higher than normal due to overloaded transformers. The line charging is around -1628 Mvar, which reflects the capacitive nature of the long AC transmisison lines.

Total System Summary				Study Case: LF - Base Case			Annex:	/ 1
No. of Substations	0	No. of Busbars	88	No. of Terminals	0	No. of Lines	104	
No. of 2-w Trfs.	72	No. of 3-w Trfs.	0	No. of syn. Machines	27	No. of asyn.Machines	0	
No. of Loads	18	No. of Shunts/Filters	0	No. of SVS	0			
Generation	=	18139,22 MW	1744,10 Mvar	18222,88 MVA				
External Infeed	=	0,00 MW	0,00 Mvar	0,00 MVA				
Load P(U)	=	17983,90 MW	0,00 Mvar	17983,90 MVA				
Load P(Un)	=	17983,90 MW	0,00 Mvar	17983,90 MVA				
Load P(Un-U)	=	-0,00 MW	-0,00 Mvar					
Motor Load	=	0,00 MW	0,00 Mvar	0,00 MVA				
Grid Losses	=	155,32 MW	1744,10 Mvar					
Line Charging	=		-1628,36 Mvar					
Compensation ind.	=		0,00 Mvar					
Compensation cap.	=		0,00 Mvar					
Installed Capacity	=	31972,47 MW						
Spinning Reserve	=	6266,75 MW						
Total Power Factor:								
Generation	=	1,00 [-]						
Load/Motor	=	1,00 / 0,00 [-]						

Figure D.2: System Summary for the 2017 Peak Demand Initial Power Flow

All the elements loaded above 70% of their capacity are shown in figure D.3. The generators are dispatched at this loading intentionally, therefore their loading is not suprising. The different transformers that are overloaded however result in increased grid losses.

Name	Type	Loading [%]	Voltage [p.u.]	Voltage [kV]	Station/Branch	Apparent Power [MVA]	Current [kA]	Current [p.u.]
Overloaded Elements								
Trafo_DTC380_GFU150_1	Tr2	75.67			DTC380	375,09	0,57	0,76
					GFU150	374,64	1,46	0,76
Trafo_DTC380_GFU150_2	Tr2	75.67			DTC380	337,58	0,52	0,76
					GFU150	337,18	1,31	0,76
Trafo_GT380_B150	Tr2	73.48			GT380	658,68	1,00	0,73
					B150	655,92	2,55	0,73
Trafo_LLS380_GFU150	Tr2	89.18			LLS380	880,34	1,36	0,89
					GFU150	883,06	3,43	0,89
Trafo_VVL220_GDO110_1	Tr2	81.95			VVL220	299,37	0,80	0,82
					GDO110	298,72	1,59	0,82
Trafo_VVL220_GDO110_2	Tr2	81.95			VVL220	161,82	0,43	0,82
					GDO110	161,47	0,86	0,82
Trafo_WEW220_GDO110	Tr2	72.40			WEW220	528,79	1,41	0,72
					GDO110	527,79	2,81	0,72
DG_GAS_B15_1	Sym	79.35			B15_1	1383,31	53,24	0,79
DG_GAS_F15	Sym	74.36			F15	57,85	2,23	0,74
DG_GAS_GDO15	Sym	86.15			GDO15	306,34	11,79	0,86
DG_GAS_GFU15	Sym	76.73			GFU15	1281,40	49,32	0,77
DG_GAS_L15	Sym	80.47			L15	540,90	20,82	0,80
DG_GAS_NH15	Sym	70.16			NH15	2266,88	87,25	0,70

Study Case: LF - Base Case | Annex: / 2

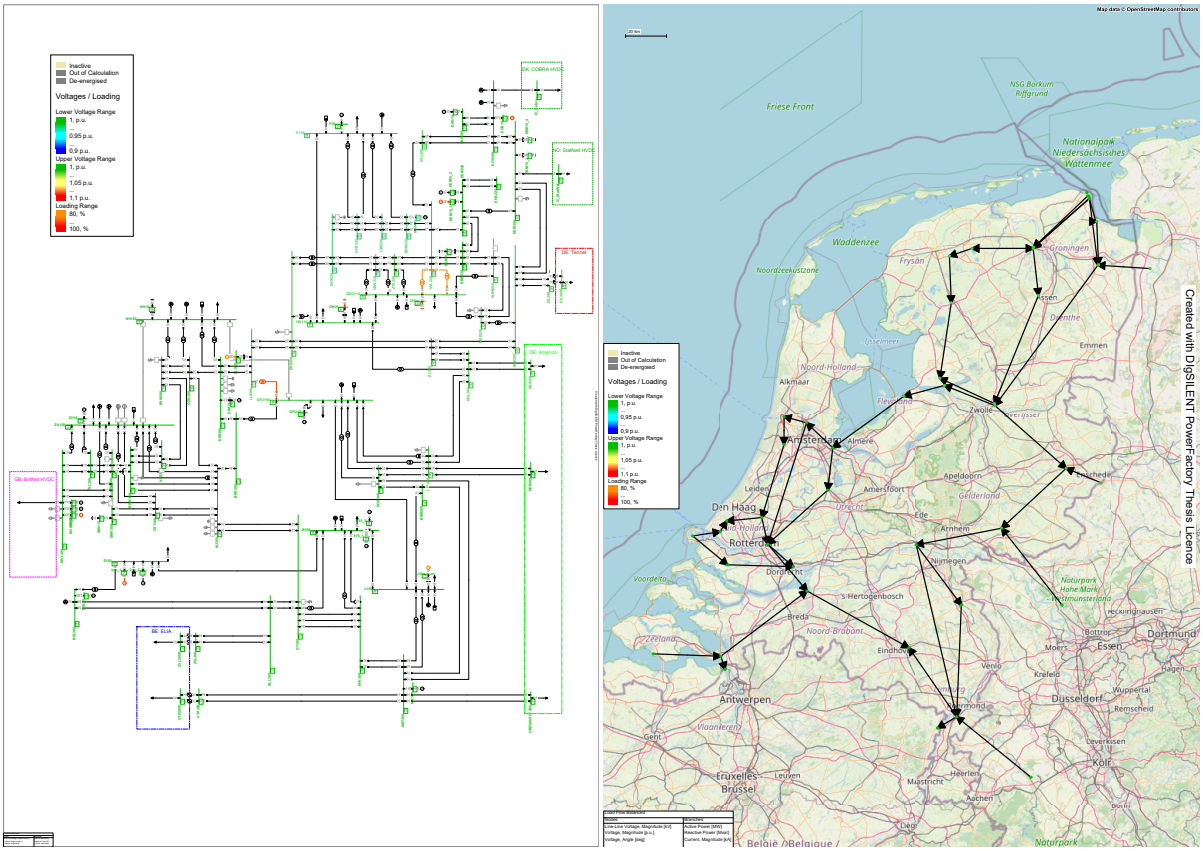
Name	Type	Loading [%]	Voltage [p.u.]	Voltage [kV]	Station/Branch	Apparent Power [MVA]	Current [kA]	Current [p.u.]
DG_GAS_ON15	Sym	87.52			ON15	194,47	7,49	0,88
DG_GAS_ZH15	Sym	78.63			ZH15	2957,29	113,83	0,79
DG_NUCL_Z15_1	Sym	88.60			Z15_1	486,34	18,72	0,89
Gen_COAL_EOS15	Sym	90.44			EOS15	1587,81	61,11	0,90
Gen_COAL_MVL15_3	Sym	87.43			MVL15_3	710,07	27,33	0,87
Gen_GAS_DIM15	Sym	77.14			DIM15	372,80	14,35	0,77
Gen_GAS_EEM15_1	Sym	90.73			EEM15_1	363,93	14,01	0,91
Gen_GAS_EEM15_3	Sym	90.75			EEM15_3	362,00	13,93	0,91
Gen_GAS_EEM15_4	Sym	79.50			EEM15_4	318,01	12,24	0,80
Gen_GAS_LLS15	Sym	83.62			LLS15	395,78	15,23	0,84
Gen_GAS_MVL15_2	Sym	78.60			MVL15_2	737,13	28,37	0,79

Figure D.3: Overloaded elements for the 2017 Peak Demand Initial Power Flow

The main overloaded grid elements are therefore the following:

- Trafo DTC380-GFU150
- Trafo GT380-B150
- Trafo LLS380-GFU150
- Trafo VVL220-GDO110
- Trafo WEW220-GDO110

A quick snapshot of the power flows for the 2017 Peak Demand simulation is shown in figure D.31. In the single line diagram the elements loaded above 80% are colored orange or red depending on the amount of overloading. (the red text box can be ignored, this was just assigned a red color). It is clear by looking at the geographical diagram that in this scenario there is a large amount of power flowing from the North of the Netherlands to the South. As mentioned before, the cross-border power flows couldn't be assigned seperately to each connection as their was only information available the total value per bidding zone. The amount was then distributed evenly among the different connections.



(a) Single Line Diagram **(b)** Geographic Representation

Figure D.4: Overview of Power Flow for Peak Demand 2017

2018 Peak Demand Scenario

In figure D.5 a summary is given of the total generation, load, grid losses, line charging etc. of the powerflow for the 2018 Peak Demand simulation. The total amount of generation in this simulation is 17184 MW and the total demand at the 110/150kV busbars is 18942 MW. Because the interconnection to neighbouring countries are modelled as (negative) demands, the system summary shows a total demand of 17066 MW, reflecting an inflow from neighbouring countries of 1876 MW. The reactive power losses in the grid are around 1141 MW, which is slightly lower than in the 2017 simulation but still higher than normal due to overloaded transformers. The line charging is around -1641 Mvar, which is around the same as for the 2017 simulation.

Total System Summary			Study Case: LF - Base Case			Annex:		/ 1
No. of Substations	0	No. of Busbars	88	No. of Terminals	0	No. of Lines	104	
No. of 2-w Trfs.	72	No. of 3-w Trfs.	0	No. of syn. Machines	27	No. of asyn.Machines	0	
No. of Loads	18	No. of Shunts/Filters	0	No. of SVS	0			
Generation	=	17184,74 MW	1141,80 Mvar	17222,63 MVA				
External Infeed	=	0,00 MW	0,00 Mvar	0,00 MVA				
Load P(U)	=	17066,00 MW	0,00 Mvar	17066,00 MVA				
Load P(Un)	=	17066,00 MW	0,00 Mvar	17066,00 MVA				
Load P(Un-U)	=	-0,00 MW	-0,00 Mvar					
Motor Load	=	0,00 MW	0,00 Mvar	0,00 MVA				
Grid Losses	=	118,74 MW	1141,80 Mvar					
Line Charging	=		-1641,60 Mvar					
Compensation ind.	=		0,00 Mvar					
Compensation cap.	=		0,00 Mvar					
Installed Capacity	=	31672,47 MW						
Spinning Reserve	=	6639,03 MW						
Total Power Factor:								
Generation	=	1,00 [-]						
Load/Motor	=	1,00 / 0,00 [-]						

Figure D.5: System Summary for the 2018 Peak Demand Initial Power Flow

All the elements loaded above 70% of their capacity are shown in figure D.6. The generators are dispatched at this loading intentionally, therefore their loading is not suprising. In this simulation, some of the lower voltage busbars were connected using tranmission lines. In this simulation, there is around 150 MW of power being transferred from Zeeland to Brabant through the 150kV connection.

Study Case: LF - Base Case								Annex:	/ 1
		Loading	Voltage			Apparent Power	Current		
Name	Type	[%]	[p.u.]	[kV]	Station/Branch	[MVA]	[kA]	[p.u.]	
Overloaded Elements									
Line_B150_Z150	Lne	70.41			B150	153,31	0,59	0,70	
					Z150	155,26	0,60	0,70	
Trafo_GT380_B150	Tr2	80.97			GT380	726,41	1,11	0,81	
					B150	724,41	2,80	0,81	
Trafo_LLS380_GFU150	Tr2	99.15			LLS380	984,95	1,51	0,99	
					GFU150	985,56	3,82	0,99	
Trafo_VVL220_GDO110_1	Tr2	72.31			VVL220	265,88	0,70	0,72	
					GDO110	265,37	1,40	0,72	
Trafo_VVL220_GDO110_2	Tr2	72.31			VVL220	143,72	0,38	0,72	
					GDO110	143,44	0,76	0,72	
DG_GAS_F15	Sym	88.20			F15	68,62	2,64	0,88	
DG_GAS_GDO15	Sym	86.06			GDO15	306,03	11,78	0,86	
DG_GAS_L15	Sym	74.63			L15	501,64	19,31	0,75	
DG_GAS_ON15	Sym	86.40			ON15	191,98	7,39	0,86	
DG_GAS_ZH15	Sym	77.76			ZH15	2924,80	112,58	0,78	
DG_NUCL_Z15_1	Sym	88.26			Z15_1	484,45	18,65	0,88	
Gen_COAL_MVL15_1	Sym	79.64			MVL15_1	946,87	36,45	0,80	
Gen_GAS_BSL15	Sym	88.97			BSL15	860,55	33,12	0,89	
Gen_GAS_DIM15	Sym	81.10			DIM15	391,96	15,09	0,81	
Gen_GAS_EEM15_1	Sym	89.92			EEM15_1	360,68	13,88	0,90	

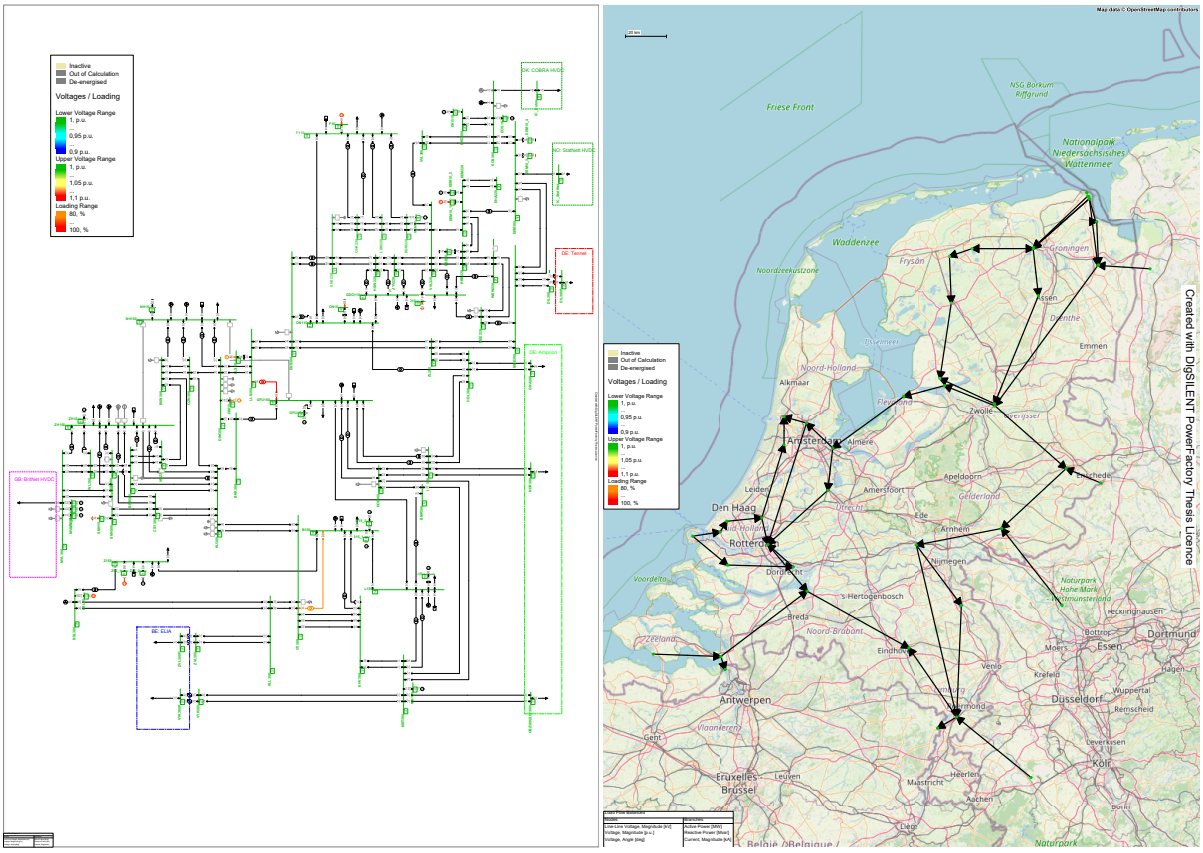
Study Case: LF - Base Case								Annex:	/ 2
		Loading	Voltage			Apparent Power	Current		
Name	Type	[%]	[p.u.]	[kV]	Station/Branch	[MVA]	[kA]	[p.u.]	
Gen_GAS_EEM15_3	Sym	85.62			EEM15_3	341,53	13,15	0,86	
Gen_GAS_LLS15	Sym	81.16			LLS15	384,15	14,79	0,81	
Gen_GAS_MVL15_2	Sym	79.40			MVL15_2	744,63	28,66	0,79	
Gen_GAS_SMH15	Sym	88.17			SMH15	417,29	16,06	0,88	

Figure D.6: Overloaded elements for the 2018 Peak Demand Initial Power Flow

The main overloaded transformers are all also mentioned for the 2017 Peak Demand scenario:

- Trafo GT380-B150
- Trafo LLS380-GFU150
- Trafo VVL220-GDO110
- Line Z150-B150

A quick snapshot of the power flows for the 2017 Peak Demand simulation is shown in figure D.7. From this diagram it can be seen that for this simulation, again the most critical element is a transformer between Lelystad 380kV and the 150kV area of Gelderland, Flevoland and Overijssel, which is loaded to 99% of its capacity. Besides this the transformer between Geertruidenberg 380kV and Brabant 150kV is also heavily loaded.



(a) Single Line Diagram **(b)** Geographic Representation

Figure D.7: Overview of Power Flow for Peak Demand 2018

2019 Low Demand Scenario

To see whether different elements might become critical for a low demand, a simulation was performed for a dispatch with low demand in 2019. This scenario also had a lower amount of renewable energy generation. In this scenario no new elements were identified as critical. The critical elements are the following:

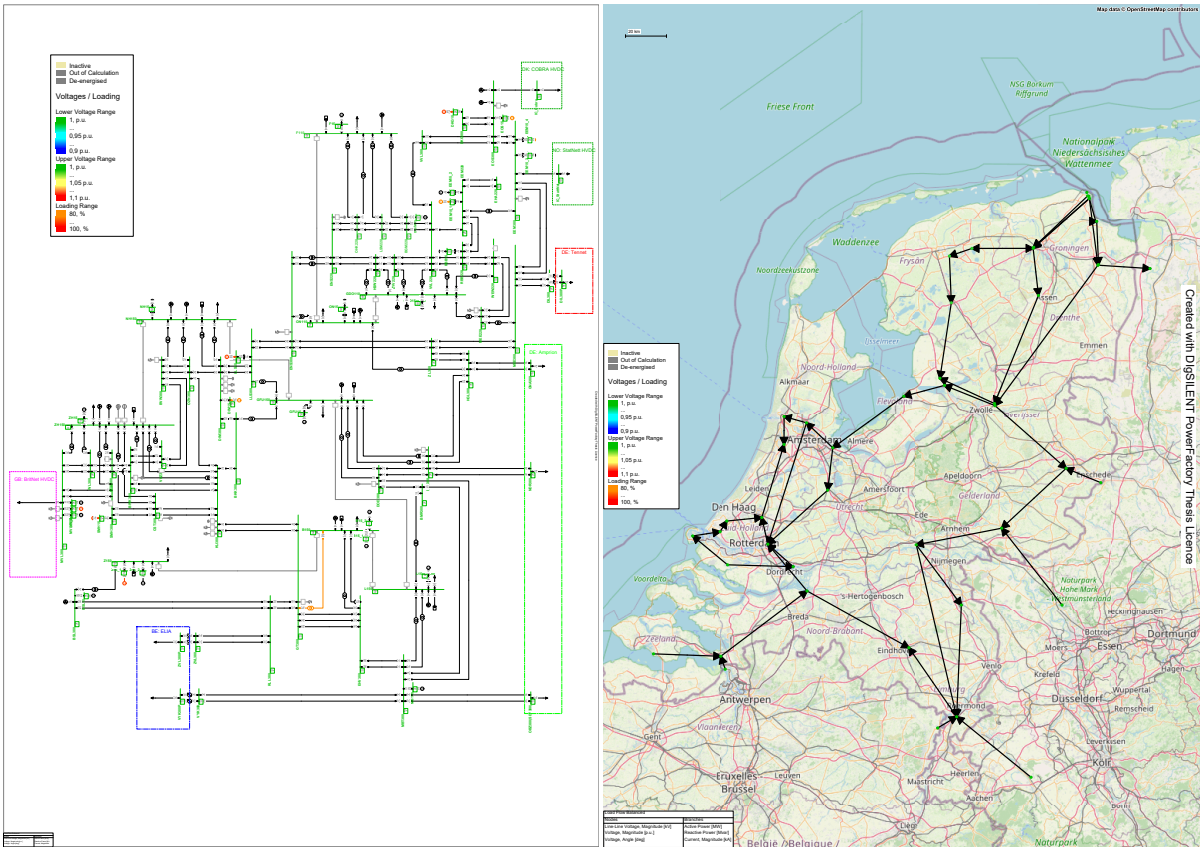
- Trafo GT380-B150
- Trafo LLS380-GFU150

Total System Summary					Study Case: LF - Base Case				Annex:		/ 1
No. of Substations	0	No. of Busbars	88	No. of Terminals	0	No. of Lines	99				
No. of 2-w Trfs.	72	No. of 3-w Trfs.	0	No. of syn. Machines	27	No. of asyn.Machines	0				
No. of Loads	18	No. of Shunts/Filters	0	No. of SVS	0						
Generation	=	14208,35	MW	727,33	Mvar	14226,95	MVA				
External Infeed	=	0,00	MW	0,00	Mvar	0,00	MVA				
Load P(U)	=	14108,90	MW	-0,00	Mvar	14108,90	MVA				
Load P(Un)	=	14108,90	MW	0,00	Mvar	14108,90	MVA				
Load P(Un-U)	=	0,00	MW	0,00	Mvar						
Motor Load	=	0,00	MW	0,00	Mvar	0,00	MVA				
Grid Losses	=	99,45	MW	727,33	Mvar						
Line Charging	=			-1620,94	Mvar						
Compensation ind.	=			0,00	Mvar						
Compensation cap.	=			0,00	Mvar						
Installed Capacity	=	31972,47	MW								
Spinning Reserve	=	9360,72	MW								
Total Power Factor:											
Generation	=	1,00	[-]								
Load/Motor	=	1,00 / 0,00	[-]								

Figure D.8: System Summary for the 2019 Low Demand Simulation

Study Case: LF - Base Case							Annex:	/ 1
		Loading	Voltage			Apparent Power	Current	
Name	Type	[%]	[p.u.]	[kV]	Station/Branch	[MVA]	[kA]	[p.u.]
Overloaded Elements								
Trafo_GT380_B150	Tr2	82.56			GT380	741,66	1,13	0,83
					B150	740,36	2,86	0,83
Trafo_LLS380_GFU150	Tr2	72.63			LLS380	723,63	1,10	0,73
					GFU150	724,57	2,80	0,73
DG_NUCL_Z15_1	Sym	86.28			Z15_1	473,59	18,23	0,86
Gen_COAL_EOS15	Sym	82.53			EOS15	1448,95	55,77	0,83
Gen_COAL_MVL15_3	Sym	79.93			MVL15_3	649,16	24,99	0,80
Gen_GAS_BSL15	Sym	79.33			BSL15	767,29	29,53	0,79
Gen_GAS_DIM15	Sym	84.29			DIM15	407,35	15,68	0,84
Gen_GAS_DKG15	Sym	85.30			DKG15	1336,33	51,44	0,85
Gen_GAS_EEM15_1	Sym	83.64			EEM15_1	335,46	12,91	0,84
Gen_GAS_EEM15_4	Sym	80.02			EEM15_4	320,09	12,32	0,80
Gen_GAS_LLS15	Sym	88.93			LLS15	420,91	16,20	0,89
Gen_GAS_MVL15_2	Sym	86.63			MVL15_2	812,39	31,27	0,87
Gen_GAS_SMH15	Sym	86.00			SMH15	407,05	15,67	0,86

Figure D.9: System Summary for the 2019 Low Demand Simulation



(a) Single Line Diagram **(b)** Geographic Representation

Figure D.10: Overview of Power Flow for Peak Demand 2018

What is interesting to mention is that for this scenario the reactive power losses of the grid are around 730 Mvar. When performing this simulation with the upgraded model for 2030, there are no overloaded grid elements and this number declines to around 360 Mvar. The line charging however does increase from -1620 Mvar to -1813 Mvar, see figure D.11.

Total System Summary					Study Case: LF - Base Case			Annex:	/ 1
No. of Substations	0	No. of Busbars	89	No. of Terminals	0	No. of Lines	106		
No. of 2-w Trfs.	73	No. of 3-w Trfs.	0	No. of syn. Machines	27	No. of asyn.Machines	0		
No. of Loads	18	No. of Shunts/Filters	0	No. of SVS	0				
Generation	=	14192,35	MW	363,40	Mvar	14197,00	MVA		
External Infeed	=	0,00	MW	0,00	Mvar	0,00	MVA		
Load P(U)	=	14108,90	MW	-0,00	Mvar	14108,90	MVA		
Load P(Un)	=	14108,90	MW	0,00	Mvar	14108,90	MVA		
Load P(Un-U)	=	-0,00	MW	0,00	Mvar				
Motor Load	=	0,00	MW	0,00	Mvar	0,00	MVA		
Grid Losses	=	83,45	MW	363,40	Mvar				
Line Charging	=			-1813,63	Mvar				
Compensation ind.	=			0,00	Mvar				
Compensation cap.	=			0,00	Mvar				
Installed Capacity	=	31972,47	MW						
Spinning Reserve	=	9376,72	MW						
Total Power Factor:									
Generation	=	1,00	[-]						
Load/Motor	=	1,00 / 0,00	[-]						

Figure D.11: System Summary for the 2019 Low Demand Simulation using the upgraded model for 2030

D.2. Transfer Capacity Analysis

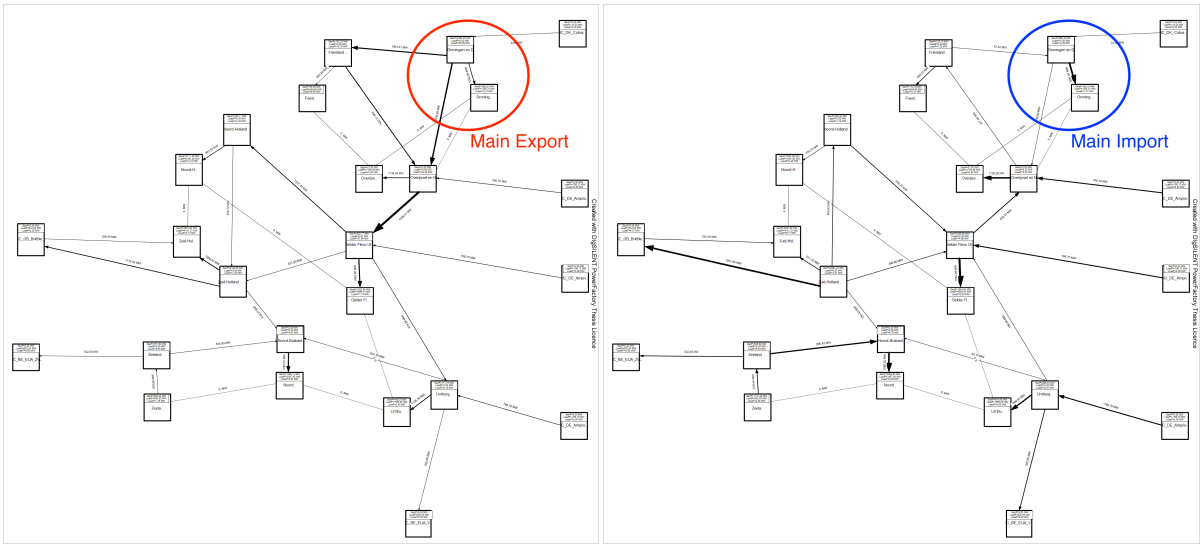
To be able to get a more comprehensive view of the critical areas of the network, additional simulations were performed. It was investigated what the power flow would look like if there is a high amount of export or import of power from/to a specific region. The division of the areas was chosen according to the zones defined in KCD2017 [31] as mentioned before in chapter 3.2.2 and elaborated on further in appendix chapter B. For a high export, this would mean that within one region the maximum amount of (synchronous) controllable generation was dispatched, while the other regions would supply the missing amount. For a high import, the minimum amount of controllable generation for that region was dispatched. Limits for the thermal loading of different components were adjusted to a maximum of 100%, so that the amount of capacity transferred between zones would be less limited. This analysis was performed for all the different zones.

For the initial (starting) power flow, all the generators were dispatched at the same capacity factor (of around 70%). The demand, interconnecting power flows and renewable generation of the peak demand scenario of 2018 was used. The static generators couldn't participate in the re-dispatching/ were not controllable.

Two groups of simulations were performed:

1. In the first, the interconnecting capacities were used according to the initial power flow.
2. For the second group of simulations the interconnections were disabled, making the Netherlands completely self-supplying.

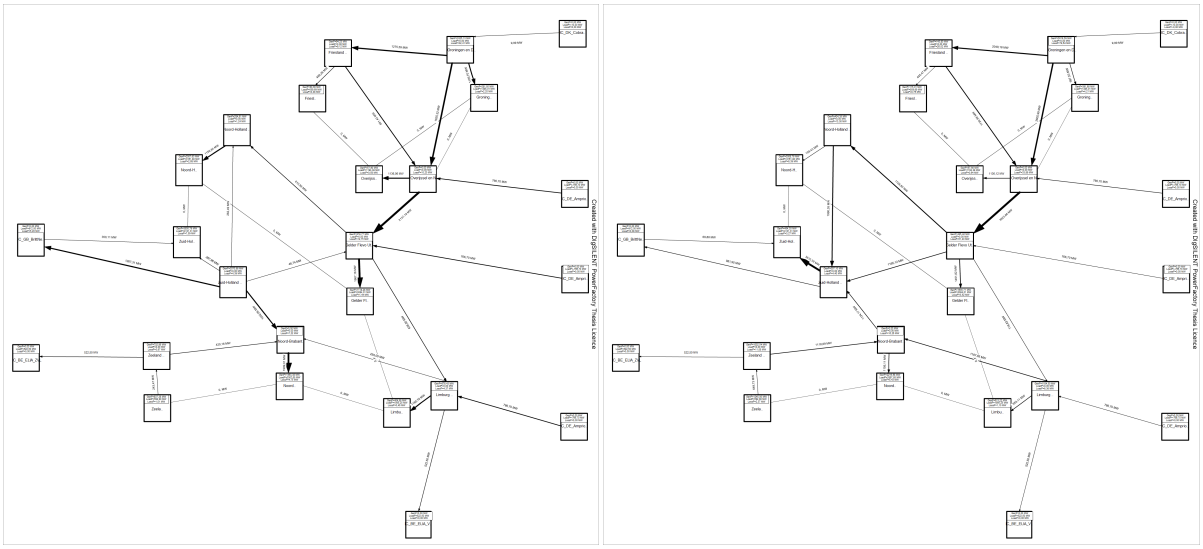
These power flows between the different zones were also visualised for these simulations using a seperate diagram within PowerFactory. In figure D.12 an example is given of Groningen and Drenthe, where the left figure shows the power flows when Groningen and Drenthe is "exporting" region, and the right figure is where the situation is flipped: the rest of the network is considered the "exporting" region and Groningen and Drenthe is chosen to be an "importing" region.



(a) GD as exporting region

(b) GD as importing region

Figure D.12: Power Flows between zones for Groningen and Drenthe



(a) ZH as exporting region **(b)** ZH as importing region

Figure D.13: Power flows between zones for Zuid-Holland

D.2.1. TCA: Results and Comparison to KCD2020

When performing these simulations the focus was on what the critical components were within the specific region being investigated. It differed whether the importing or exporting scenario was more critical for a region. As most of the generation capacity is located in the North of the Netherlands, in almost all ”importing” scenarios, there is a large power flow coming from the North towards the south of the Netherlands, see also figure D.13. This results in the same elements becoming overloaded as were mentioned before for the peak demand simulation (except for when GD was the importing zone).

In table D.1 the different elements that were overloaded in these scenarios are mentioned. It is important to consider that some of these elements were already overloaded in the base scenario of a proportional generation dispatch (all generators in the whole system were loaded at the same capacity factor). These are indicated by a ”Y” in the last column of the table. 30 simulations were performed in total (some configurations of simulations were not possible, such as defining ON as an importing or exporting region, due to lack of total generation capacity within the region).

Table D.1: Limiting/Critical Network Components that were identified during TCA analysis

Overloaded Element	Zone	Max. Loading (%)	# Scenarios Overloaded	Avg. Loading if Overloaded	Base PF Overloaded?
Trafo BGM220-F110	Groningen and Drenthe	78	3	74	N
Trafo DTC380-GFU150	Gelderland, Flevoland en Overijssel	89	10	77	Y
Trafo ENS380-ENS220	Groningen and Drenthe	103	8	83	N
Trafo GT380-B150	Noord-Brabant	157	23	95	Y
Trafo LLS380-GFU150	Gelderland, Flevoland en Overijssel	120	27	93	Y
Trafo VVL220-GDO110	Groningen and Drenthe	92	27	79	Y
Trafo WEW220-GDO110	Groningen and Drenthe	84	9	76	Y
Trafo BKK380-GFU150	Gelderland, Flevoland en Overijssel	119	7	98	N
Trafo BMR380-L150	Limburg	88	3	79	N
Trafo EHV380-B150	Noord-Brabant	100	2	98	N
Trafo DIM380-NH150	Noord-Holland	78	1	78	N
Line BVW380-VHZ380	Zuid-Holland	85	1	85	N
Line DIM380-LLS380	Zuid-Holland	76	1	76	N
Line KIJ380-BKK380	Zuid-Holland	73	1	73	N
Line OZN380-DIM380	Zuid-Holland	79	1	79	N

According to KCD2017 the projects listed in previous sections should alleviate the critical areas (and the corresponding components) in the network until 2025 [31]. Whether this is also true when peak demand occurs is not mentioned. In KCD2020 impact of different projects is shown by listing which

components they impact and what the current ”risk” of the component is for different years and scenarios. These risks are not just about availability of a component or the power quality but also about safety, financial aspects, compliance, environment, customers and reputation [2]. Therefore we cannot compare the list of critical elements 1 on 1 to the list found from the simulations (as these are soley about overloading of components). Some of the above listed critical transformers show up in projects mentioned in KCD2020, as shown in table D.14. There are however many more components listed in KCD2020 with similar risk ratings [2]. Only the transformers are compared, as the lines were overloaded only in one specific scenario, which will be discussed further in the chapter D.3.

From Simulations	Section of KCD2020	Project	2020	2025	2030
Trafo BGM220-F110	HV	Netversterking Oostelijk Friesland			n-1
Trafo DTC380-GFU380	LV	Splitsing FGU-net	n-1	n-1	n-0
Trafo ENS380-ENS220	HV	Ens 380KV, vergroten transformator-capaciteit 380-220kV	n-1	n-1	n-0
Trafo GT380-B150	HV	Geertruidenberg 380kV, 3e koppeltransformator	n-1	n-1	n-0
Trafo LLS380-GFU150	LV	Splitsing FGU-net		n-1	n-0
Trafo VVL220-GDO110	LV	Deelnet Groningen Stad 110kV			n-1
Trafo WEW220-GDO110	overig	Uitbreiding naar 3 trafo's			
Trafo BKK380-GFU150	HV	Splitsing FGU-net	n-1	n-0	n-0
Trafo BMR380-L150	HV	Boxmeer 380kV, uitbreiden en reconstructie station			n-1
Trafo EHV380-B150	HV	Wijchen 380kV, nieuw station	n-1	n-1	n-1
Trafo DIM380-NH150	LV	Vijfhuizen-Nieuwemeer 150kV kabelverbinding		n-0	n-0

Figure D.14: List of how critical components are from simulations according to KCD2020

D.3. Critical Components in Detail

In the current model, there are several limiting/critical components when peak demand occurs. Almost all of these critical components are transformers to lower-voltage areas. Although most of these components are in high loaded areas also according to KCD2017, it is worth investigating whether these components have been modelled properly and whether there are other components missing that might influence the power flow simulations. The situation in which the different components are overloaded are described in more detail in this section. The elements that identified as being critical or very often overloaded (23-27/30 simulations) in the current model are:

- Trafo LLS380-GFU150
- Trafo VVL220-GDO110
- Trafo GT380-B150

Other components worth mentioning that are overloaded (7-10/30 simulations) in different simulations are:

- Trafo ENS380-ENS220
- Trafo WEW220-GDO110
- Trafo DTC380-GFU380

Other than this, components that are overloaded only in very specific simulations are also mentioned. In simulations where there is a large import of generation in the west of the Netherlands (ZH, Z or NH) undervoltages are more likely to occur. In general the the whole system is more prone to have undertha overvoltages as there is a high demand and generators are highly loaded throughout the rest of the Netherlands when one region is set to ”importing”. This could have to do with the programming of the transformers (losses etc.) or with the amount of generation capacity available for regulation. Only in the simulation where ZH is set as importing region, are there high voltage transmisson lines that are loaded above 70% due to also large amounts of reactive power flowing through the system.

D.3.1. Trafo BGM220-F110

This element is overloaded in the TCA simulations of GD being assigned as exporting region (and the rest of the network importing) or ZH being assigned specifically as importing region (and the rest of the network is exporting). In both of the scenarios where this transformer is overloaded, it is in the direction of BGM220 to F110. This is because there is a much higher load at F110 than there is generation capacity at the lower voltage busbar. When looking at the summary for this busbar in figure D.15, it is visible that most of the power flowing in is coming through the transformer of BGM220-F110 and LSM220-F110, while the transformers at OHK220-F110 only have a small outflowing amount of reactive power, but nothing flowing in.

| Grid: Grid_HVNL | System Stage: Grid_HVNL | Study Case: LF - Base Case | Annex: / 1 |

	rated Voltage [kV]	Bus-voltage [p.u.]	Bus-voltage [kV]	[deg]	Active Power [MW]	Reactive Power [Mvar]	Power Factor [-]	Current [kA]	Loading [%]	Additional Data
F110										
	110,00	0,98	107,34	15,44						
Cub_6	/Lod	Load_F110			559,69	0,00	1,00	3,01		Pl0: 559,69 MW Ql0: 0,00 Mvar
Cub_7	/Genstat	DG_PV_F110			0,00	0,00	1,00	0,00	0,00	
Cub_8	/Genstat	DG_WOL_F110			45,10	0,00	1,00	0,24	12,89	
Cub_11	/Tr2	Trafo_F110/15			-49,70	-38,35	-0,79	0,34	25,23	Tap: 0,00 Min: -4 Max: 4
Cub_12	/Tr2	Trafo_OHK220_F110_			0,55	8,22	0,07	0,04	2,28	Tap: 0,00 Min: -16 Max: 16
Cub_13	/Lne	Line_ON110_F110								Pv: cLod: L: 50,00 km
Cub_3	/Tr2	Trafo_OHK220_F110_			0,59	8,89	0,07	0,05	2,28	Tap: 0,00 Min: -16 Max: 16
Cub_4	/Tr2	Trafo_LSM220_F110			-184,70	10,00	-1,00	0,99	47,39	Tap: 0,00 Min: -16 Max: 16
Cub_5	/Tr2	Trafo_BGM220_F110			-281,33	11,23	-1,00	1,51	72,13	Tap: 0,00 Min: -16 Max: 16

Figure D.15: Single Line Diagram with overloading of the Transformer BGM220-F110

D.3.2. Trafo DTC380-GFU150

Only in different base scenarios was this components limited, meaning that when the interconnections were disabled, this component was no longer critical. This can be explained by the fact that there is an interconnector connected to DTC380 via NDR380.

D.3.3. Trafo ENS380-ENS220

This element is often overloaded when there is a large amount of power flowing from the North of the Netherlands to the South, as it is the only connection between the 220KV grid in the North and the 380kV grid, see the circle in figure D.18. For the TCA simulations this was in the case of GD exporting, B importing, GFU importing, NH importing, ZH importing, Z importing but also exporting.

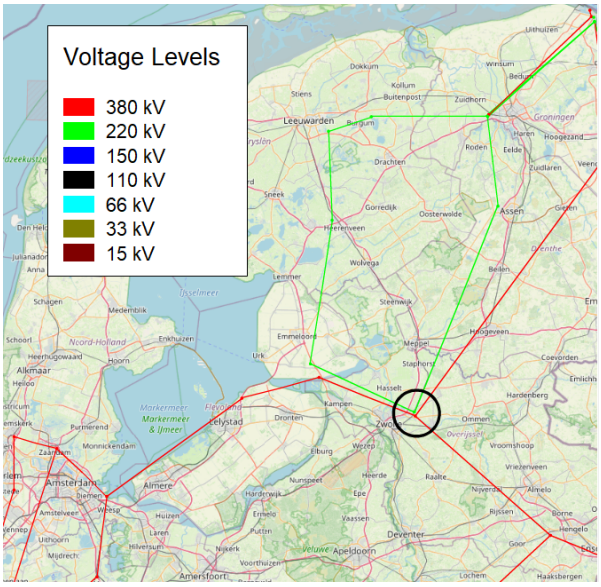


Figure D.16: Geographic Representation of the Dutch EHV grid

D.3.4. Trafo GT380-B150

This is one of the elements that gets overloaded most often in the different scenarios (23 times out of 30) when the base topology is used. The amount of overloading however declines when the new high voltage station of TIL380 in Tilburg with transformers to B150 is introduced. The transformer GT380-B150 does however become loaded to 93% of its capacity in a scenario in which Noord-Brabant is assigned as main importing region. In all other scenarios, the loading is reduced to around 45%.

D.3.5. Trafo LLS380-GFU150

This element is most often identified as critical. It is an element that connects the area of Lelystad to the lower voltage grid of GFU. In almost every scenario with high demand (27 out of 30), this transformer becomes overloaded. The average loading is around 93% for the different simulations. For the Peak demand scenarios, this transformer is overloaded 87% and 96% in 2017 and 2018 respectively. In this case there is a difference of around 1500MW between the load (around 3000MW) and the maximum generation at the lower voltage busbar (1500 MW though in the peak demand scenario the dispatch is 1300MW).

D.3.6. Trafo VVL220-GDO110

The transfromers between VVL220 and GDO110 often become overloaded. The direction is from the 380kV region to the lower voltage busbar. Interesting is that there is also a substantial amount of power flowing from the 110kV busbar back to the high voltage grid at HSN220 and ZYV220.

Grid: Grid_HVNL	System Stage: Grid_HVNL	Study Case: LF - Base Case	Annex: / 1

	rated Voltage [kV]	Bus-voltage [p.u.]	[kV]	[deg]	Active Power [MW]	Reactive Power [Mvar]	Power Factor [-]	Current [kA]	Loading [%]	Additional Data
GDO110										
	110,00	0,99	108,43	13,50						
Cub_11 /Lod		Load_GDO110			1385,01	0,00	1,00	7,37		Pl0: 1385,01 MW Ql0: 0,00 Mvar
Cub_13 /Genstat		DG_PV_GDO110			0,00	0,00	1,00	0,00	0,00	
Cub_8 /Genstat		DG_WOL_GDO110			72,10	0,00	1,00	0,38	12,87	
Cub_14 /Tr2		Trafo_GDO110/15			-300,25	-28,41	-1,00	1,61	59,99	Tap: 0,00 Min: -4 Max: 4
Cub_15 /Tr2		Trafo_VVL220_GDO11			-160,86	4,68	-1,00	0,86	81,63	Tap: 0,00 Min: -16 Max: 16
Cub_16 /Tr2		Trafo_HSW220_GDO11			264,17	3,58	1,00	1,41	38,29	Tap: 0,00 Min: -16 Max: 16
Cub_18 /Lne		Line_ON110_GDO110			107,25	-18,53	0,99	0,58	50,39	Pv: 4511,28 kW cLod: 3,33 Mvar L: 50,00 km
Cub_3 /Tr2		Trafo_MEE220_GDO11			-385,88	11,07	-1,00	2,06	52,92	Tap: 0,00 Min: -16 Max: 16
Cub_4 /Tr2		Trafo_WEW220_GDO11			-524,58	13,93	-1,00	2,79	71,94	Tap: 0,00 Min: -16 Max: 16
Cub_5 /Tr2		Trafo_VVL220_GDO11			-297,58	8,67	-1,00	1,59	81,63	Tap: 0,00 Min: -16 Max: 16
Cub_6 /Tr2		Trafo_ZYV220_GD110			-154,81	3,11	-1,00	0,82	39,27	Tap: 0,00 Min: -16 Max: 16
Cub_7 /Tr2		Trafo_HSW220_GDO11			139,63	1,89	1,00	0,74	38,29	Tap: 0,00 Min: -16 Max: 16

Figure D.17: Overview of the elements connected to the GDO110 busbar and their loadings for the 2017 Peak demand simulation

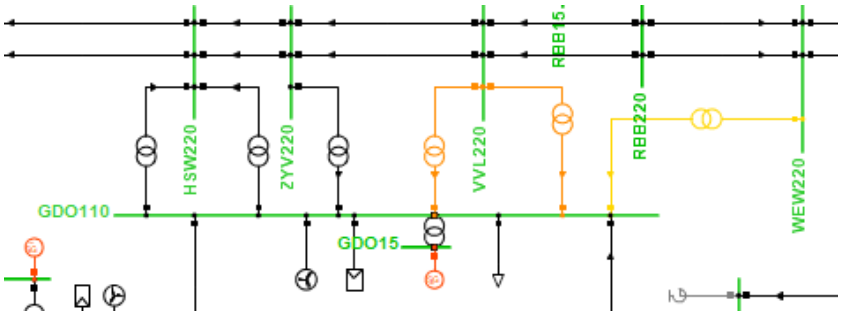


Figure D.18: Overview of the GDO110 busbar and the connected transformers for the 2017 Peak demand simulation

It was investigated whether this could have to do with a congestion of the transmission lines around this busbar, however as can be seen in figure D.19 the transmission line between VVL220 and ZYV220 is only around 25% loaded.

Grid: Grid_HVNL	System Stage: Grid_HVNL	Study Case: LF - Base Case	Annex: / 1

Name	Type	Loading [%]	Busbar	Active Power [MW]	Reactive Power [Mvar]	Power.- factor [-]	Current [kA]	Current [p.u.]
VVL220_ZYV220_W	Lne	25,90	ZYV220	-243,219	6,997	-1,00	0,647	0,259
			VVL220	243,723	-2,511	1,00	0,648	0,259
VVL220_ZYV220_Z	Lne	25,90	ZYV220	-243,219	6,997	-1,00	0,647	0,259
			VVL220	243,723	-2,511	1,00	0,648	0,259

Figure D.19: Line Loading of VVL220-ZYV220 for the peak demand simulation of 2017

D.3.7. Trafo WEW220-GDO110

As with the transformer mentioned above, this transformer is a connection to GDO110. This element sometimes become overloaded though less frequent than the trafo VVL220-GDO110. It is overloaded when GD or F is exporting, but also when certain other regions are set to importing. The maximum loading in these scenarios is around 75-80%.

D.3.8. Trafo BKK380-GFU150

This transformer could be seen as the ”other” transformer that can become overloaded when trying to meet the high demand of GFU150. It mainly becomes overloaded when there is power flowing from the West of the Netherlands to other areas in the network. Especially in scenarios in which GD or GFU is importing (meaning the generation in GFU is even lower than normal) this element becomes heavily loaded.

D.3.9. Trafo BMR380-L150

This transformer is a connection between BMR380 and the lower voltage area Limburg 150KV. This transformer is seen as less ”critical” and only becomes overloaded in the case that either Noord-Brabant (B) or Limburg (L) is ”importing” meaning their generation is lower than normal. In this case the loadings are between 70-88% depending on the scenario. For the peak demand simulations based on historical dispatches this element is loaded to 52% and 56% respectively.

D.3.10. Trafo EHV380-B150

This transformer only becomes overloaded in the transfer capacity analysis when Brabant (B) is set to being the main importing region. In this scenario there is a demand of around 3300 MW at the B150 busbar. The generation within brabant is set to 10% of its capacity (around 220 MW production) and around 3100 MW is imported from Zuid-Holland (1400 MW), Zeeland (750MW) and Limburg (900 MW). Both this transformer and the trafo GT380-B150 (mentioned before) become severly overloaded in this case to around 100 and 145% respectively as can be seen in figure D.20.

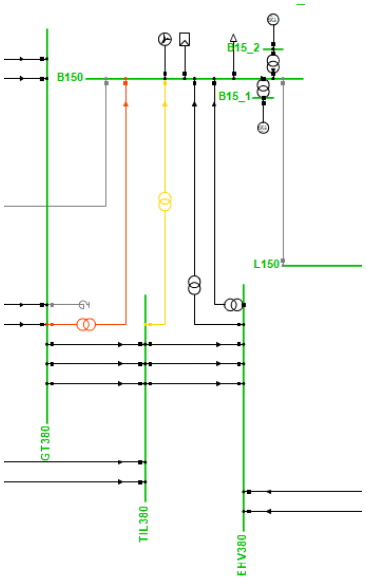


Figure D.20: Loadings for the Brabant base ”Importing” simulation

D.3.11. Trafo DIM380-B150

This transformer only become overloaded in one specific simulation, where Noord-Holland is set as importing region for the base case (meaning there is also cross-border flow). The transformer in this case is loaded to 78%. As can be seen below in figure D.21 the other transformers are loaded to around 50% and the generation at the lower voltage busbar supplies around 400 MW (gas, onshore and offshore wind) of the 3150 MW demand.

Grid: Grid_HVNL	System Stage: Grid_HVNL	Study Case: LF - Base Case	Annex: / 1

			rated Voltage [kV]	Bus-voltage [p.u.]	Bus-voltage [kV]	[deg]	Active Power [MW]	Reactive Power [Mvar]	Power Factor [-]	Current [kA]	Loading [%]	Additional Data
NH150												
			150,00	0,99	148,81	-7,73						
Cub_6	/Lod	Load_NH150					3161,80	0,00	1,00	12,27		P10: 3161,80 MW Q10: 0,00 Mvar
Cub_7	/Genstat	DG_WOL_NH150					51,50	-0,00	1,00	0,20	12,88	
Cub_8	/Genstat	DG_WOZ_NH150					53,20	0,00	1,00	0,21	17,73	
Cub_9	/Genstat	DG_PV_NH150					0,00	0,00	1,00	0,00	0,00	
Cub_13	/Tr2	Trafo_DIM380_NH150					-1042,73	111,39	-0,99	4,07	78,30	Tap: 0,00 Min: -16 Max: 16
Cub_14	/Tr2	Trafo_NH150/15					-290,70	-207,30	-0,81	1,39	8,82	Tap: 0,00 Min: -4 Max: 4
Cub_15	/Lne	Line_NH150_ZH150										Pv: cLod: L: 50,00 km
Cub_16	/Lne	Line_NH150_GFU150										Pv: cLod: L: 50,00 km
Cub_3	/Tr2	Trafo_OZN380_NH150					-804,13	43,98	-1,00	3,12	54,12	Tap: 0,00 Min: -16 Max: 16
Cub_4	/Tr2	Trafo_BVW380_NH150					-533,34	10,67	-1,00	2,07	53,77	Tap: 0,00 Min: -16 Max: 16
Cub_5	/Tr2	Trafo_DIM380_NH150					-386,20	41,26	-0,99	1,51	78,30	Tap: 0,00 Min: -16 Max: 16

Figure D.21: Power flow data for the Noord-Holland base ”Importing” simulation

D.3.12. Other Components

The reason to group these components together is because they become overloaded in the same simulation. Only in the base case where Zuid-Holland is set to be an ”importing” region (and there is cross-border flow), do these transmission lines become overloaded. In no other scenarios are there overloaded transmission lines.

The numbers in this simulation seem unrealistic. The generators outside of Zuid-Holland are all loaded between 90-96% of their capacity with the exception of the (small) generator in F110 being loaded at 116% due to large reactive power production. The grid losses in this simulation are also unrealistically high. The total generation is around 18200 MW. There is approximately 3400 Mvar reactive power grid loss (240 MW active power loss) and a line charging of -1750 Mvar. Nevertheless, to be complete this simulation is included. The data for power flow and different overloaded elements (except the generators) is given in figures D.23 and D.24. The lines are loaded to 85,76,73 and 79% respectively for the order mentioned below. It concerns the following components:

- Line BVW380-VHZ380
- Line KIJ380-BKK380
- Line DIM380-LLS380
- Line OZN380-DIM380

As highlighted above in this case, there are also many other components being overloaded as well as a lot of under voltage issues with bus voltages of around 0,96 p.u. This is visualised in figure D.22.

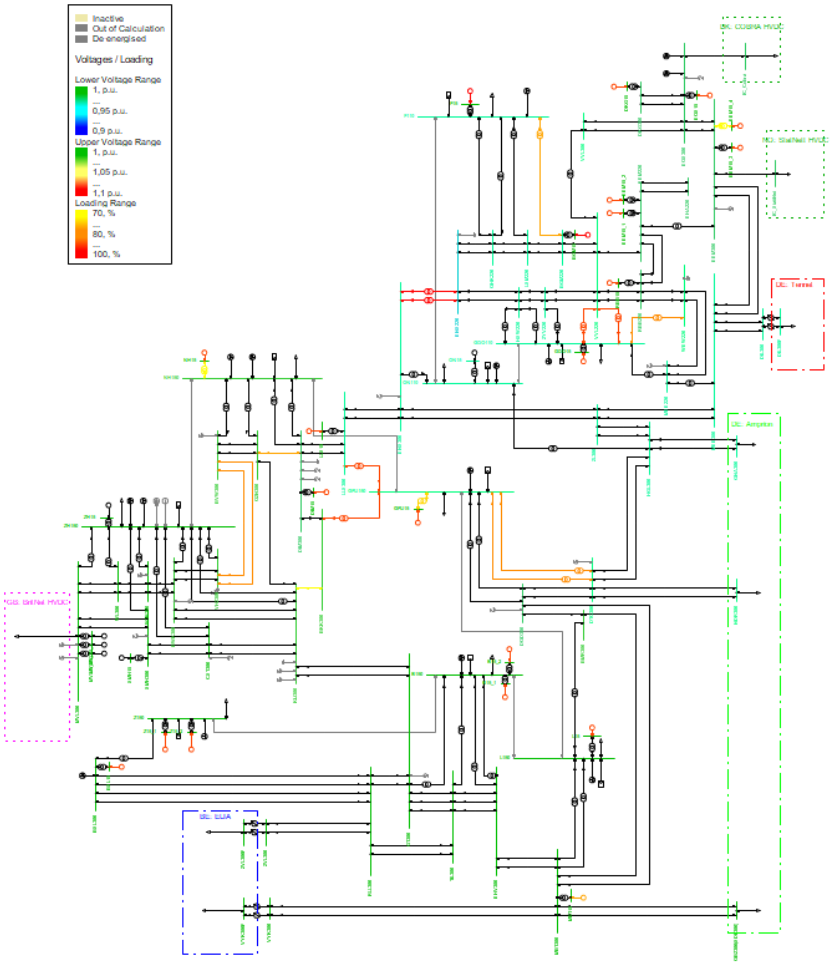


Figure D.22: ZH importing base simulation

Study Case: LF - Base Case						Annex:		/ 1
Name	Type	Loading [%]	Voltage [p.u.]	[kV]	Station/Branch	Apparent Power [MVA]	Current [kA]	[p.u.]
Overloaded Elements								
BVW380_VHZ380_W	Lne	85.24			BVW380	828,58	1,28	0,85
					VHZ380	828,03	1,28	0,85
BVW380_VHZ380_Z	Lne	85.24			BVW380	828,58	1,28	0,85
					VHZ380	828,03	1,28	0,85
DIM380_LLS380_W	Lne	76.11			LLS380	1209,61	1,90	0,76
					DIM380	1219,98	1,89	0,76
DIM380_LLS380_Z	Lne	76.11			LLS380	1209,61	1,90	0,76
					DIM380	1219,98	1,89	0,76
KIJ380_BKK380_W	Lne	73.44			BKK380	1188,04	1,84	0,73
					KIJ380	1191,30	1,83	0,73
OZN380_DIM380_G	Lne	79.11			OZN380	1477,59	2,28	0,79
					DIM380	1472,51	2,29	0,79
Trafo_BGM220_F110	Tr2	77.92			BGM220	300,97	0,82	0,78
					F110	300,52	1,64	0,78
Trafo_BKK380_GFU150	Tr2	109.56			BKK380	538,57	0,83	1,10
					GFU150	534,80	2,11	1,10
Trafo_DKG380/15	Tr2	70.52			DKG380	1412,24	2,19	0,71
					DKG15	1438,58	55,37	0,71
Trafo_DTC380_GFU150_1	Tr2	83.76			DTC380	407,77	0,64	0,84
					GFU150	408,86	1,61	0,84

Figure D.23: Power flow data for the Zuid-Holland base ”Importing” simulation, part 1

Name	Type	Loading [%]	Voltage [p.u.]	Voltage [kV]	Station/Branch	Apparent Power [MVA]	Current [kA]	Current [p.u.]
Trafo_DTC380_GFU150_2	Tr2	83.76			DTC380	366,99	0,57	0,84
					GFU150	367,97	1,45	0,84
Trafo_EEM380/15.4	Tr2	72.07			EEM380	360,59	0,56	0,72
					EEM15_4	367,55	14,15	0,72
Trafo_ENS380_ENS220_1	Tr2	103.23			ENS380	743,43	1,18	1,03
					ENS220	738,54	2,03	1,03
Trafo_ENS380_ENS220_2	Tr2	103.23			ENS380	991,25	1,57	1,03
					ENS220	984,72	2,71	1,03
Trafo_GFU150/15	Tr2	75.87			GFU150	1510,99	5,96	0,76
					GFU15	1547,80	59,57	0,76
Trafo_LLS380_GFU150	Tr2	89.10			LLS380	860,56	1,35	0,89
					GFU150	869,79	3,43	0,89
Trafo_NH150/15	Tr2	72.28			NH150	2904,06	11,35	0,72
					NH15	2948,91	113,50	0,72
Trafo_VVL220_GDO110_1	Tr2	92.80			VVL220	334,14	0,90	0,93
					GDO110	332,26	1,80	0,93
Trafo_VVL220_GDO110_2	Tr2	92.80			VVL220	180,62	0,49	0,93
					GDO110	179,60	0,97	0,93
Trafo_WEW220_GDO110	Tr2	83.65			WEW220	601,71	1,62	0,84
					GDO110	598,99	3,25	0,84

Figure D.24: Power flow data for the Zuid-Holland base ”Importing” simulation, part 2

D.4. Optimal Power Flow

For each of the different initial peak demand power flows described above, it is interesting to investigate what happens if an optimal power flow study is added. Using the power flow as a basis, the generators are redispatched to minimize or maximize a chosen objective function. For this study this is to minimize either the system costs or system losses. PowerFactory uses a interior point method algorithm to perform a non-linear optimization. For minimization of losses the objective function is to minimize the active power losses. For minimization of costs the objective function is to minimize the total costs of dispatch of the generators. Different controls that the OPF can use for optimization can be chosen, in this case generator active power dispatch and reactive power dispatch were selected. Different constraints can be selected to consider, in this case active and reactive power limits for generators (set to 0.1-1 p.u. and +-1 p.u. respectively), maximum loadings for lines (set to 80%) and transformers (set to 80%), minimum and maximum voltages for terminals (set to min 0.99 p.u. and max 1.01 p.u.) and reactive power reserve targets for generators (set to 50%).

The optimization is performed using the Newton-Lagrange method, where equality and inequality constraints are taken into account. This can be represented mathematically by the following: $min = f(x)$ for $g(x) = 0$ and $h(x) \leq 0$. A slack variable is introduced for each inequality constraint gives $g(x) = 0$ and $h(x) + s = 0$ and $s \leq 0$. A logarithmic penalty weighing factor is introduced and the following function is minimized: $f(x) - \mu * \sum_i * log(s_i)$ where μ is the penalty weighing factor. This factor is reduced throughout the optimization, for which maximum and minimum values can be defined by the user. A smaller minimum penalty weighing factor can lead to solutions closer to the constraint limits but more iterations are required to reach a solution.

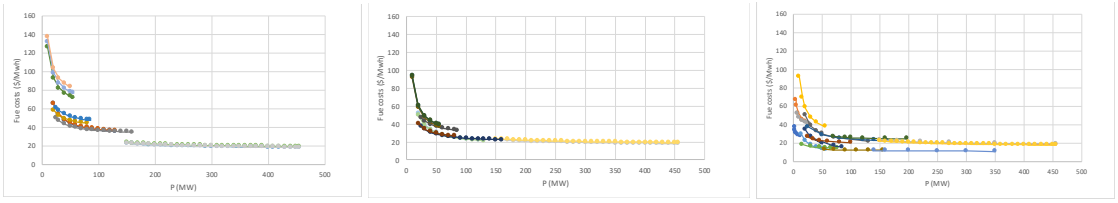
By defining the generator cost functions, which are used in the objective function of the optimization, different merit order effects can be investigated. In section D.4.1 first the approach to defining the generator cost-functions is discussed. Next the settings and predefined limits for different components is mentioned. Finally results are discussed for both types of simulations.

D.4.1. Generator Cost-functions

In PowerFactory there is the option to run an optimal power flow that minimizes the costs of the system. This function uses the generator costs of each generator and tries to redispatch in a way as to minimize these generator costs. For conventional thermal generators this costfunction is typically assumed to be quadratic. In the current model the cost function for renewable generation (solar, wind) is assumed to be zero, as the marginal costs of production are also zero. For nuclear generation, the cost function is modelled to reflect a marginal cost of slightly higher than zero.

Zooming into to the costfunction for the thermal generators, there are many different papers available that use quadratic cost functions [42], [43], [44], [45], [46], [47], [48]. These papers are mainly investigate how to best solve optimal power flows for classic generator dispatches.

The cost functions used to solve these problems differ quite a bit. Some authors choose to clearly define differences between small and large scale thermal generation [46], whereas other authors use an almost smooth cost function that can be applied to all generators [43] as is illustrated in figure D.25. In this figure the LCOE for different amount of generation per generator is shown. In reality, the cost functions will probably also depend on the lifetime of different generators. An example in which cost functions can differ for generators of the same capacity is a study done by [42] and also [44] as can be seen in figure D.25c. Many of the numbers used in these papers are based on cost functions listed in older articles published around 1996 [45] and [47]. Therefore it might be that the numbers used in these functions are outdated.



(a) LCOE for thermal generator units 1 (10 units) [46]

(b) LCOE for thermal generators units 2 (10 units)[43]

(c) LCOE for thermal generators units 3 (13 units) [42]

Figure D.25: Example of Cost Functions Thermal Generators

The cost functions currently used are of the same type as Gaing has proposed, where the same smooth cost function is used for all thermal generators belonging to the same category. The categories are defined as: Coal, Gas and Nuclear. This was chosen this way because most of the generators connected at 220/380kV are relatively large ($> 100MW$).

However, this assumption does mean that differences for the current installed gas power plants is neglected (efficiency, lifetime, capacity etc) making the model less realistic. The future model could be improved by considering the different cost functions for different technologies (OCGT vs CCGT for example), capacities (must run vs peak) and lifetime. Data from the IEA Report from 2020 on the marginal cost of different fuels indicates that for Belgium for example the marginal cost of OCGT is 68 USD/MWh while for CCGT this is only 45 USD/MWh [69].

The cost function for thermal generators used is shown figure D.27. Considering the merit order it is reasonable to assume that we are at a turning point in which for certain periods of time gas becomes cheaper to dispatch than coal. Marginal costs were approximated using the fuel costs from the annual market update of 2019 by Tennet [22]. There it states that the annual average market price of gas decreased to 14,1 Euro/MWh in 2019. The price of hard coal has also decreased to around 8 Euro/MWh. Due to carbon pricing of around 25 Euro/tCo2 however it can be expected that the costs of generation are higher.

In the future scenarios that are going to be investigated, it is likely that the merit order will always favor gas over coal. Therefore, in the base scenario, it was chosen to increase the marginal price of coal to be above the price of gas. As mentioned introducing these cost functions leads to redispatching units in the following merit order: Wind & Solar, Nuclear, Gas&Wkk, Coal (when running the OPF). The following marginal costs were used:

- Nuclear: 8 USD/MWh
- Coal: 20 USD/MWh
- Gas: 14 USD/MWh

The cost function is calculated as: Cost ($\frac{€}{h}$) = $a + b * P + c * P^2$ with P in MW, a in ($\frac{€}{h}$), b in ($\frac{€}{MW*h}$) , c in $\frac{€}{MW^2*h}$. The different used cost-coefficients are listed below in table D.2 and the resulting LCOE for each amount of production is shown in figure D.27.

Table D.2: Cost coefficients used for the quadratic cost function

Technology	a (€/h)	b (€/MWh)	c (€/MW^2h)
Gas	680	14	0,002
Coal	1000	20	0,002
Nuclear	0	8	0

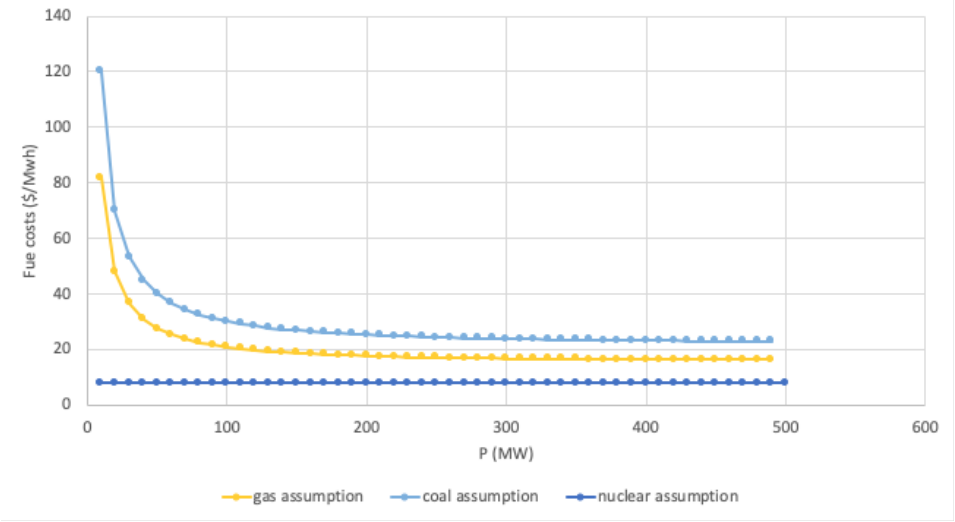


Figure D.26: LCOE per active power dispatch for gas, coal and nuclear

However, as the quadratic term of the function "c" is so low (also the case in the compared literature [46], [44],[42]), the cost curve of the generator for each of the dispatches appears almost linear. The initial costs reflected by "a" are low compared to the total production costs.

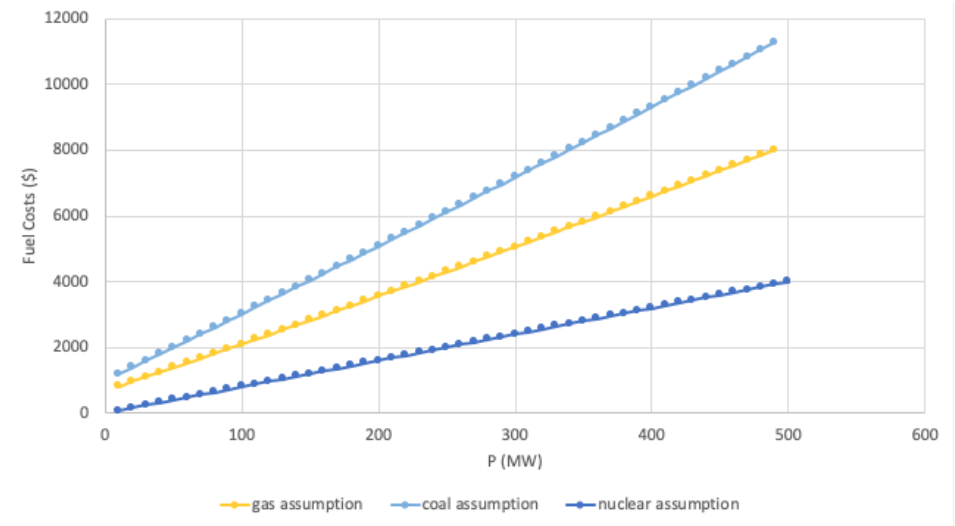


Figure D.27: Total generator costs per active power dispatch for gas,coal and nuclear

D.4.2. Settings

The settings of the OPF were to use the previous load flow as initialisation. For this load flow all generators were assumed to be operating at equal capacity factor (of around 70%). The settings that were used in PowerFactory are shown in figure D.28

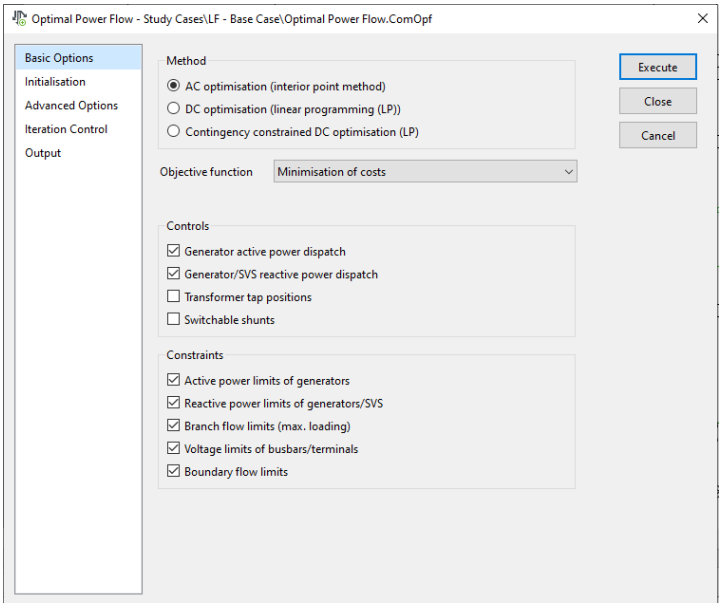


Figure D.28: Settings for the Optimal Power Flow (OPF) simulations

The limits for the terminals was set to +-0.01 p.u., as otherwise the optimization would also produce results where busbars were close to a 5% deviation of the target voltage (initially it was set to +-0.05 p.u.). The generators were set to respect their own ”type” constraints. They would have to operate within a range of 0.1-1 p.u. of active power if operational. Their reactive power limits were set to -1 and 1 p.u. as discussed earlier in the section on system components, see 3.2.3. The transmission lines and both types of transformers were set to have a maximum loading of 80% as a hard constraint.

D.4.3. Results for OPF

D.4.4. 2017 Peak Demand Simulation

Reduction of Grid Losses

During the initial power flow, many different elements were overloaded as was discussed in section D.1.2. By performing the OPF to minimize the system losses, the grid losses are reduced. The active power loss is reduced from 155 MW to 46 MW and the reactive power loss is reduced from 1744 MVar to 185 Mvar. The system summary is shown in figure D.29. In the same manner, for minimization of costs the active power loss is decreased to 64 MW and the reactive power loss to 349 Mvar, this is shown in figure D.30

Total System Summary				Study Case: LF - Base Case			Annex:	/ 1
No. of Substations	0	No. of Busbars	88	No. of Terminals	0	No. of Lines	104	
No. of 2-w Trfs.	72	No. of 3-w Trfs.	0	No. of syn. Machines	27	No. of asyn.Machines	0	
No. of Loads	18	No. of Shunts/Filters	0	No. of SVS	0			
Generation	= 18030,06 MW		184,67 Mvar		18031,01 MVA			
External Infeed	= 0,00 MW		0,00 Mvar		0,00 MVA			
Load P(U)	= 17983,90 MW		-0,00 Mvar		17983,90 MVA			
Load P(Un)	= 17983,90 MW		0,00 Mvar		17983,90 MVA			
Load P(Un-U)	= -0,00 MW		0,00 Mvar					
Motor Load	= 0,00 MW		0,00 Mvar		0,00 MVA			
Grid Losses	= 46,16 MW		184,67 Mvar					
Line Charging	=		-1670,10 Mvar					
Compensation ind.	=		0,00 Mvar					
Compensation cap.	=		0,00 Mvar					
Installed Capacity	= 31972,47 MW							
Spinning Reserve	= 6375,91 MW							
Total Power Factor:								
Generation	= 1,00 [-]							
Load/Motor	= 1,00 / 0,00 [-]							

Figure D.29: System Summary for the OPF for 2017 Peak Demand for loss minimization

Total System Summary				Study Case: LF - Base Case			Annex:	/ 1
No. of Substations	0	No. of Busbars	88	No. of Terminals	0	No. of Lines	104	
No. of 2-w Trfs.	72	No. of 3-w Trfs.	0	No. of syn. Machines	27	No. of asyn.Machines	0	
No. of Loads	18	No. of Shunts/Filters	0	No. of SVS	0			
Generation	= 18047,45 MW		349,15 Mvar		18050,83 MVA			
External Infeed	= 0,00 MW		0,00 Mvar		0,00 MVA			
Load P(U)	= 17983,90 MW		-0,00 Mvar		17983,90 MVA			
Load P(Un)	= 17983,90 MW		0,00 Mvar		17983,90 MVA			
Load P(Un-U)	= -0,00 MW		0,00 Mvar					
Motor Load	= 0,00 MW		0,00 Mvar		0,00 MVA			
Grid Losses	= 63,55 MW		349,15 Mvar					
Line Charging	=		-1657,99 Mvar					
Compensation ind.	=		0,00 Mvar					
Compensation cap.	=		0,00 Mvar					
Installed Capacity	= 31972,47 MW							
Spinning Reserve	= 6358,52 MW							
Total Power Factor:								
Generation	= 1,00 [-]							
Load/Motor	= 1,00 / 0,00 [-]							

Figure D.30: System Summary for the OPF for 2017 Peak Demand for cost minimization

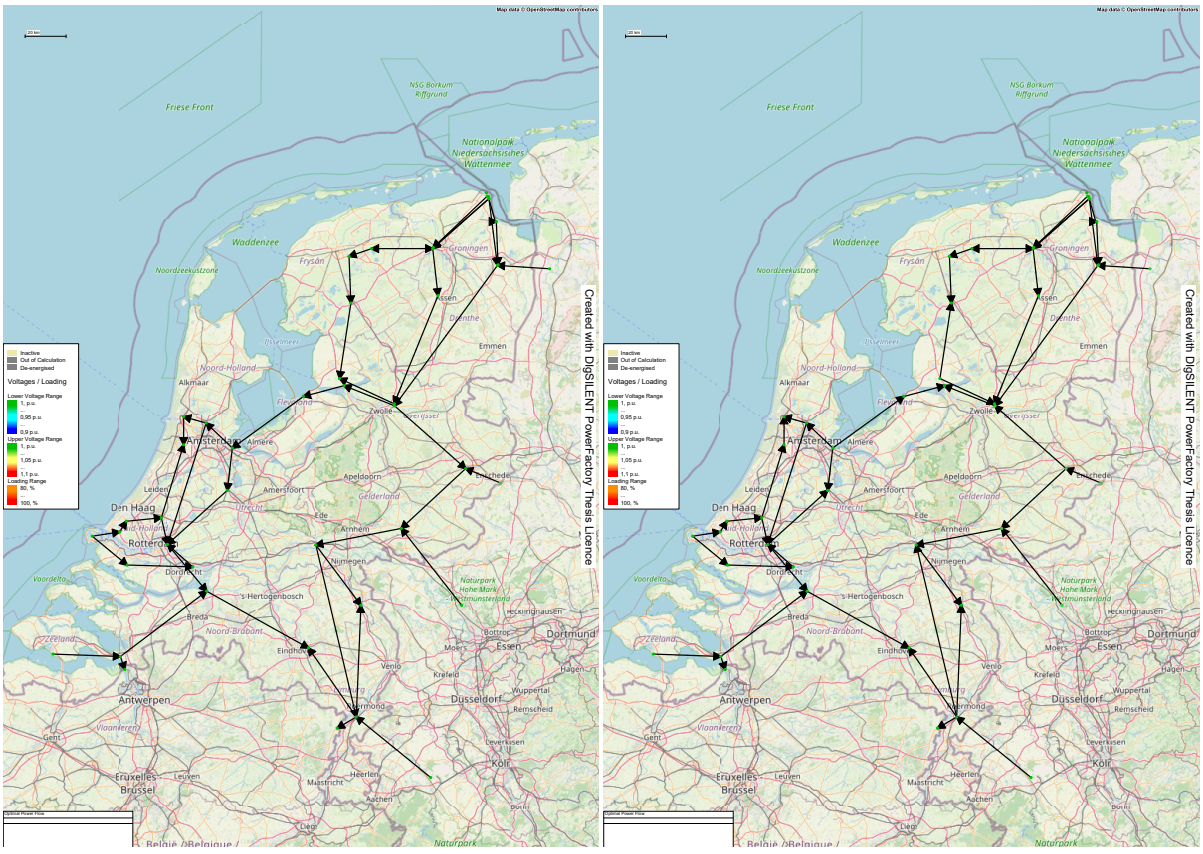
Regional Shift

The total amount of generation change per region for both of the simulations is shown in table D.3. From here it is clear that a large amount of generation is shifted from the area of Groningen and Drenthe to other regions such as Zuid-holland, Noord-Brabant and Noord-Holland). For the system cost minimization however this shift is less pronounced (1900 MW reduction vs 3200 MW reduction in GD).

Table D.3: Adjustment of Active and Reactive Power Dispatch for OPF of 2017 Peak Demand

Name	OPF loss min.		OPF cost min.	
	Δ P (MW)	Δ Q (Mvar)	Δ P (MW)	Δ Q (Mvar)
Friesland 110kV	18,4	-34,5	-8,6	-26,0
Friesland 380/220kV	139,1	-1,5	65,5	3,1
Gelder Flevo Utrecht 380	30,5	-107,0	-124,0	-83,6
Gelder Flevo en Utrecht 110kV	227,9	-167,1	70,2	-152,1
Groningen en Drenthe 110kV	9,2	-58,4	-77,3	-51,3
Groningen en Drenthe 220/380kV	-3262,7	-761,9	-1916,8	-628,0
Limburg 150kV	63,3	-24,2	-42,8	-36,3
Limburg 380kV	356,7	-104,1	203,1	-67,7
Noord-Brabant 150kV	812,1	-0,4	594,4	-12,7
Noord-Brabant 380kV	0,0	0,0	0,0	0,0
Noord-Holland 150kV	612,3	-13,6	398,0	-73,7
Noord-Holland 380kV	51,3	-53,8	-93,3	-44,8
Overijssel en Noordoostpolder 110kV	9,2	-84,6	-64,4	-60,0
Overijssel en Noordoostpolder 380kV	0,0	0,0	0,0	0,0
Zeeland 150kV	-261,3	-40,5	-65,7	-23,9
Zeeland 380kV	-30,4	-22,7	29,5	-22,5
Zuid-Holland 150kV	405,3	-4,6	205,5	-72,0
Zuid-Holland 380kV	710,1	-80,3	735,0	-43,3

From figure D.35b it can be seen that the direction of power flowing through the high voltage area of Flevoland (GFU) changes when minimizing system losses.



(a) OPF for reduced system costs **(b)** OPF for reduced system losses

Figure D.31: OPF results in geographical representation

Merit Order

When performing the OPF it is interesting to see that initially the simulations for the reduction in system losses actually had a larger decline in coal production than OPF for cost minimization.

For the OPF for system loss minimization, the shift in generation leads to a decrease in coal production of -254 MW, as shown in figure D.4. For the OPF for cost minimization there is actually an increase in coal generation of 150 MW. In the case where static generators are allowed to participate in the OPF (normally considered uncontrollable as this is only solar and wind generation in the model) the amount of coal production does decline by 530 MW. The share of coal powered generation of the total amount of conventional generation (gas,nuclear,wkk and coal) however does increase from 13% to 14%.

These results show that although renewable generation is clearly favoured over conventional sources, there is not a clear incentive yet to minimize the amount of coal production compared to nuclear or gas production in this model. In all of the simulations the amount of nuclear production also declines from 486 MW to: 280 MW, 197 MW, 216 MW for the order of simulations shown in table D.4.

Table D.4: Active Power Dispatch of Coal Generation for different OPF simulations

Generator Name	Unit	Initial PF	OPF cost min.	OPF loss min.	OPF cost min. with stat gen
DG_BIOM/COAL_B15_2	MW	0,0	495,2	618,6	413,2
Gen_COAL_EOS15	MW	1578,0	625,8	175,8	356,6
Gen_COAL_MVL15_1	MW	0,0	794,1	676,0	586,2
Gen_COAL_MVL15_3	MW	709,0	521,8	562,4	404,6
Total Production	*MW*	*2287,0*	*2436,9*	*2032,8*	*1760,6*
Difference	**MW**		**+149,9**	**-254,2**	**-526,4**

Something interesting happens if simulations are performed where static generators are considered controllable and can be redispatched for the OPF. The system summary of the simulation shows that the total reactive power losses become negative. Generators in this case are under-excited (lagging) compared to the other simulations were the generators are always slightly over-excited (leading).

```
-----------------------------------------------------------------------------------------------------------------------------
| Total System Summary                                   | Study Case: LF - Base Case          | Annex:                 / 1  |
-----------------------------------------------------------------------------------------------------------------------------
|                                                                                                                           |
| No. of Substations     0          No. of Busbars        88         No. of Terminals      0          No. of Lines          104  |
| No. of 2-w Trfs.       72         No. of 3-w Trfs.      0          No. of syn. Machines  27         No. of asyn.Machines  0    |
| No. of Loads           18         No. of Shunts/Filters 0          No. of SVS            0                                    |
|                                                                                                                           |
| Generation            =   18030,75  MW         -333,36   Mvar     18033,83  MVA                                                |
| External Infeed       =       0,00  MW            0,00   Mvar         0,00  MVA                                                |
| Load P(U)             =   17983,90  MW            0,00   Mvar     17983,90  MVA                                                |
| Load P(Un)            =   17983,90  MW            0,00   Mvar     17983,90  MVA                                                |
| Load P(Un-U)          =      -0,00  MW           -0,00   Mvar                                                                |
| Motor Load            =       0,00  MW            0,00   Mvar         0,00  MVA                                                |
| Grid Losses           =      46,85  MW         -333,36   Mvar                                                                |
| Line Charging         =                       -1657,16   Mvar                                                                |
| Compensation ind.     =                           0,00   Mvar                                                                |
| Compensation cap.     =                           0,00   Mvar                                                                |
|                                                                                                                           |
| Installed Capacity    =   31972,47  MW                                                                                     |
| Spinning Reserve      =   10386,71  MW                                                                                     |
|                                                                                                                           |
| Total Power Factor:                                                                                                       |
|   Generation          =         1,00  [-]                                                                                  |
|   Load/Motor          =  1,00 / 0,00  [-]                                                                                  |
|---------------------------------------------------------------------------------------------------------------------------|
```

Figure D.32: System Summary for the OPF for 2017 Peak Demand for cost minimization with static generator participation

D.4.5. 2018 Peak Demand Simulation

Reduction of Grid Losses

The system summary for the OPF with loss minimization is shown in figure D.37. The OPF for cost minimization is shown in figure D.34. In the initial power flow the active power losses were 118,74 MW and the reactive power losses were 1141 Mvar. For both simulations these losses are reduced.

Total System Summary					Study Case: LF - Base Case			Annex:	/ 1
No. of Substations	0	No. of Busbars	88	No. of Terminals	0	No. of Lines	104		
No. of 2-w Trfs.	72	No. of 3-w Trfs.	0	No. of syn. Machines	27	No. of asyn.Machines	0		
No. of Loads	18	No. of Shunts/Filters	0	No. of SVS	0				
Generation	=	17117,06	MW	245,08	Mvar	17118,82	MVA		
External Infeed	=	0,00	MW	0,00	Mvar	0,00	MVA		
Load P(U)	=	17066,00	MW	-0,00	Mvar	17066,00	MVA		
Load P(Un)	=	17066,00	MW	0,00	Mvar	17066,00	MVA		
Load P(Un-U)	=	-0,00	MW	0,00	Mvar				
Motor Load	=	0,00	MW	0,00	Mvar	0,00	MVA		
Grid Losses	=	51,06	MW	245,08	Mvar				
Line Charging	=			-1671,11	Mvar				
Compensation ind.	=			0,00	Mvar				
Compensation cap.	=			0,00	Mvar				
Installed Capacity	=	31672,47	MW						
Spinning Reserve	=	6706,71	MW						
Total Power Factor:									
Generation	=	1,00	[-]						
Load/Motor	=	1,00 / 0,00	[-]						

Figure D.33: System Summary for the OPF for 2018 Peak Demand for loss minimization

Total System Summary					Study Case: LF - Base Case			Annex:	/ 1
No. of Substations	0	No. of Busbars	88	No. of Terminals	0	No. of Lines	104		
No. of 2-w Trfs.	72	No. of 3-w Trfs.	0	No. of syn. Machines	27	No. of asyn.Machines	0		
No. of Loads	18	No. of Shunts/Filters	0	No. of SVS	0				
Generation	=	17135,30	MW	432,75	Mvar	17140,77	MVA		
External Infeed	=	0,00	MW	0,00	Mvar	0,00	MVA		
Load P(U)	=	17066,00	MW	-0,00	Mvar	17066,00	MVA		
Load P(Un)	=	17066,00	MW	0,00	Mvar	17066,00	MVA		
Load P(Un-U)	=	-0,00	MW	0,00	Mvar				
Motor Load	=	0,00	MW	0,00	Mvar	0,00	MVA		
Grid Losses	=	69,30	MW	432,75	Mvar				
Line Charging	=			-1657,28	Mvar				
Compensation ind.	=			0,00	Mvar				
Compensation cap.	=			0,00	Mvar				
Installed Capacity	=	31672,47	MW						
Spinning Reserve	=	6688,47	MW						
Total Power Factor:									
Generation	=	1,00	[-]						
Load/Motor	=	1,00 / 0,00	[-]						

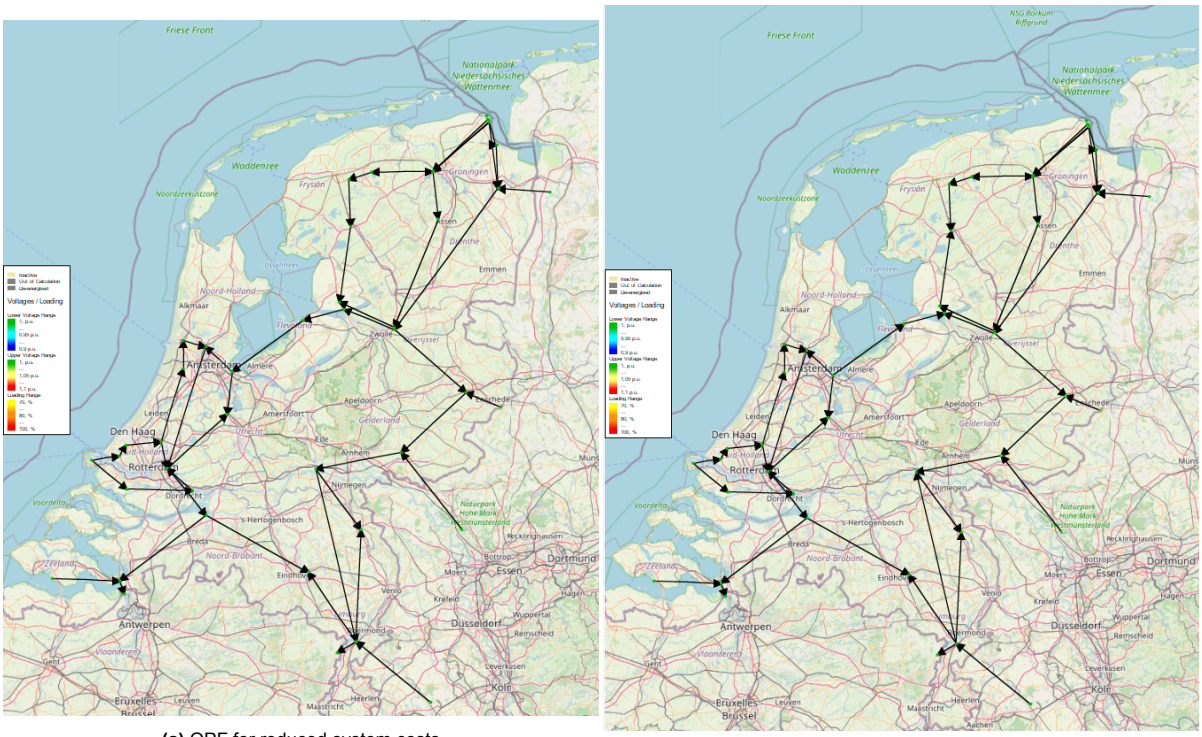
Figure D.34: System Summary for the OPF for 2018 Peak Demand for cost minimization

Regional Shift

The same trends in redispatching are visible as for the OPF 2017 peak demand simulations. The results are given in table D.5.

Table D.5: Regional Change in Active and Reactive Power Dispatch for OPF of 2018

Name	OPF loss min.		OPF cost min.	
	Δ P (MW)	Δ Q (Mvar)	Δ P (MW)	Δ Q (Mvar)
Friesland 110kV	1,9	-21,4	-24,7	-12,3
Friesland 380/220kV	138,2	-0,6	64,6	4,4
Gelder Flevo Utrecht 380	40,4	-69,1	-127,5	-45,6
Gelder Flevo en Utrecht 110kV	447,2	-82,5	320,2	-62,4
Groningen en Drenthe 110kV	-16,0	-35,9	-78,7	-26,5
Groningen en Drenthe 220/380kV	-2292,3	-430,6	-1086,9	-306,5
Limburg 150kV	103,7	-11,7	14,5	-15,6
Limburg 380kV	661,5	-64,3	544,6	-24,6
Noord-Brabant 150kV	548,9	7,2	358,7	0,1
Noord-Brabant 380kV	0,0	0,0	0,0	0,0
Noord-Holland 150kV	740,9	56,6	477,4	-2,7
Noord-Holland 380kV	36,8	-32,4	-121,3	-25,7
Overijssel en Noordoostpolder 110kV	8,1	-60,5	-62,7	-32,6
Overijssel en Noordoostpolder 380kV	0,0	0,0	0,0	0,0
Zeeland 150kV	-286,1	-38,7	-154,8	-24,9
Zeeland 380kV	-113,0	-15,1	-214,2	-30,0
Zuid-Holland 150kV	421,9	37,7	187,1	-29,9
Zuid-Holland 380kV	-509,9	-135,6	-145,7	-74,3



(a) OPF for reduced system costs

(b) OPF for reduced system losses

Figure D.35: OPF results in geographical representation

Merit Order

Just as in the 2017 Simulations, the cost minimization OPF actually shows an increase in coal production of 28 MW, while the OPF for loss minimization has a decline of 526 MW in coal production. However, when static generators are included in the controllable dispatch then the coal production declines with 672 MW as the merit order of the renewable energies is favoured.

Table D.6: Active Power Dispatch of Coal Plants for different 2018 OPF simulations

Generator Name	**Unit**	**Initial PF**	**OPF cost min.**	**OPF loss min.**	**OPF cost min. with stat gen**
DG_BIOM/COAL_B15_2	MW	454	527,8	619,0	425,6
Gen_COAL_EOS15	MW	784	507,0	163,3	290,9
Gen_COAL_MVL15_1	MW	946	700,2	479,0	457,9
Gen_COAL_MVL15_3	MW	0	476,7	396,5	336,9
Total Production	*MW*	*2184*	*2211,6*	*1657,8*	*1511,3*
Difference	**MW**		**+27,6**	**-526,2**	**-672,7**

D.4.6. 2019 Low Demand Simulation

Reduction in Grid losses

For the OPF simulations of a low demand scenario in 2019, the active and reactive power losses are decreased. The active power loss decreases from 100 MW to 40MW and 30MW (see figure D.34 and D.37. The reactive power losses of the grid go from being +700 MW to -345 for the OPF for cost minimization and -464 MW for the OPF for loss minimization .

Total System Summary				Study Case: LF - Base Case			Annex:	/ 1
No. of Substations	0	No. of Busbars	88	No. of Terminals	0	No. of Lines	99	
No. of 2-w Trfs.	72	No. of 3-w Trfs.	0	No. of syn. Machines	27	No. of asyn.Machines	0	
No. of Loads	18	No. of Shunts/Filters	0	No. of SVS	0			
Generation	=	14148,84 MW	-344,83 Mvar	14153,04 MVA				
External Infeed	=	0,00 MW	0,00 Mvar	0,00 MVA				
Load P(U)	=	14108,90 MW	0,00 Mvar	14108,90 MVA				
Load P(Un)	=	14108,90 MW	0,00 Mvar	14108,90 MVA				
Load P(Un-U)	=	-0,00 MW	-0,00 Mvar					
Motor Load	=	0,00 MW	0,00 Mvar	0,00 MVA				
Grid Losses	=	39,94 MW	-344,83 Mvar					
Line Charging	=		-1634,54 Mvar					
Compensation ind.	=		0,00 Mvar					
Compensation cap.	=		0,00 Mvar					
Installed Capacity	=	31972,47 MW						
Spinning Reserve	=	9420,23 MW						
Total Power Factor:								
Generation	=	1,00 [-]						
Load/Motor	=	1,00 / 0,00 [-]						

Figure D.36: System Summary for the OPF for 2019 (Low Demand) for loss minimization

Total System Summary				Study Case: LF - Base Case			Annex:	/ 1
No. of Substations	0	No. of Busbars	88	No. of Terminals	0	No. of Lines	99	
No. of 2-w Trfs.	72	No. of 3-w Trfs.	0	No. of syn. Machines	27	No. of asyn.Machines	0	
No. of Loads	18	No. of Shunts/Filters	0	No. of SVS	0			
Generation	=	14137,19 MW	-464,02 Mvar	14144,80 MVA				
External Infeed	=	0,00 MW	0,00 Mvar	0,00 MVA				
Load P(U)	=	14108,90 MW	0,00 Mvar	14108,90 MVA				
Load P(Un)	=	14108,90 MW	0,00 Mvar	14108,90 MVA				
Load P(Un-U)	=	0,00 MW	-0,00 Mvar					
Motor Load	=	0,00 MW	0,00 Mvar	0,00 MVA				
Grid Losses	=	28,29 MW	-464,02 Mvar					
Line Charging	=		-1643,92 Mvar					
Compensation ind.	=		0,00 Mvar					
Compensation cap.	=		0,00 Mvar					
Installed Capacity	=	31972,47 MW						
Spinning Reserve	=	9431,88 MW						
Total Power Factor:								
Generation	=	1,00 [-]						
Load/Motor	=	1,00 / 0,00 [-]						

Figure D.37: System Summary for the OPF for 2019 (Low Demand) for loss minimization

Regional Shift

Like in the previous simulations, there is a large shift of generation from the region of Groningen and Drenthe to other regions (B, NH, GFU, ON).

Table D.7: Regional Change in Active and Reactive Power Dispatch for OPF of 2019 (Low Demand)

Name	**OPF loss min.**		**OPF cost min.**	
	ΔP (MW)	ΔQ (Mvar)	ΔP (MW)	ΔQ (Mvar)
Friesland 110kV	33,2	-23,4	-28,9	7,6
Friesland 380/220kV	137,9	-3,9	-72,5	3,5
Gelder Flevo Utrecht 380	-0,9	-62,3	-198,1	10,4
Gelder Flevo en Utrecht 110kV	486,9	-70,5	-361,0	-23,4
Groningen en Drenthe 110kV	151,2	-33,0	-123,1	3,7
Groningen en Drenthe 220/380kV	-2600,2	-562,1	1056,8	101,2
Limburg 150kV	354,4	-11,5	-141,4	-10,2
Limburg 380kV	162,4	-60,9	168,3	42,3
Noord-Brabant 150kV	1209,3	9,2	-432,6	-39,5
Noord-Brabant 380kV	0,0	0,0	0,0	0,0
Noord-Holland 150kV	903,1	9,2	-89,4	-42,6
Noord-Holland 380kV	-40,2	-32,4	-146,3	6,9
Overijssel en Noordoostpolder 110kV	98,1	-46,6	-88,1	15,4
Overijssel en Noordoostpolder 380kV	0,0	0,0	0,0	0,0
Zeeland 150kV	-636,5	-71,4	249,7	18,8
Zeeland 380kV	-602,5	-77,4	295,3	10,7
Zuid-Holland 150kV	508,4	-44,2	18,7	-28,8
Zuid-Holland 380kV	-235,9	-110,3	-95,7	43,3

Merit Order

Again, the amount of coal production declines for the different OPF simulations. However, the share of coal generation compared to the total amount of conventional generation declines only for the OPF of loss min. from 14,8% to 14,0%. For both of the two cost simulations, the share increases to around 15,2%.

Table D.8: Active Power Dispatch of Coal Plants for different 2019 OPF simulations

Name	**Unit**	**Initial PF**	**OPF loss min.**	**OPF cost min.**	**OPF cost min. with stat. gen**
DG_BIOM/COAL_B15_2	MW	0,0	588,4	385,1	323,5
Gen_COAL_EOS15	MW	1444,0	321,1	701,6	343,9
Gen_COAL_MVL15_1	MW	0,0	521,0	531,4	441,1
Gen_COAL_MVL15_3	MW	649,0	431,0	377,7	327,4
Total Production	*MW*	*2093,0*	*1861,4*	*1995,8*	*1435,9*
Difference	**MW**		**-231,6**	**134,4**	**-559,9**

This again emphasizes that when minimizing costs, although renewable generation is favoured, there is not yet a clear distinction between coal, gas and nuclear generation in the optimization. Again, nuclear generation declines in all simulations despite the lower associated generator costs. For many of the simulations the transformer of GT380-B150 is overloaded, which is close to the region where the nuclear production is. It will be investigated in further research whether this might be the cause of the decline in nuclear production when performing the OPF's.

Grid Losses Overview

The reason to include this analysis is to compare whether the parameters of the different components of the synthetic model lead to roughly the same amount of grid losses as the real EHV Dutch Transmission Network. The only publicly available information shows a annual grid loss of around 1.3 TWh for 2018 and 2019, giving around 1% of annual electricity generation being lost (for a total of 119 TWh annual generation) [70]. The grid losses of the synthetic model are between 0.6 - 0.8% for the initial power flows of 2017-2019. Seeing as in all cases there are no highly loaded transmission lines this number seems reasonable.

Below in table D.9 an overview of the amount of Active Power loss, Reactive Power loss and the amount of Line charging is given for all the different simulations. It is clear that the amount of line charing stays pretty constant for the different simulations. As mentioned before barely any lines being overloaded, only for the initial power flow of the peak demand of 2018 a line is loaded to 70% of its capacity. For the

2017 and 2018 simulations, different transformers are overloaded for the initial power flow as discussed in sections D.1.2 and D.1.2 of appendix D. For the 2019 simulation only 2 transformers are overloaded, also discussed in section D.1.2 of appendix D, as this is a scenario with a lower demand than peak demand.

Table D.9: Overview of the Grid Losses for the different simulations in PowerFactory

Scenario	Type	Active Power Loss (MW)	Reactive Power Loss (Mvar)	Line charging (Mvar)
2017 Peak Demand	Initial PF	155	1744	-1628
2017 Peak Demand	OPF for Loss Min.	46	185	-1670
2017 Peak Demand	OPF for Cost Min.	64	349	-1658
2017 Peak Demand	OPF for Cost Min.*	47	-333	-1657
2018 Peak Demand	Initial PF	119	1142	-1642
2018 Peak Demand	OPF for Loss Min.	51	245	-1671
2018 Peak Demand	OPF for Cost Min.	69	433	-1657
2019 Low Demand	Initial PF	99	727	-1621
2019 Peak Demand	OPF for Loss Min.	40	-345	-1635
2019 Peak Demand	OPF for Cost Min.	28	-464	-1644

When comparing the different scenarios it is visible that grid losses are lower when either: a) there is a lower demand, or b) static generators are allowed to participate in the re-dispatching for the optimal power flow (OPF) as is indicated in table D.9 under type: OPF for Cost Min*. In some cases the reactive power loss (2017 OPF for Cost Min*, 2019 OPF for Loss & Cost Min) becomes negative, indicating that the grid has become inductive. This means that the different generators in the system will operate in a leading manner and they will have to absorb reactive power.

E

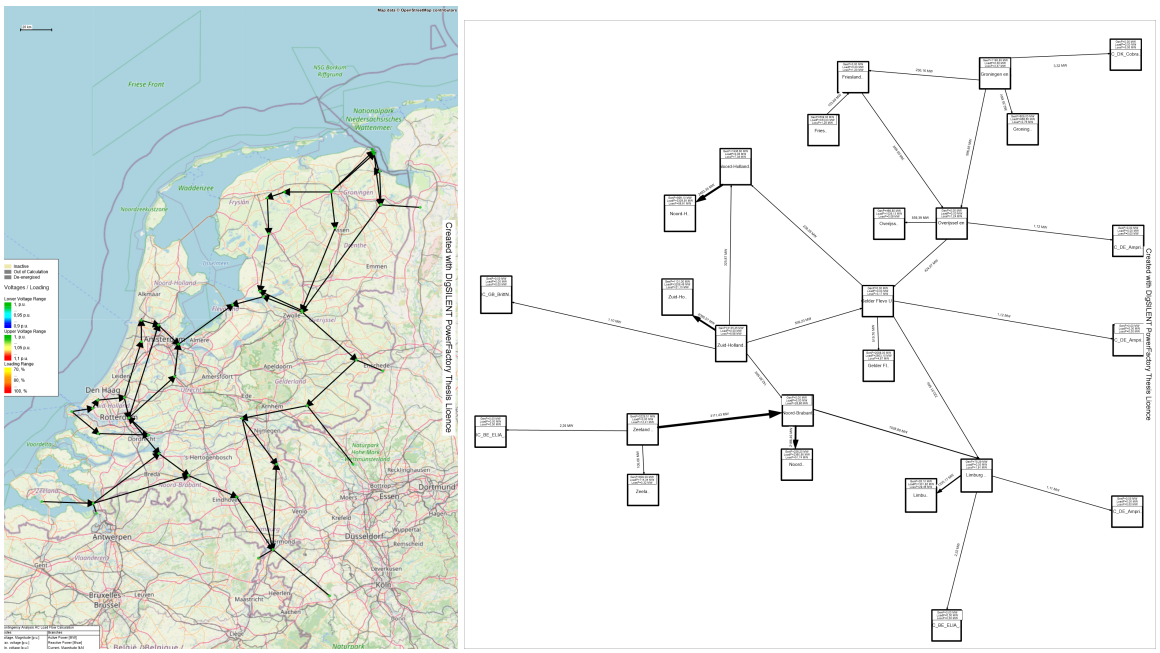
More Detailed discussion of the results for the Case Study

E.1. Case A: Only Wind Generation

For this case there are large flows of power coming from offshore wind farms directed more inland. Due to the high capacity factor of the wind farms, redispatching for OPF is only marginal. For a self-sufficient transmission system not using interconnections, the most beneficial case to ensure grid security is when the electrolysers are distributed evenly among the three locations.

87% Wind, 16 GW Demand (Base Case A0)

For the initial power flow there are no overloaded components. There are however large power flows occuring from Zeeland to Noord-Brabant and from different EHV to HV regions as can be seen in figure E.1b. Considering the contingency analysis, no elements on the national ring are critical for n-1 security, though there is significant overloading of transfomers connecting the EHV to the HV parts of the grid for some contingency cases, in the areas of Noord-Holland, Brabant and Limburg.



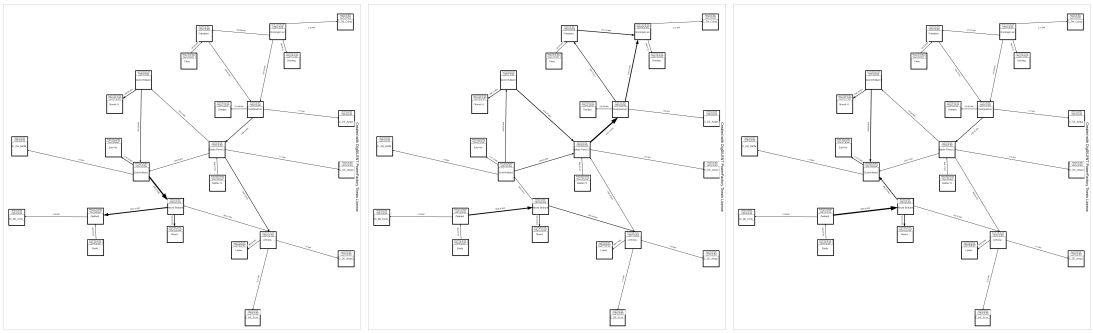
(a) Contingency Analysis results for Case A0

(b) Power Flows between regions for Case A0

Figure E.1: Power Flow Results for Case A0

100% Wind, 12 GW Demand and 6.5 GW Electrolysers (Cases A1-7)

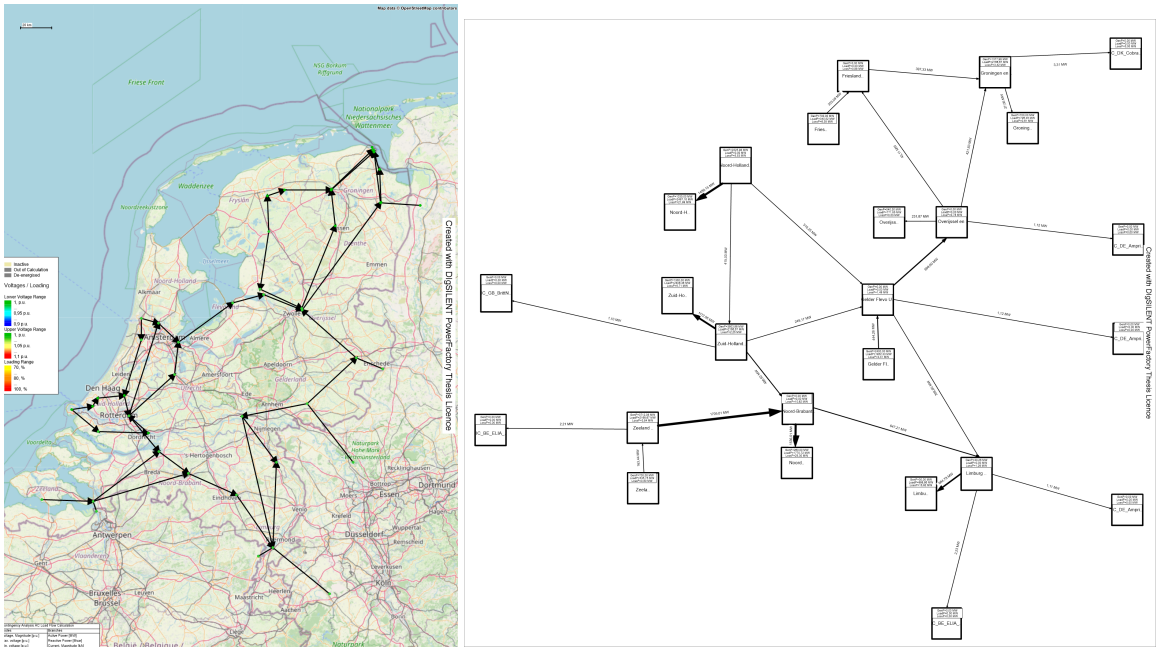
When the electrolyser is located at BSL380 there is a large amount of power of around 2600 MW flowing towards Zeeland. However when it is located at EEM380 or MVL380 large power flows occur from Zeeland to Brabant in the opposite direction of around 3800 MW, shown in figure E.2. In all cases where there is an electrolyser located at EEM380, the power flow direction between the center of the Netherlands (GFU) and the north of the Netherlands (F and GD) reverses compared to the case without electrolysers. The amount of power flowing however depends on the case, with an extreme of 5200 MW going from GFU to GD when there is only a single electrolyser located at EEM380.



(a) Power Flows for Electrolyser at BSL380 **(b)** Power Flows for Electrolyser at EEM380 **(c)** Power Flows for Electrolyser at MVL380

Figure E.2: Power Flows for Single Electrolyser Locations

The contingency analyses show that depending on the case different essential parts of the national ring become highly loaded. The most benefical situation is when the electrolysers are distributed proportionally among all three locations, case A4, for which results are shown in figure E.3. In that case no elements are identified as critical for n-1 security.

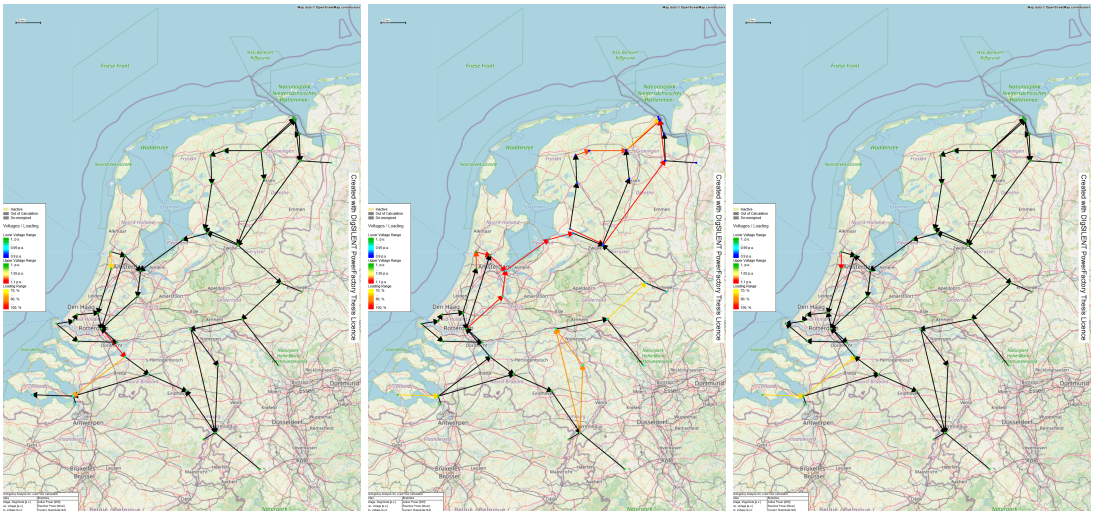


(a) Contingency Analysis for electrolysers at EEM380, MVL380 and BSL380 - Case A4 **(b)** Power Flows between regions for electrolysers at EEM380, MVL380 and BSL380 - Case A4

Figure E.3: Results for Case A4

If electrolysers are introduced only at one single location, different EHV connections become critical

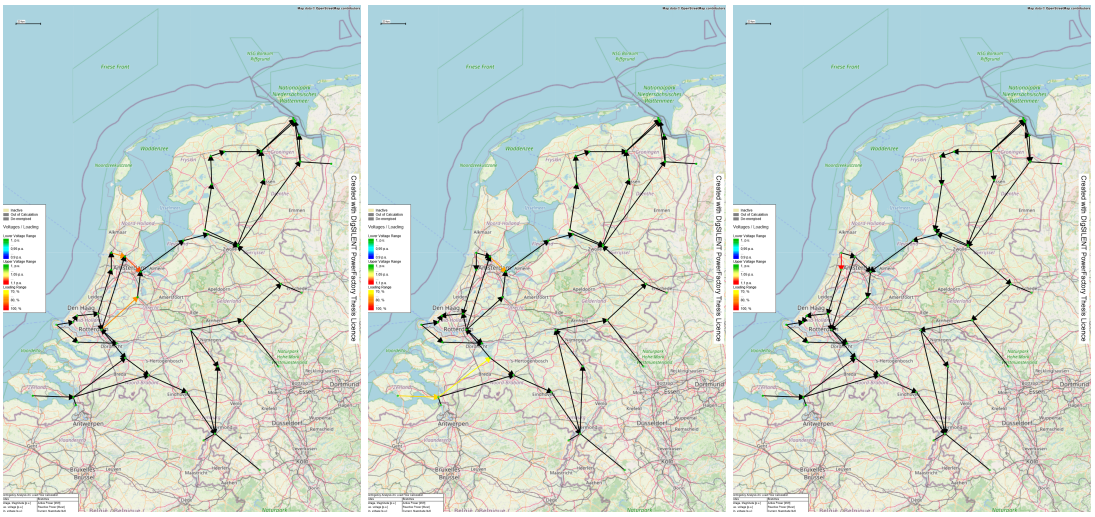
for n-1 security, illustrated in figure E.4. When the electrolyser is located at BSL380 the connection between Zuid-Holland and Brabant (KIJ380-GT380) becomes critical, shown in figure E.4a. When the electrolyser is located at EEM380 a large part of the national ring becomes critically overloaded as can be seen in figure E.4b. When the electrolyser is located at MVL380 the ring is less critically loaded, see E.4c. There are however other important connections from Zeeland to Brabant (BSL-RLL-GT) as well as from Noord-Holland to Zuid-Holland (BVW-VHZ) that become overloaded to 100% and 70% respectively for a contingency case where one of the two parallel lines fail.



(a) CA for Electrolyser at BSL380 - Case A1 **(b)** CA for Electrolyser at EEM380 - Case A2 **(c)** CA for Electrolyser at MVL380 - Case A3

Figure E.4: Geographic Diagram of contingency Analysis for n-1 security

For situations in which the electrolysers are distributed 50-50-0, the most beneficial case is A6 where the ring is loaded to a maximum of 78% . For case A7 only the connection of BVW-VHZ is loaded critically to 100%. For case A5 more elements of the ring become critical, especially the connections between Zuid-Holland, Noord-Holland and the center of the Netherlands (GFU) making this the least ideal case.



(a) CA for Electrolyser at BSL380 and EEM380 - Case A5 **(b)** CA for Electrolyser at MVL380 and EEM380 - Case A6 **(c)** CA for Electrolyser at MVL380 and BSL380 - Case A7

Figure E.5: Geographic Diagram of contingency Analysis for n-1 security

Further Investigation of Case A

When electrolyser demand is increased to 10GW and 18% of solar generation is added, for a low demand the connection between Beverwijk and Vijfhuizen (on the Noord- to Zuid- Holland Connection mentioned above) can become loaded to 85% if one of the two transmission lines fail. An alternative is to locate one electrolyser at Maasvlakte and one in Eemshaven, each of 5 GW. In this case contingency analysis shows potential high loadings between Eemshaven and Oude Schip of 90% and loadings of 70-72% on the connection Borssele-Rilland-Geertruidenberg. The connection between Beverwijk and Vijfhuizen however is no longer highly loaded. When alternatives are considered of 4 GW at MVL and 1 GW at BSL, the connection between BSL-RIL-GT is no longer critical.

E.2. Case B: Only Solar Generation

For this case large power flows from HV to EHV regions and between different EHV regions can be observed. This can be explained by the fact that the amount of solar generation per region is not distributed according to demand but according to the amount of installed capacity listed in the scenario KA2030 in KCD2020 [2].

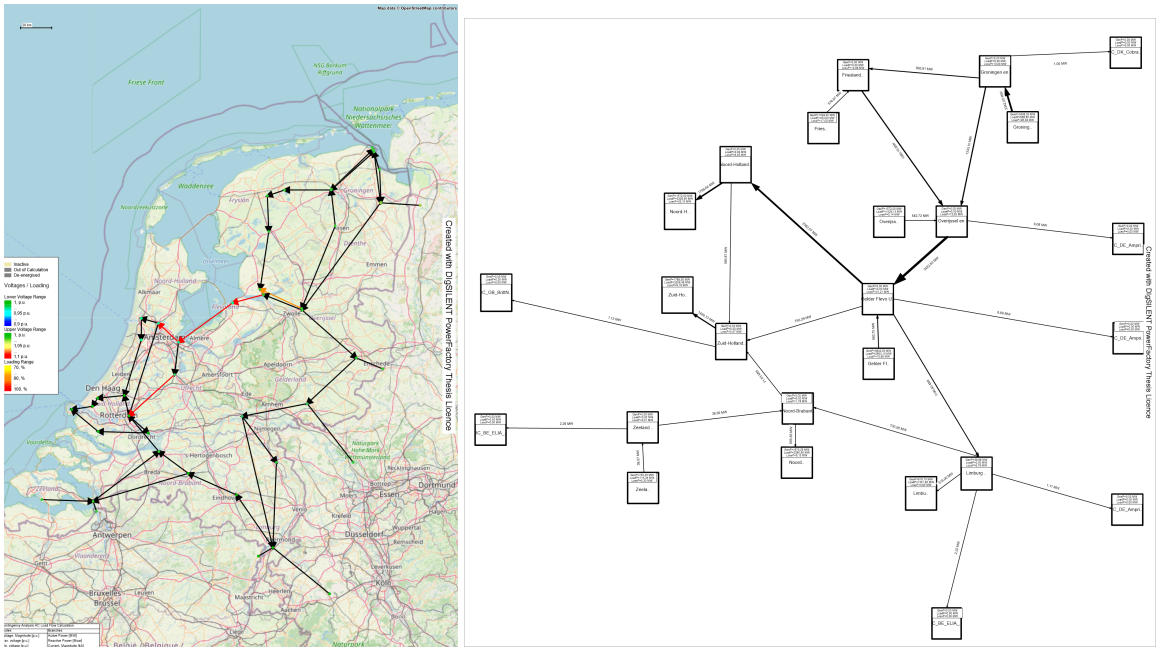
65,5% Solar, 16 GW Demand (Base Case B0)

For the initial power flow, there are no severly overloaded transmission lines though the connection between Oostzaan and Diemen (NH) is already loaded to 76 %. There are several transformers that show high loadings. Transformers between ENS220-ENS380 and GD110-HSW380 are highly loaded due to large exports to more southern regions. Also the transformer between BKK380 and GFU110 is loaded to 79% due to a large export of electricity from the HV to the EHV region. In general, a large transport can be seen from the North of the Netherlands to the South (from GD and F to GFU and from GFU to B,L,ZH,NH) as is shown in figure E.6b. Also many regions that show large exports of electricity from HV to EHV regions as all the solar generation is assumed to be located in the HV areas.

The contingency analysis shows many critical elements for n-1 security. Transformers between the EHV and HV areas in GD,GFU and NH become overloaded for selected contingency cases. Important connections on the Dutch EHV ring between ZH-NH-GFU also become heavily loaded (96-100%) for different cases as is shown in figure E.6a.

For the optimal power flow, the critical components of the initial power flow are mitigated, where a redispatching of solar generation leads to an increase in production for the regions of Noord-Holland, Zuid-Holland, Brabant, Limburg and Zeeland, while there is a decrease in production for Groningen & Drenthe, Friesland and Overijssel & Noordoostpolder.

From the base case B0 it looks the most promising to install the electrolyser in the north of the Netherlands as in many cases there is a large amount of power flowing from the North to the South of the Netherlands. Power flows between regions could be lowered if the installed capacities of solar were increased in the regions Zuid-Holland, Noord-Holland, Brabant and Limburg. This way generation and demand would be brought closer together.



(a) Contingency Analysis results for Case B0 **(b)** Power Flows between regions for Case B0

Figure E.6: Power Flow Results for Case B0

91% Solar, 12 GW Demand and 10 GW Electrolysers (Cases B1-7)

When electrolysers are located at only single locations, cases B1-3, the initial power flows do not converge. The power flows do converge for cases B4-B7. In all the cases there is a problem of low voltages in the North of the Netherlands, likely due to the reactive power losses of overloaded transformers in the region of GD and a large amount of power flowing to the South. This is illustrated also in the initial load flow of case B4 shown in figure E.7. Also other regions such as GD and GFU also show overloading of transformers overloading between HV and EHV areas. For Case B7, there are very low voltage throughout the whole transmission system and critical parts of the national ring become heavily loaded (ON-GFU-NH-ZH). Also parts of the ring in the South (B and L) become overloaded, due to the power flowing through MBT380 to Zeeland. Optimal power flows do not converge due to these overloadings for the initial power flows, and contingency analyses are not interesting to investigate.

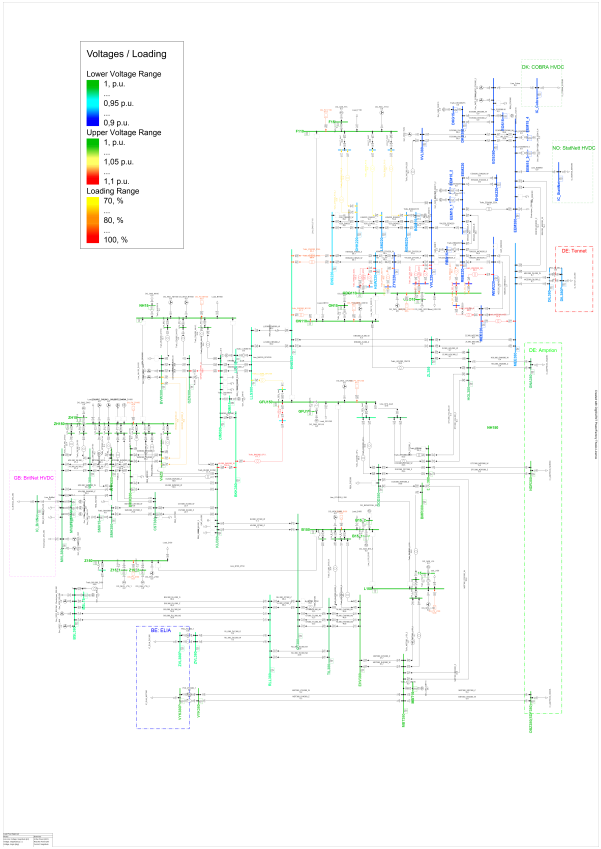
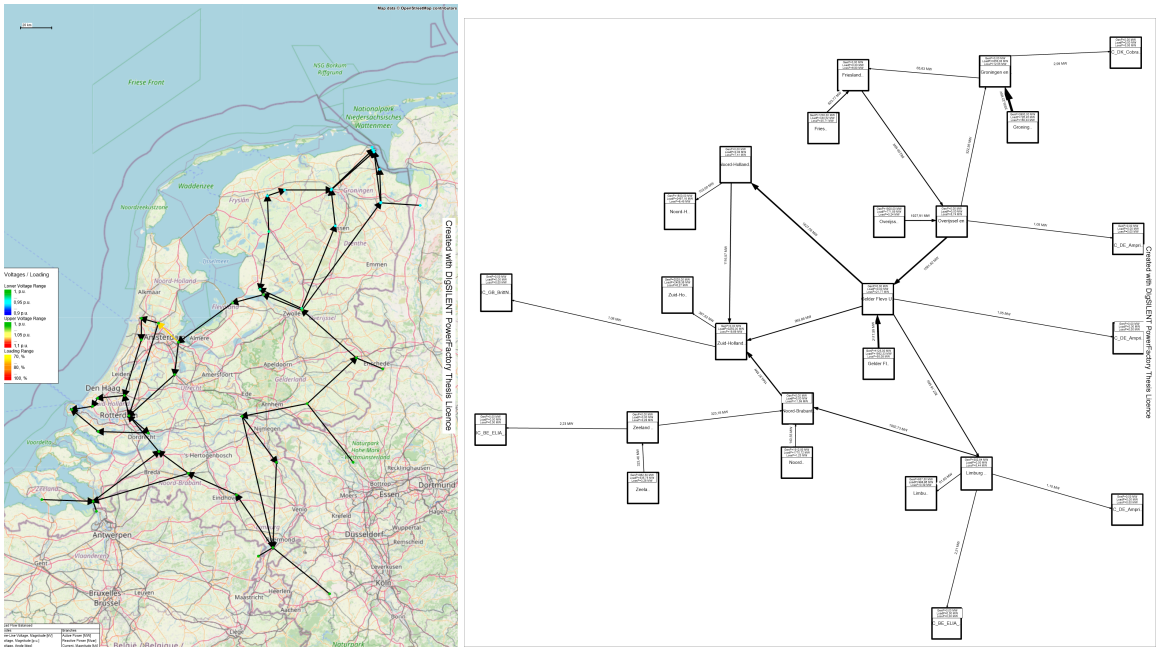


Figure E.7: Single Line Diagram of Initial Power Flow - Case B4

75% Solar, 12 GW Demand and 6.5 GW Electrolysers (Cases B1-7*)

Following these results, an alternative dispatch of only 6.5GW of Electrolysers, and a solar production of 75% of installed capacity was investigated, also to be able to compare case B to case A. These powerflows did all converge, although significant undervoltages again were found in either the North of the Netherlands when there was an electrolyser located at EEM380 or in the South of the Netherlands when electrolysers were located at MVL380 and BSL380.

For all power flows, when there is an electrolyser located at MVL380, the system experiences the least amount of undervoltages. The most favourable case is B6* where electrolysers are distributed over MVL380 and EEM380. For this case, the highest loading of a transmission line is between Oostzaan and Diemen (NH) which is loaded to 71,9%. The transformers connecting BKK380 to GFU150 is overloaded to 100% of their apparent power (not possible in real life). Besides this transformers between the EHV and HV region of GD are loaded to 80%. A snapshot of the geographical diagram is given in figure E.8a. The largest power flows between EHV regions in this case is between the center of the Netherlands (GFU) and Noord-Holland of around 1800 MW, shown in figure E.8b.



(a) Power Flows for Case B6

(b) Power Flows between regions for Case B6

Figure E.8: Power Flow Results for Case B6*

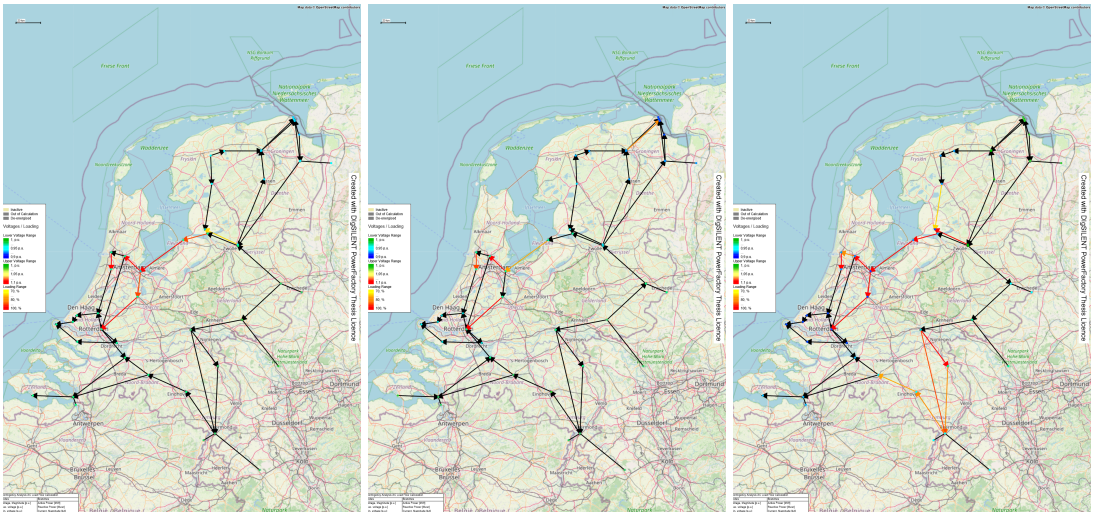
OPF was not posisble for Cases B1-3*. OPF of Case B4* then showed that for a redispatch, the amount of solar production from the regions of GD, F and ON is lowered to 45%, 53% and 56% respectively while production in other regions increases. For the OPF, case B5* shows that almost all solar generation is loaded to 100%, except GD and GFU as shown in figure E.1. This is because for the initial power flow, the loading of the solar powered generation was increased to 90% to reach a feasible solution (for the other cases, initial dispatches are possible of around 75% solar generation). For case B7*, where electrolysers are both located in the South (at BSL and MVL) the OPF did also not converge.

Table E.1: OPF solar generation in % of total installed capacity for northern regions for adjusted Cases B4*, B5* and B6*

Electrolyser Location	P2x Dem. (MW)	Case Number	F (%)	GD (%)	GFU (%)	ON (%)
BSL, EEM, MVL	6500	B4*	52	45	56	81
BSL, EEM	6500	B5*	99	77	66	98
MVL, EEM	6500	B6*	54	45	59	76

Contingency analysis was only possible for the cases B4*,B6* and B7*. As the initial power flow already

showed extreme undervoltages, these results are not very realistic. In the most beneficial case of B6* parts of the ring between GFU and NH become overloaded as well as specific connections between NH-ZH.



(a) CA for Electrolysers at MVL380, BSL380 and EEM380 - Case B4*

(b) CA for Electrolysers at MVL380 and EEM380 - Case B6*

(c) CA for Electrolysers at MVL380 and BSL380 - Case B7*

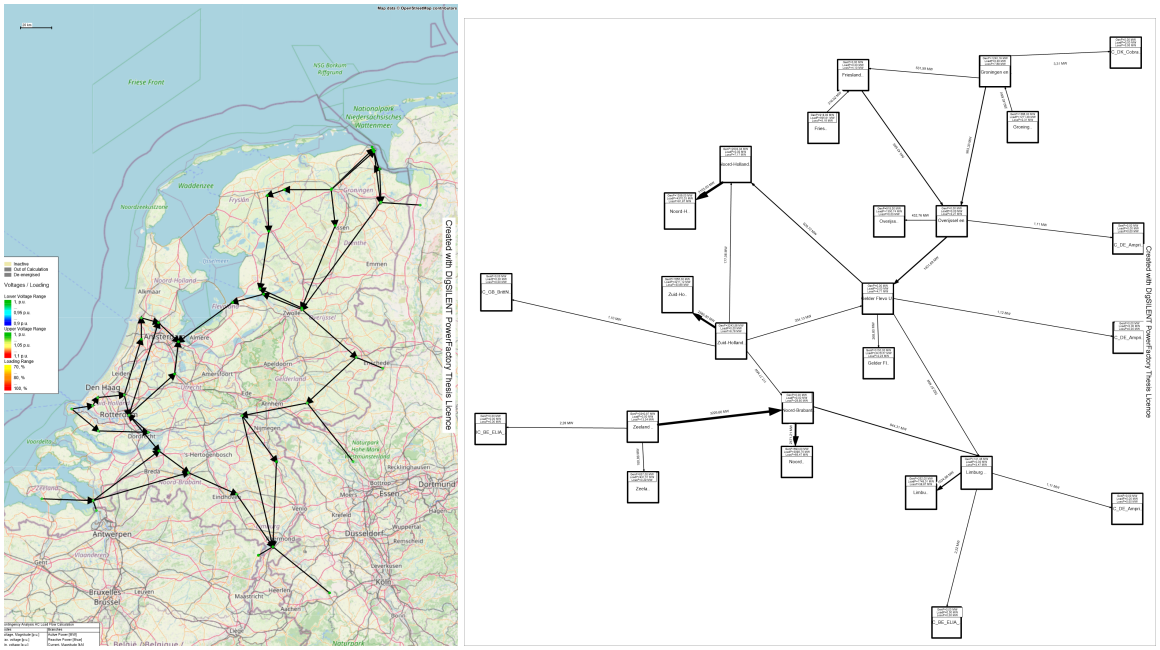
Figure E.9: Geographic Diagram of contingency Analysis for n-1 security

E.3. Case C: Mix of VRES and Peak Demand

This case is chosen to investigate a situation when there is very high VRES generation simultaniously with peak demand (21GW). For this situation it is assumed that 100% of the wind capacity is operational and 52% of the solar generation. This case is especially interesting for Optimal Power Flows, to see how the system would redispatch if both solar and selected offshore wind capacity can be adjusted.

Case C0: 18% Solar, 90% Wind, 21GW Demand

The initial power flows show large power flows (around 3,2 GW) from Zeeland to Brabant as well as large flows from the HV to the EHV network in Noord-Holland and Zuid-Holland. No elements are loaded above 73%.



(a) Contingency Analysis for case C0 **(b)** Power Flows between regions for Case C0

Figure E.10: Power Flow Results for Case C0

For the optimal power flow, the redispatching is very effective as now solar and some selected wind generators mentioned in section 4.5.2 can participate. The loadings of wind farms are decreased in general, and the loadings of all the solar generators is increased except for in Groningen & Drenthe and Friesland. Especially in Noord-Holland, Limburg and Brabant there is a large increase in solar generation. This case illustrates how local production close to demand is favoured. Flow from the EHV to the HV in all regions decrease, especially for Noord-Holland and Zuid-Holland. Also the amount of power flowing from Zeeland to Brabant decreases from approximately 3200 to 1700 MW.

Table E.2: Generators participating in OPF

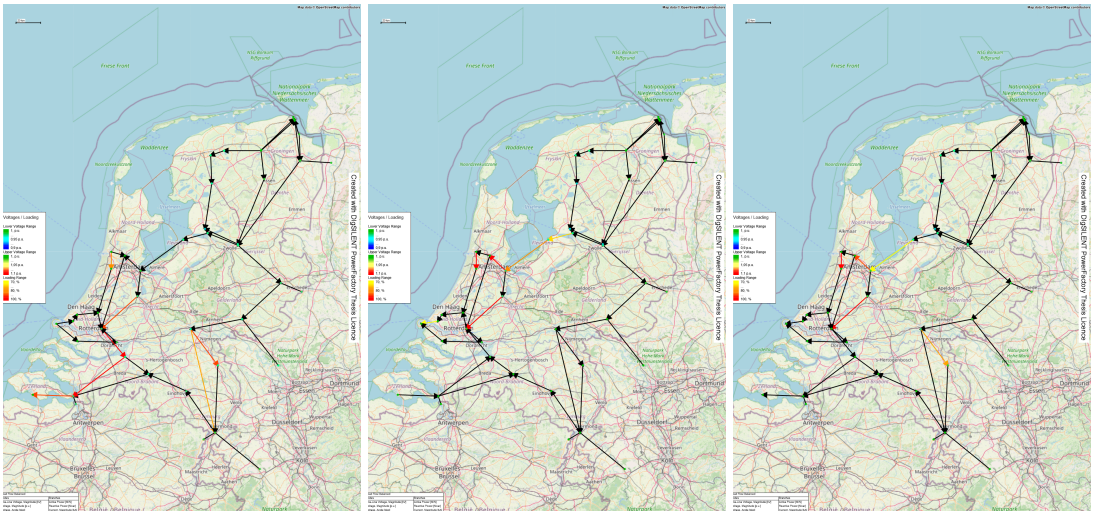
Name	PF Dispatch	OPF Dispatch	Difference
	%	%	(+/-)
DG_PV_B150	26	67	41
DG_PV_F110	18	12	-6
DG_PV_GDO110	18	13	-5
DG_PV_GFU150	18	31	13
DG_PV_L150	28	73	45
DG_PV_NH150	34	82	48
DG_PV_ON110	19	21	2
DG_PV_Z150	18	25	7
DG_PV_ZH150	20	43	23
Gen_WOZ_EOS380_2	108	54	-54
Gen_WOZ_HKW	94	39	-55
Gen_WOZ_IJMA	91	24	-67
Gen_WOZ_IJMB	92	22	-70
Gen_WOZ_TNW	91	43	-47

Contingency Analysis for the base case shows a lot of overloaded transformers going from EHV to HV regions, mainly transformers in NH,L,B,GFU. Besides the transformer between ENS220 and ENS380 is loaded to around 95%. There are no critical elements identified on the EHV ring.

Case C1-7: 52% Solar, 100% Wind, 21GW Demand and 10GW Electrolysers

For these cases mainly solar production is increased, as initially wind was already operational at 90% of its installed capacity. A total demand of 10GW for the electrolysers is investigated.

For the initial power flow all cases except C2 (with a single electrolyser at EEM380) converge. Case C5 (with electrolysers at MVL380 & EEM380) and Case C6 (with electrolysers at EEM380 & BSL380) are the most favorable with no overloaded components. Case C4 shows a high loading of the grid transformer between BBK380 and GFU150. Cases C1, C3 and C7 show heavy loading of different parts of the EHV ring as well as overloading of different transformers as illustrated in figure E.11. Another noticable result is that in general the transformers between EHV and HV parts of the network are loaded significantly less than in previous cases A and B.



(a) Load Flow Results for Electrolyser at BSL380 - Case C1 **(b)** Load Flow Results for Electrolyser at MVL380 - Case C3 **(c)** Load Flow Results for Electrolysers at MVL380 and BSL380 - Case C7

Figure E.11: Geographic Diagram of contingency Analysis for n-1 security

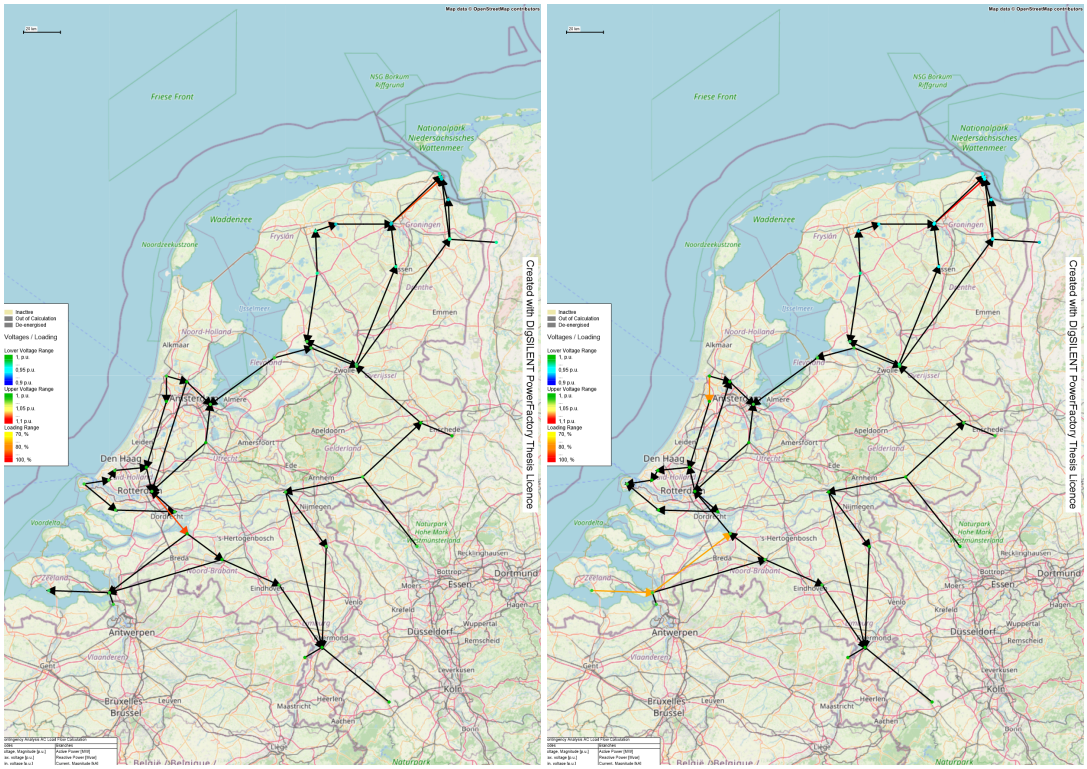
The optimal power flow shows the redispatching of several PV generators. In Brabant the generation is increased from 52% to 90% or more of its installed capacity for all scenarios. In Friesland, Groningen & Drenthe, Gelderland, Flevoland & Utrecht solar powered generation is decreased for all cases. For

some regions such as Zeeland, the amount of generation varies significantly depending on where the electrolyser is placed. If the electrolyser is placed at MVL, the amount of generation significantly increases in Zeeland. The amount of desired solar generation increases in Zuid-Holland and Noord-Holland for all scenarios. When an electrolyser is placed in the North of the Netherlands at EEM380, the desired decrease in solar generation in northern (and central) regions (GD,F,GFU) is less.

Table E.3: Apparent Power Dispatch of Selected Components for Power Flow and Optimal Power Flow Cases C3-C7. *In these cases extra reactive power compensation was needed (by using statcoms)

Case and P2x Location	**C3: MVL**			**C4: BSL,MVL,EEM**			**C5: BSL,EEM**			**C6: EEM,MVL**			**C7: BSL,MVL**		
	PF	OPF	***Diff.***	PF	OPF	***Diff.***	PF	OPF	***Diff.***	PF	OPF	***Diff.***	PF	OPF	***Diff.***
	%	%	***(+/-)***	%	%	***(+/-)***	%	%	***(+/-)***	%	%	***(+/-)***	%	%	***(+/-)***
DG_PV_B150	54	98	***44***	52	91	***39***	52	91	***38***	53	90	***38***	53	95	***42***
DG_PV_F110	52	11	***-41***	52	17	***-35***	52	23	***-29***	52	23	***-29***	52	11	***-41***
DG_PV_GDO110	52	18	***-34***	52	25	***-27***	52	33	***-19***	52	30	***-22***	52	17	***-35***
DG_PV_GFU150	52	29	***-23***	52	42	***-10***	52	42	***-10***	52	39	***-14***	52	36	***-16***
DG_PV_L150	55	95	***40***	53	88	***35***	53	89	***35***	53	87	***34***	56	91	***36***
DG_PV_NH150	58	93	***36***	54	91	***37***	54	92	***38***	54	93	***38***	57	91	***34***
DG_PV_ON110	55	64	***9***	52	54	***2***	52	66	***13***	52	63	***11***	55	53	***-2***
DG_PV_Z150	52	85	***33***	52	54	***2***	52	56	***4***	52	40	***-13***	52	77	***24***
DG_PV_ZH150	54	99	***45***	52	90	***38***	52	83	***31***	52	91	***39***	52	96	***44***
Gen_WOZ_EOS380_2	100*	65	***-76***	100*	67	***-56***	100*	100*	***-37***	100*	100*	***-36***	100*	61	***-80***
Gen_WOZ_HKW	100*	25	***-80***	100*	68	***-36***	100*	64	***-39***	100*	72	***-31***	100	61	***-39***
Gen_WOZ_IJMA	100	97	***-3***	100*	83	***-18***	100	84	***-16***	100	52	***-48***	100	93	***-7***
Gen_WOZ_IJMB	100*	100*	***-2***	100*	85	***-16***	10	46	***36***	100	89	***-11***	100	95	***-5***
Gen_WOZ_TNW	100*	53	**-55**	100*	71	**-31**	100*	100*	-6	100*	100*	**-6**	100*	48	**-58**

For the best cases C5 and C6 the results of the contingency analysis are shown in figure E.12. For both cases transfromers between EHV and HV regions again are often critical for n-1 security in regions: GD, GFU, NH and L. Some of these transformers show loadings up to 100%. For Case C5 the contingency analysis shows a maximum loading of 90 % for the connection between Zeeland and Brabant (KIJ380-GT380). Also in the region of Groningen & Drenthe a maximum loading of 100 % is given for the connection EOS380-EEM380. For Case C6 The connection between ZH-NH (BVW-VHZ) is loaded to a maximum of 80%. Connections between Zeeland and Brabant (BSL-RLL-GT) are loaded to a maximum of 79%.



(a) CA for Electrolyser at BSL380 and EEM380 - Case C5 **(b)** CA for Electrolyser at MVL380 and EEM380 - Case C6

Figure E.12: Geographic Diagram of contingency Analysis for n-1 security

E.4. Case D and E: Average Summer and Winter Capacity Factors

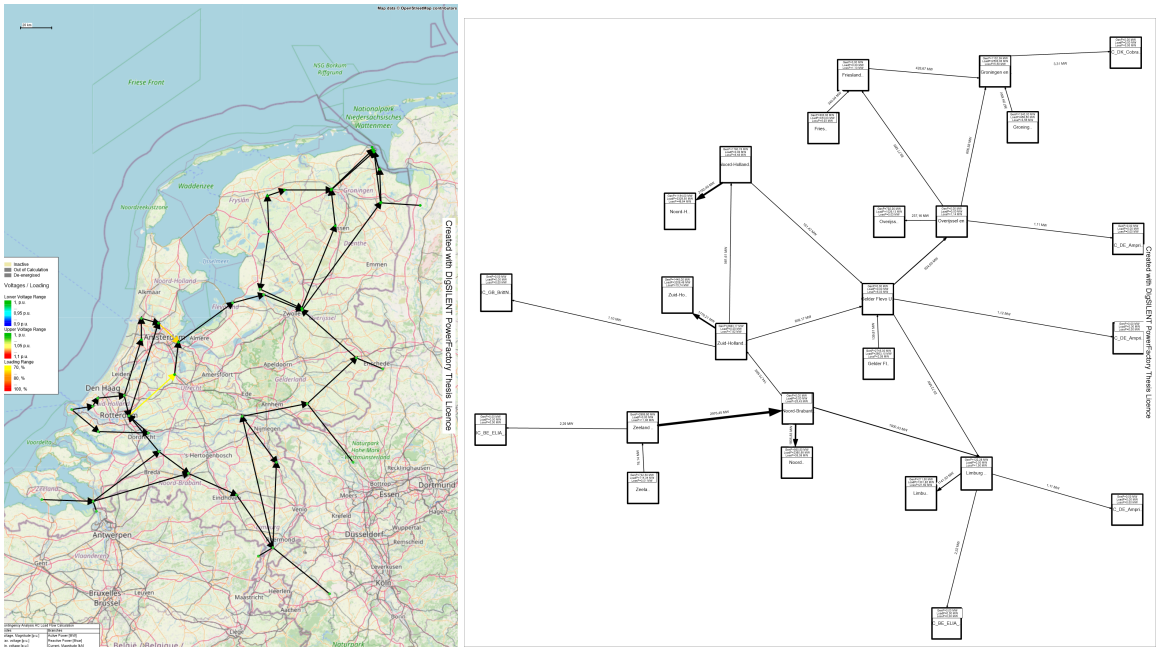
These cases are used to investigate what on average a power flow could look like if average capacity factors of summer and winter for solar and wind generation are used for a high demand of 16GW. Again, this case is mainly interesting for Optimal Power Flows, to see how the system would redispatch if both solar and selected offshore wind capacity can be adjusted.

Case D: 15% Solar, 80% Wind, 16GW Demand, 2.3GW Electrolysers (Winter)

For the initial power flows, in none of the cases studied are there overloaded components. Power Flows show similarities with Case C.

Optimal power flow shows a decrease in dispatch of solar generation for northern regions Groningen & Drenthe and Friesland similar to earlier investigated cases. Even when an electrolyser is located in EEM380 (case D2) the dispatch of solar in these to regions does not exceed 12% while other regions show an increase in dispatch. As in previous scenarios the regions with the highest new dispatch of solar generation are Limburg (65-70% of installed capacity), Noord-Holland (59-68%), Brabant (55-58%) and Zuid-Holland (27-48%) depending on the investigated case.

Contingency Analysis again shows different critical transformers from EHV to HV area's. Besides this, the only contingency analysis case with higher loadings on the national ring is case D2, when there is a single electrolyser located in the north of the Netherlands (EEM380). In that case connections between ZH-GFU and NH-GFU are loaded to 75%. This shown in figure E.13a.



(a) CA for electrolyser at EEM380 - Case D2 **(b)** Power Flows between regions for Case D2

Figure E.13: Contingency Analysis and Power Flow Results for Case D2

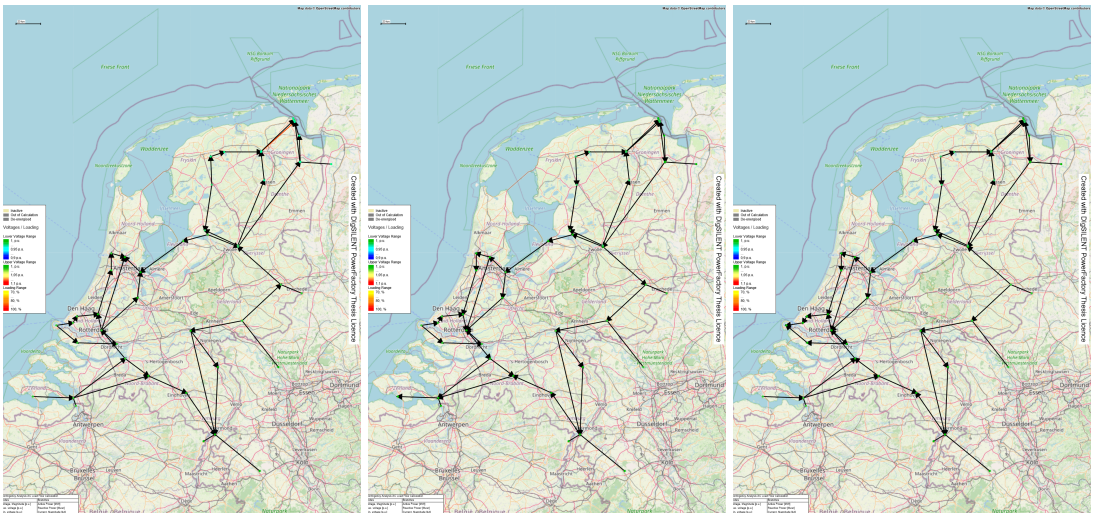
Case E: 60% Solar, 30% Wind, 16GW Demand, 4.2GW Electrolysers (Summer)

It is interesting to compare this Case to Case B (with only solar production and a lower demand E.2). Due to the lower amount of solar production per region together with an increased demand, this case shows less overloading of transformers between the EHV and HV grid for the initial power flows.

Suprisingly, cases E2,5,6 show better results for the initial power flow as well as for the contingency analysis than cases E1,3,4,7. For the initial power flow of case E2, not a single component is highly loaded. For cases E5 and E6, the transformer between GFU150 and BKK380 (GFU to Zeeland) becomes loaded to 71% and 79% respectively.

This results is a large contrast to earlier cases where a single electrolyser at EEM380 was not the most ideal option, such as Case B E.2. This illustrates how the high loading of the transformers in the northern regions of the Netherlands was leading to undervoltages too extreme to allow convergence of the initial power flow.

Contingency Analysis results are shown for all cases in figure E.14 and E.15. The contingency analysis shows that when there are electorlysers located at Borssele or Maasvlakte certain parts of the national ring become critical for n-1 security due to the large amount of power flowing from the North to the South of the Netherlands.

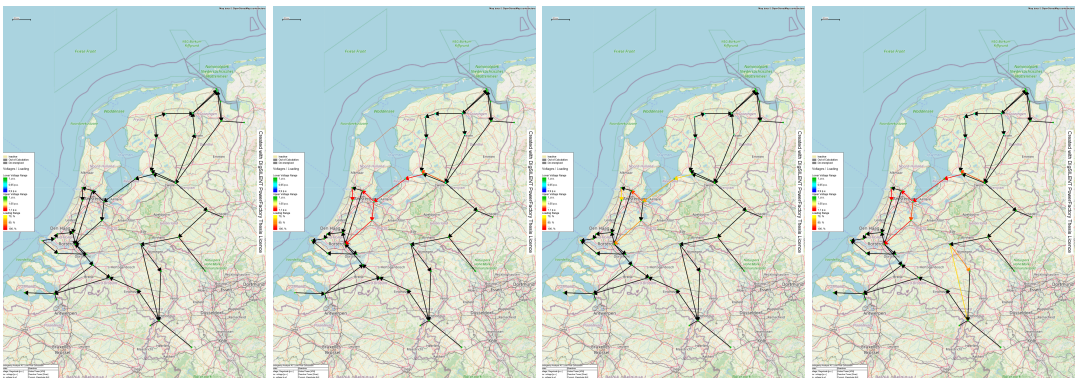


(a) CA for Electrolyser at EEM380 - Case E2

(b) CA for Electrolyser at BSL380 and EEM380 - Case E5

(c) CA for Electrolyser at MVL380 and EEM380 - Case E6

Figure E.14: Contingency Analysis of most favorable cases E2,5,6



(a) CA for Electrolyser at BSL380 - Case E1

(b) CA for Electrolyser at MVL380 - Case E3

(c) CA for Electrolyser at MVL380, BSL380 and EEM380 - Case E4

(d) CA for Electrolyser at MVL380 and BSL380 - Case E7

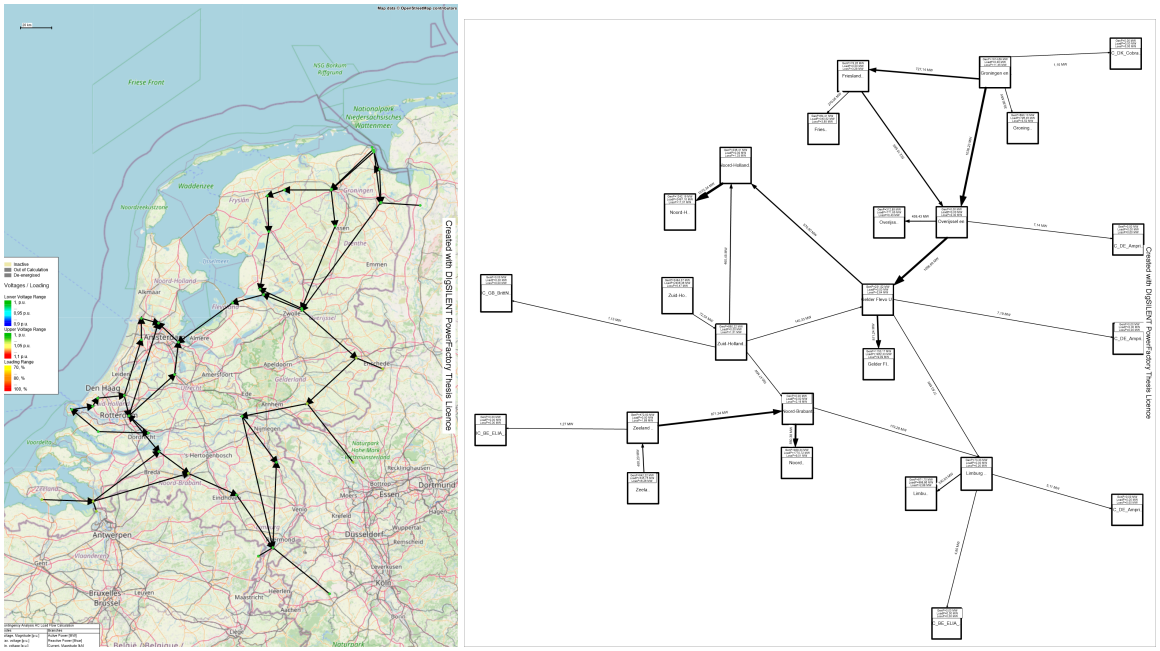
Figure E.15: Contingency Analysis of less cases E1,3,4,7

E.5. Case F and G: Dunkelflaute

Case F represents a day when there is no VRES generation (for example during a 'dunkelflaute') and there is a demand of 12GW. Case G is a more extreme scenario, where there is a peak demand of 21 GW during times of no VRES production. In this case it is assumed that interconnections can be used to their full capacity. Considering the decline in conventional generations considered in KCD2020 [2] it is not strange that a large demand will not be possible without making use of other forms of flexibility such as interconnections or back up generation from storage

Case F: No VRES, 12GW Demand and 92% Conventional Generation

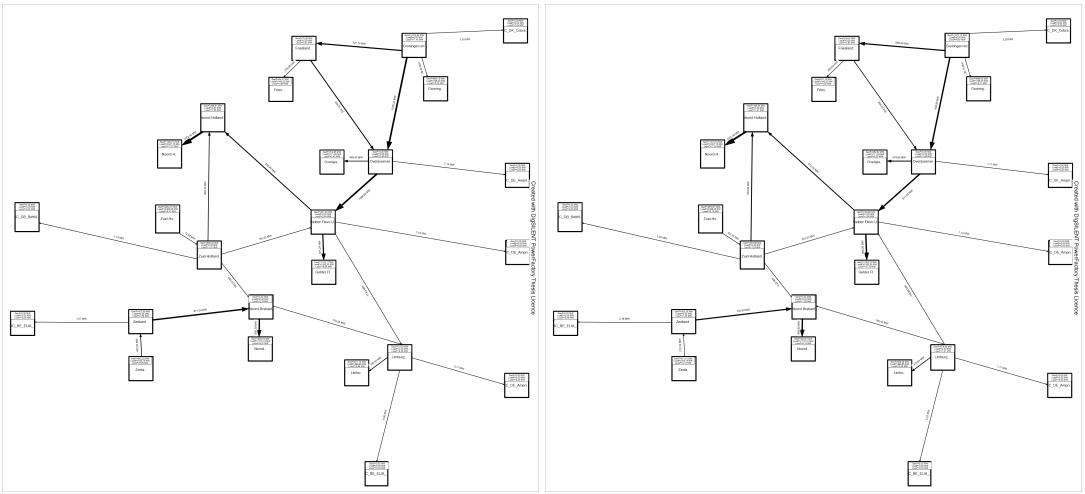
In this case it is assumed that the amount of installed capacity of conventional generation will decline proportionally in each region. Ofcourse, this is not realistic for the real situation but it avoids speculating on which generators will be taken out of service first.
The initial power flow shows maximum transfers of around 1100 MW between different regions as shown in figure E.16. The contingency analysis shows a maximum loading of 76% for one transformer between the EHV and HV part of Noord-Holland, besides this no other elements are identified as critical.



(a) CA for electrolyser at EEM380 - Case F1 **(b)** Power Flows between regions for Case F1

Figure E.16: Contingency Analysis and Power Flow Results for Case F1

The optimal power flow shows a decline in generation dispatched in the north of the Netherlands as well as generally lower transfers of power between different EHV regions. The increase or decrease in loading is given per generator in table E.4 and the change in power flow between regions is shown in figure E.17.



(a) Initial Power Flows between regions Case F1 **(b)** Optimized Power Flows between regions for Case F1

Figure E.17: Power Flow and OPF Results for Case F1

Table E.4: Redispatching of Conventional Generators for OPF of Case F1

Generator Name	Terminal Location	Zone in PowerFactory	PF Dispatch (%)	OPF Dispatch (%)	Difference (+/-)
DG_GAS_B15_1	LV	Noord-Brabant 150kV	83	82	-1
DG_GAS_F15	LV	Friesland 110kV	83	77	-6
DG_GAS_GDO15	LV	Groningen en Drenthe 110kV	83	84	1
DG_GAS_GFU15	LV	Gelder Flevo en Utrecht 110kV	83	76	-7
DG_GAS_L15	LV	Limburg 150kV	83	77	-6
DG_GAS_NH15	LV	Noord-Holland 150kV	83	86	3
DG_GAS_ON15	LV	Overijssel en Noordoostpolder 110kV	84	68	-16
DG_GAS_Z15_2	LV	Zeeland 150kV	83	71	-12
DG_GAS_ZH15	LV	Zuid-Holland 150kV	83	86	3
DG_NUCL_Z15_1	LV	Zeeland 150kV	83	71	-12
Gen_GAS_BGM15	Bergum	Friesland 380kV	84	59	-25
Gen_GAS_BSL15	Borssele	Zeeland 380kV	86	77	-9
Gen_GAS_DIM15	Diemen	Noord-Holland 380kV	86	67	-19
Gen_GAS_DKG15	Doekegat	Groningen en Drenthe 220/380kV	86	81	-6
Gen_GAS_EEM15_1	Eemshaven	Groningen en Drenthe 220/380kV	83	78	-5
Gen_GAS_EEM15_2	Eemshaven	Groningen en Drenthe 220/380kV	84	80	-4
Gen_GAS_EEM15_3	Eemshaven	Groningen en Drenthe 220/380kV	83	79	-4
Gen_GAS_EEM15_4	Eemshaven	Groningen en Drenthe 220/380kV	83	71	-12
Gen_GAS_LLS15	Lelystad	Gelder Flevo en Utrecht 380kV	86	70	-16
Gen_GAS_MBT15	Maasbracht	Limburg 380kV	27	80	54
Gen_GAS_MVL15_2	Maasvlakte	Zuid-Holland 380kV	87	72	-15
Gen_GAS_RBB15	Robbenplaat	Groningen en Drenthe 220/380kV	83	60	-23
Gen_GAS_SMH15	Simonshaven	Zuid-Holland 380kV	84	68	-16

Case G: No VRES, 21GW Demand, 75% Conventional Generation and 100% Interconnections

This last case was meant as an extreme scenario. In case of peak demand during no VRES production, both conventional generation as well as interconnection capacities will need to be used. In reality these interconnections may not always be available, however for this case it is assumed that 100% of the capacity of each interconnections is available.

The initial powerflow already shows many overloaded components as can be seen in figure E.18. The connection between the Germany and Dutch EHV Grid at DIL380 is loaded to 100% of its transmission line and step-voltage regulator capacity. High loadings can be seen for different transformers between the HV regions of ON,GFU and the busbars connecting the east of the Dutch EHV network to the German side of the Grid through the connections with Amprion at Gronau and Niederrhein. Also transfromers between the EHV and HV parts of Noord-Holland are heavily loaded.

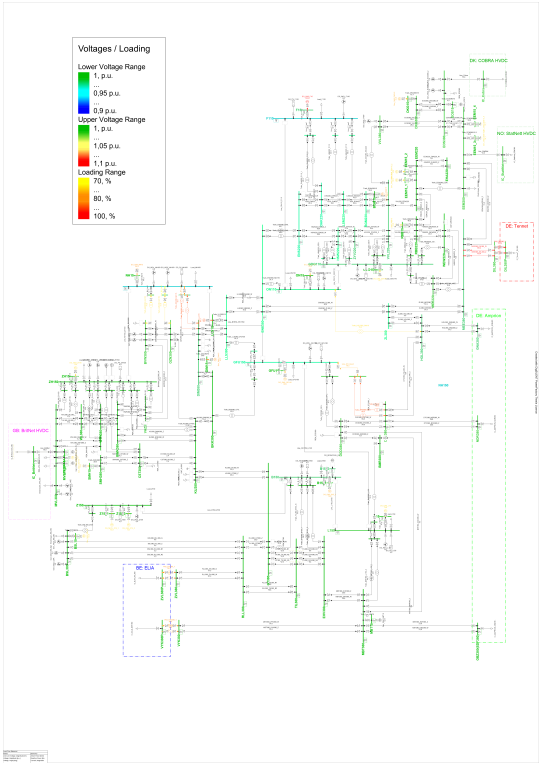


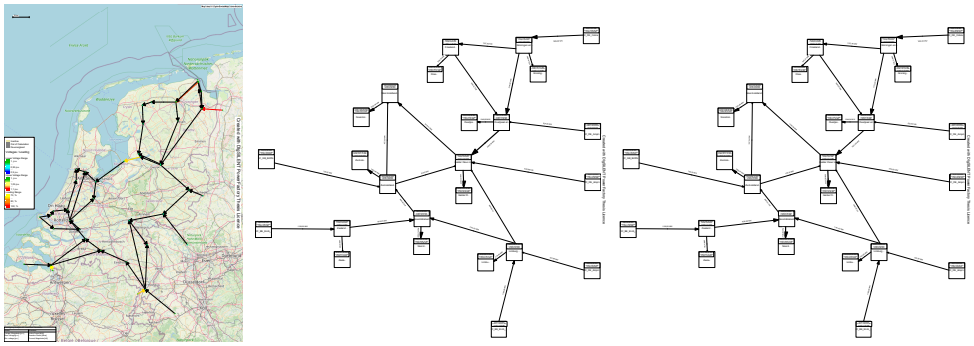
Figure E.18: Single Line Diagram with overloaded components for Case G1

Contingency Analysis and OPF is not possible. After investigating the situation, it is clear that undervoltages in Noord-Holland are very extreme due to the low amount of generation at the HV busbar (1015 MW) compared to a very high demand (4370 MW). To a lesser extent this is also true for Friesland, with a higher demand (600 MW) and low amount of generation (53 MW) leading to undervoltages. Besides this, the overloading of the transformers on the east side of the network could be due to the assumptions regarding the division of the cross-zonal capacities, for which the details are discussed in section B.2.3.

Case G*: No VRES, 19.6GW Demand, 90% Conventional Generation and 70% Interconnections

A second dispatch is set, where the amount of generation at HV busbars is increased to 90% of the installed capacity and only 70% of the interconnection capacity is used. Also, the demand within Noord-Holland is lowered from a peak demand of 4300 MW to 3000 MW leading to a total demand of 19630 MW.

In this case the initial power flow shows no highly loaded components. Now optimal power flow as well as contingency analysis is possible. For the Optimal Power Flow again a lower dispatch of the generators in the North of the Netherlands is observed which can be seen when comparing figure E.19b and figure E.19c. Results also then show higher dispatches for ZH,NH,B and GFU. As discussed above however, these power flows assume a much lower demand for Noord-Holland compared to other regional peak demands that were set. The resulting power flows are not representative or comparable (assuming curtailment of demand is not an option). Contingency Analysis shows many overloaded transformers and potential risks of undervoltages. However the only high loaded transmission line on the national ring is in GFU between Lelystad and Ens (LLS380-ENS380) as can be seen in figure E.19a.



(a) Contingency Analysis for Case G1*

(b) Initial Power Flow between regions for Case G1*

(c) Optimal Power Flow between regions for Case G1*

Figure E.19: Power Flow and OPF Results for Case F1

E.6. Transit Flow Cases

These cases were added to see how the addition of electrolysers could potentially help alleviate the transmission system in case of large transit flows. Currently, the Dutch Transmission System often has to facilitate large power flows from Germany through the Dutch EHV network to the West of Belgium (even going on to France) [51] [52]. This can lead to critical parts of the national ring being overloaded [51]. In the future it is expected that the amount of cross-border power flows will only increase. According to the development plans, it is likely that large exports of electricity will occur from Great Britain and the Nordics to the Continent. This is mainly due to the expected increase in offshore wind capacities in these countries. As the generation portfolio of more central continental countries is less focused on offshore wind and more on nuclear (France), solar or gas-powered generation (other central European countries), the expected direction will be from North to South/more inland [51].

These interconnections are also necessary for countries with large installed capacities of VRE to be able to meet their electricity demand in times of low VRE production. Thus for all parties it is important that the flexibility of the entire European Transmission System is increased [52]. In the future it could be possible that many different countries are interconnected through offshore wind farms located in the North Seas [59] [52].

Overview

The case was modified from Case C to have a demand of 16 GW instead of a peak demand of 21 GW. On top of that a total demand of 10 GW for the elecrolysers is added in different configurations. The amount of solar production and wind production were adjusted to 38% and 90% respectively. An overview of the different imports and exports through different connections is given below in table E.5. For each of the different cases the 7 different earlier mentioned distributions of electrolysers were considered.

Table E.5: Cross-border power flows considered

Name in PowerFactory	Country	Max. Capacity	X	NZ	ZN	WE	EW	ALL	ALLR
IC_AMPRION_GNA380	Germany	750	0	0	0	0	0	0	0
IC_AMPRION_NDR380	Germany	1500	0	0	0	800	-800	400	-400
IC_AMPRION_OBZ380(SDF380)	Germany	750	0	500	-500	0	0	500	-500
IC_BritNed_MVL380	United Kingdom	1000	0	0	0	-800	800	-900	900
IC_COBRA_EOS380	Denmark	700	0	-500	500	0	0	-600	600
IC_ELIA_MBT380	Belgium	1700	0	1000	-1000	0	0	1500	-1500
IC_ELIA_ZVL380	Belgium	1700	0	1000	-1000	0	0	1500	-1500
IC_StatNett_EEM380	Norway	700	0	-500	500	0	0	-600	600
IC_TenneT_DIL380	Germany	2000	0	-1500	1500	0	0	-1800	1800

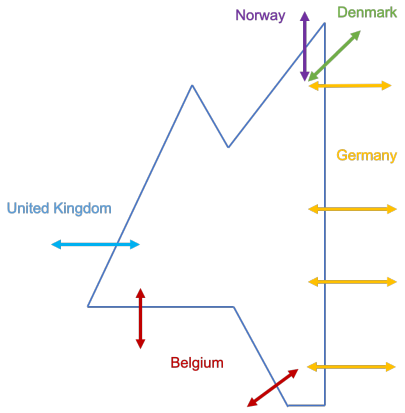


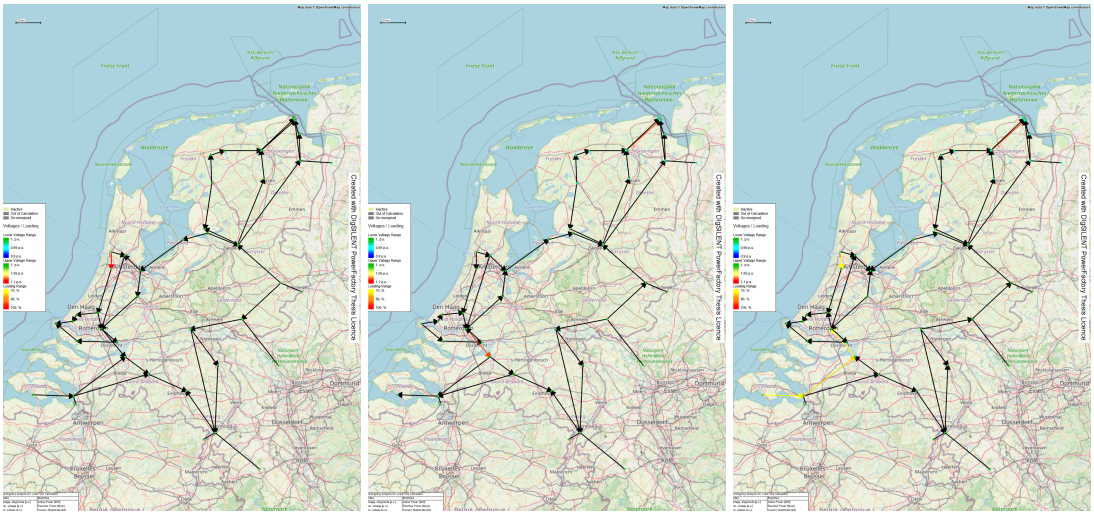
Figure E.20: Illustration of cross-border electrical interconnections

Case X1-7: Base Case without Transit Flow

This case has the initial dispatches of 38% solar, 90% wind, 16 GW demand and 10 GW electrolyser demand. These cases are used as a basis for comparison to see whether the optimal electrolyser location changes if transit flows are taken into account. For this case many similarities with Case C can be identified.

Cases X1-3 all show that a 10GW demand of the electrolysers placed in a single locations leads to a large strain on the transmission system giving congestion issues. Case X2 will not converge for the initial power flow. Cases X4-6 all show no overloaded components for initial simulations. Case X7 shows high loading on the national ring between Zuid-Holland and Noord-Holland between VHZ380-BVW380.

Considering the contingency analysis, Case X5 and X6 seem the most promising. Case X5 also shows only a maximum loading of 86,5% on the national ring between KIJ380-RLL380. For Case X6, only a maximum loading of 72% occurs on the national ring, however in general more connections are loaded to around 70% and different transformers are also overloaded. Case X4 shows overloading between VHZ380-BVW380. Case X7 shows many overloadings. The contingency analysis results for the most ideal cases are visualised below in figure E.21.



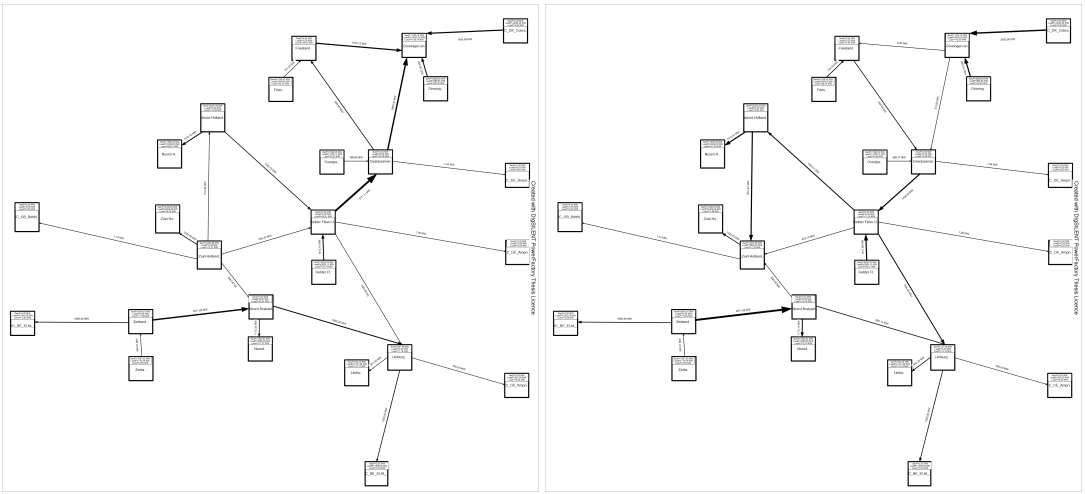
(a) Contingency Analysis for Case X4 **(b)** Contingency Analysis for Case X5 **(c)** Contingency Analysis for Case X6

Figure E.21: Contingency Analysis Results for Cases X4,5,6

Case NZ1-7: North to South Transit Flow

Cases NZ1 and NZ3 show worse results than Cases X1 and X3, indicating that for large transit flows from North to South a single electrolyser at either Borssele or Maasvlakte of 10GW would increase congestion issues. Every Case except for Case NZ6 shows a loading of 70% or higher for at least one critical network element (in the Dutch EHV ring).

Where in Case X2 the initial power flow does not converge, it does for Case NZ2. This means that when transit flows are introduced from North to South, the transmission system is more capable to deal with a high electrolyser demand in the North of the Netherlands. For the case of a single electrolyser in Eemshaven, the demand however still gives a netto power flow of 2.6 GW from the South towards Groningen and Drenthe. When a second electrolyser is introduced in either Maasvlakte or Borrsele, Cases NZ5 and NZ6, the directions switches to a netto power flow of around 3.1-3.2 GW to the South as can be seen when comparing the figures E.22a and E.22b. Both cases NZ5 and NZ6 show no overloading of components for the initial power flow. Contingency Analysis shows that Case NZ6 gives the best results.

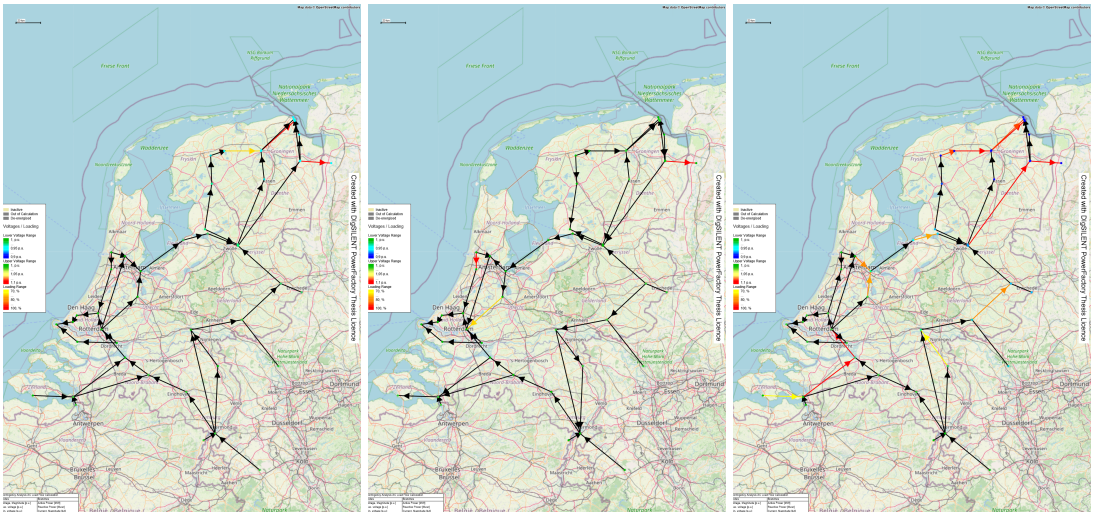


(a) Power Flows between regions for Case Z2 **(b)** Power Flows between regions for Case Z6

Figure E.22: Power Flow Results for Cases Z2 and Z6

Case ZN1-7: South to North Transit Flow

These transit flows are currently less common, however could occur from time to time and are therefore also included. Results show that the added demand of an electrolyser at Eemshaven, could make congestion issues worse in the case of South to North transit flows. Although Cases ZN1 and ZN3 show better results than X1 and X3, the cases with the least amount of overloaded components on the national ring for the initial power flows are again cases ZN4-7. The reason for this is that connection to MVL380 and BSL380 become overloaded due to the high demand of the electrolysers for these cases. Contingency Analysis shows that the best cases for this transit flow are case ZN4 and ZN7. This means that there is a higher electrolyser demand in the South and that the installed capacity is spread out between Maasvlakte and Borssele. The results for these cases as well as for case ZN6 (for comparison) is given in figure E.23



(a) Contingency Analysis for Case ZN4 **(b)** Contingency Analysis for Case ZN6 **(c)** Contingency Analysis for Case ZN7

Figure E.23: Contingency Analysis Results for Cases ZN4,6,7

Case WE1-7: West to East Transit Flow

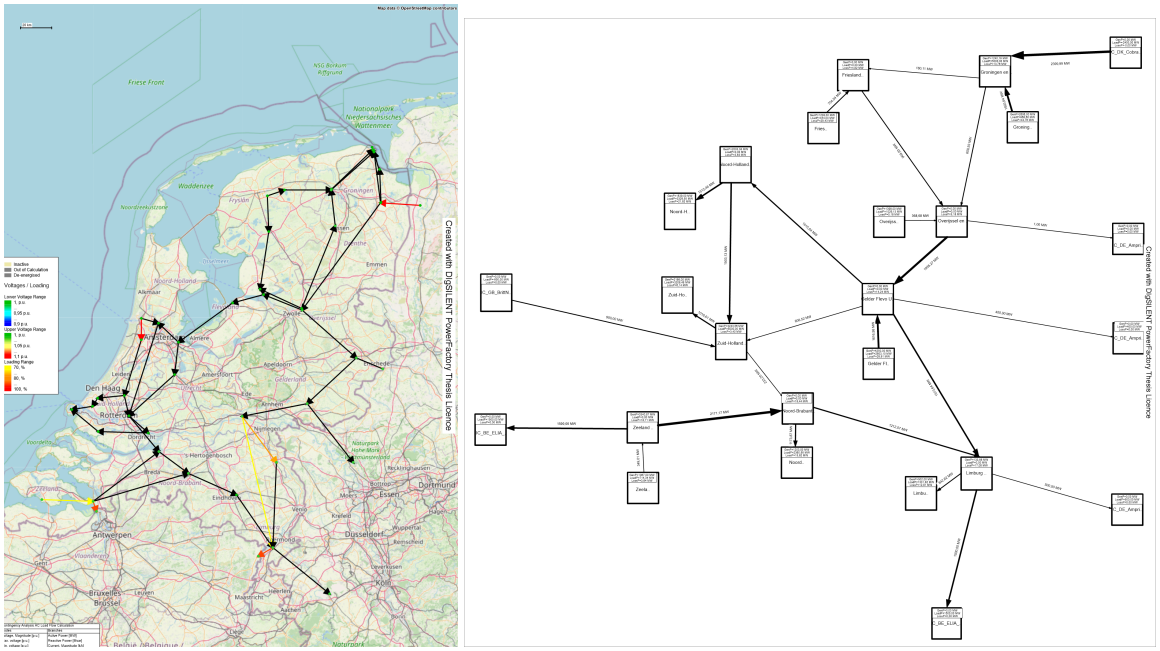
This case shows a transit flow in case of large imports from Great Britain. Currently these capacities are estimated to be 1000 MW in 2030 [31]. As this is lower than the interconnection capacities in the North and South this case leads to less congestion issues compared to transit flows from North to South. Again the best solutions are where there is one electrolyser located in the North and one in the South.

Case EW1-7: East to West Transit Flow

These transit flows are currently less common, however could occur from time to time and are therefore also included. If a single electrolyser is located at Borssele or Maasvlakte, the congestion issues for these cases get worse. However, in both the cases of EW5 and EW6, there are no overloaded components on the national ring, indicating a 5 MW electrolyser demand in the South can be combined with this loopflow.

Case ALL1-7: Combined Transit Flow

The most dominant loop flows from North to South and from West to East are combined in this scenario. Results show that introducing a single electrolyser in Borssele or Maasvlakte leads to high overloadings of the national ring due to an increased flow of electricity going South as was also the case for Cases NZ. The most ideal case ALL6 shows no overloading of any grid elements for the initial power flow. The results for the contingency analysis as well as the power flows between regions is given in figure E.24.



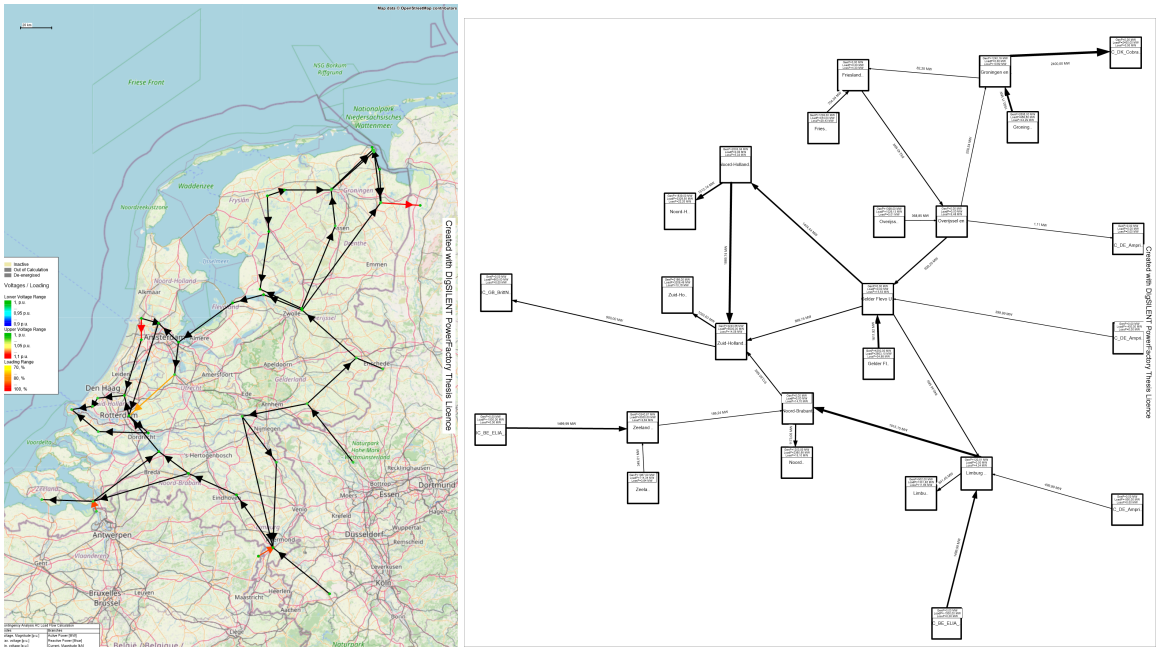
(a) CA for electrolyser at MVL380 and EEM380 - Case ALL6

(b) Power Flows between regions - Case ALL6

Figure E.24: Contingency Analysis and Power Flow Results for Case ALL6

Case ALLR1-7: Combined Reversed Transit Flow

When there is an electrolyser located in Eemshaven in this case, significant risks of undervoltages and overloading of elements of the national ring occur. This shows that for a scenario in which the transit flow direction is reversed, it would not be interesting to an introduce electrolyser in the North of the Netherlands. When there are two electrolysers located in the South-West, case ALLR7, only a high loading of the national ring is seen for the connection BVW380-VHZ380 from the North to the South. Case ALLR7 shows less overloading than the initial case with no loopflows as now there is more electricity coming from the South to Supply the demand in Zeeland and/or Zuid-Holland. Results for this case are given in figure E.25



(a) CA for electrolyser at MVL380 and EEM380 - Case ALLR7

(b) Power Flows between regions - Case ALLR7

Figure E.25: Contingency Analysis and Power Flow Results for Case ALLR6

E.7. Optimal Distribution Cases: 6-3-1 GW for Eemshaven, Maasvlakte and Borssele

E.7.1. Results of 6-3-1 Distribution for Windy Case

In case of a 21 GW regional demand, and no transit flows (Windy-HB), contingency analysis shows no critical elements. When transit flows are introduced (Windy-HT) contingency analysis shows many critical elements. When electrolysers import 3.9 GW, and there is no export in the South (Windy-HI), the contingency analysis no longer shows any critical elements.

In case of a 15 GW regional demand and no transit flows (Windy-MB), contingency analysis shows no critical elements. When transit flows are introduced (Windy-MT) contingency analysis shows only two elements are loaded at 70-80% in Brabant. When electrolysers import 3.9 GW, and there is no export in the South (Windy-MI), the contingency analysis show one connection loaded to 70% in Eemshaven.

In case a 12 GW regional demand and no transit flows (Windy-LB), contingency analysis shows risk of potential undervoltages in Groningen & Drenthe (0.9 p.u.) due to a high electrolyser demand. This scenario is for a high electrolyser demand of 9 GW of which 5.4 GW is located in Groningen & Drenthe. Also a connection between Friesland and Groningen & Drenthe is loaded to 70% and a connection between Noord-Holland and Gelderland, Flevoland & Overijssel is loaded to 80%. When transit flows are introduced (Windy-LT), the contingency analysis shows no critical elements. When electrolysers import 1 GW from the North (Windy-LI), giving a total electrolyser demand of 10 GW, contingency analysis shows only one connection loaded to 70% in Eemshaven.

E.7.2. Results of 6-3-1 Distribution for Sunny Case

In case of a 21 GW regional demand, and no transit flows (Sunny-HB), contingency analysis shows many critical elements on the ring from the North of the Netherlands to the South-West, similar to case B, discussed in section 4.6.2. This is due to the high amount of installed solar capacity in the North of the Netherlands. When transit flows are introduced (Sunny-HT), the initial power flow already shows many critical elements on the national ring from the North of the Netherlands (starting in Groningen

& Drenthe) to the West (Noord-Holland). The contingency analysis shows overloadings (loadings of 100%) for many elements of the national ring. When electrolysers import 3.9 GW, and there is no export in the South (Sunny-HI), the initial power flow shows a loading of 70% for only one connection in Noord-Holland. This indicates that the added electrolyser demand has helped to mitigate the high loadings of elements of the national ring. Contingency analysis again shows high loadings of elements on the national ring from the North of the Netherlands (starting in Groningen & Drenthe) to the West (Noord-Holland).

In case of a 15 GW regional demand and no transit flows (Sunny-MB), contingency analysis shows a loading of 70% for only one connection in Eemshaven. When transit flows are introduced (Sunny-MT) contingency analysis shows many overloaded elements on the national ring to 100%. When electrolysers import 3.9 GW, and there is no export in the South (Sunny-MI), the contingency analysis show less overloaded connections than for the previous case. There are however still potential risks of overloadings of elements on the national ring from the North of the Netherlands (starting in Groningen & Drenthe) to the West (Noord-Holland).

In case a 12 GW regional demand and no transit flows (Sunny-LB), contingency analysis shows risk of potential undervoltages in Groningen & Drenthe (0.9 p.u.) due to the lack of transformer capacity between the 110/150kV and 220/380kV parts of the network in Groningen & Drenthe. This scenario has a high electrolyser demand of 9 GW of which 5.4 GW is located in Groningen & Drenthe as well as a low regional demand at the 110/150kV busbar leading to the risk of overloading of these transformers. Besides this, a connection between Friesland and Groningen & Drenthe is loaded to 80% as well as a specific connection to Eemshaven of 100% (in Groningen & Drenthe) for same contingency analysis. When transit flows are introduced (Sunny-LT), the contingency analysis shows critical elements on the national ring for Noord-Holland and Zuid-Holland up to 96% loading as well as in Brabant up to 88% loading. The risk for potential under voltages in the North of the Netherlands is now less pronouced (0.98 p.u.). When electrolysers import 1 GW from the North (Sunny-LI), giving a total electrolyser demand of 10 GW, contingency analysis shows a reduction of the loadings on the connections for Noord-Holland and Zuid-Holland to a maximum of 87% loading as well as in Brabant to 72% loading. There is however, an increased risk of high loadings for different connections to Eemshaven of up to 85%.

F

Guidlines and Snapshot of Python Model

F.1. Guidelines

In this part of the appendix, the guidelines are given for setting up the model using PowerFactory and Python. The general description of which programs are used for which purpose is given in chapter 3 section 3.1. An overview of how the method works when running simulations is presented in section 3.2.1, and an overview of the python script and its various functions in section 3.3.

F.1.1. Setting Up

First the right set up within PowerFactory and Python is needed to set the correct version of python in PowerFactory, to install the packages needed for the script and to set the base folders that the script will refer to. For the correct set up:

1. Open the Model in PowerFactory
2. Set the right External Directory in PowerFactory to access the script under: Edit>Project Data>Project Settings>External Data>External Data Directory In this folder you should have located the python script.
3. Install the “win32” package as well as “pandas” in the Python version that will be used by PowerFactory.
    - For Win32: From the command line: ”py -m pip install -pywin32”. Website for troubleshooting: https://packaging.python.org/tutorials/installing-packages/#ensure-you-can-run-python-from-the-command-line.
    - To adjust the version of python set in Powerfactory (e.g. 3.8): Tools>Configuration>External Applications. This is also referenced to from the Python Script under: #Getting the PowerFactory Application. Adjust this version if you are using a different version of Python in PowerFactory.
4. Set the correct folder in Python where the input excel files are located, as well as the folder in which the visual diagrams (snapshots of the simulations) can be stored.

F.1.2. Guidelines for PowerFactory

The script needs to be run from within PowerFactory (so it will not work if you run the script from python!). To run the script:

1. Go to: Data Manager>Library>Scripts>”Scenarios 2017-2019” or ”Scenarios 2030” depending on which model you want to activate and run scenarios for
2. When excel opens and asks you to update, click “Don’t Update”. **An Important Note:** Do not touch or modify things in the excel file while the script is running, it will make the script stop running immediately.

3. If for some reason the simulations are cut off due to other reasons, for windows computer sometimes an error is given that the script wont run due to an error with a genpy folder. In this case go to the temporary directory in your computer (users>yourname>appdata>local>Temp>gen_py) and delete the gen_py folder. Restart your computer and you should be ok.

To perform an analysis with the Base Model:

1. First always run the python script: “Scenarios 2017-2019” to set the right case study, study time and installed capacities.
2. Within the script you can adjust whether simulations should be run or whether only the installed capacities and other settings should be reset. (for this see python guidelines)
3. Check if the study time is set to 1-1-2017 (otherwise network variations will be added)
4. Activate the Network Variation: Remove Impedances to go to the previous version of the model used for the initial simulations

To perform an analysis with the 2030 Model:

1. First always run the python script: “Scenarios 2030”, to set the right case study, study time and installed capacities.
2. Within the script you can adjust whether simulations should be run or whether only the installed capacities and other settings should be reset. (for this see python guidelines)
3. Check if the study time is set to 1-1-2030 (otherwise network variations will be added)
4. Deactivate the Network Variation: Remove Impedances, to ensure the new model with added impedances to HV areas

F.1.3. Guidelines for the Python Script

For a description about how the python script is built up, see chapter 3 section 3.3. For the Python script it is important to do three things: make sure the folder settings and file references are set up (see section F.1.1), select the type of simulations you would like to perform and select the scenarios for which you would like to run the simulations. To choose which simulations to run and whether results need to be stored:

1. You can comment/uncomment the commands under: “def simulations()” to also store the results of the simulations and export relevant diagrams. See also the snapshot in figure F.1

    - Uncomment: loadflow(), optimalpowerflow() or contingencyanlaysis() depending on the simulation type you would like to run.
    - Only activate the loadflowresults(), optimalpowerflowresults(), contingencyresults() if you are not in a rush, it take a lot of computational time to write all the different results to the excel file
    - Note: Activating the diagramsLF(), diagramsOPF() and diagramsCA() will only add limited computational time

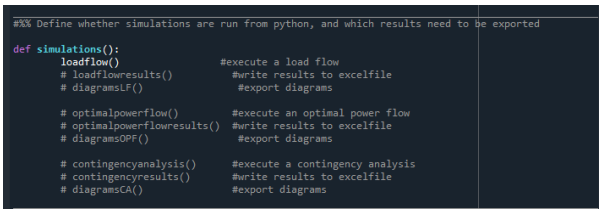
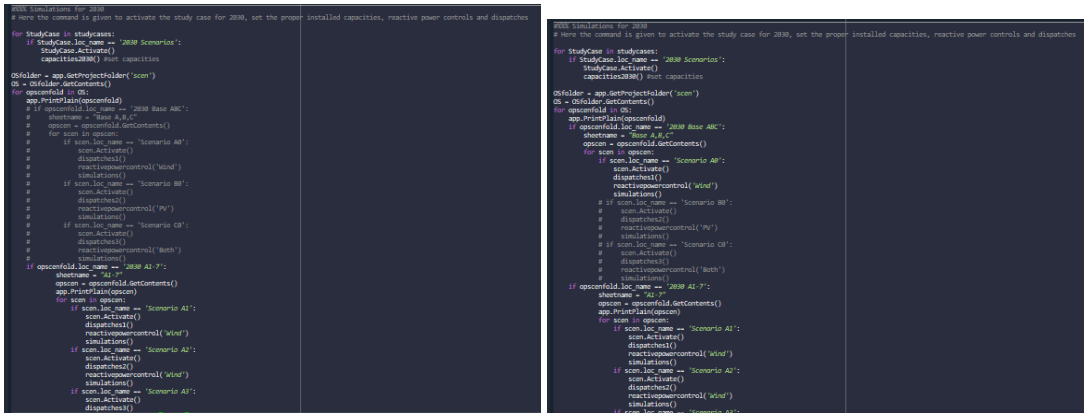


Figure F.1: Commenting Python Script to select output of simulations and results

2. In the last part of the script, you can uncomment or comment which scenarios you would like to adjust or even entire folders with scenarios, see also snapshot F.2a and F.2b. The python script refers to the specific folder structure created in PowerFactory, therefore if folders are merged or names are adjusted this will need to be changed in the script.



(a) Commenting Python Script to exclude whole folder **(b)** Commenting Python Script to exclude selected scenarios

Figure F.2: Power Flow Results for Case B0

F.1.4. Excel Files

Considering the used excel files:

- Do not adjust the layout of the excel file, specific references are made within the python script to certain cells (unless you change the python script of course).
- For the input file: ”Scenario Input Data”, in the sheet ”Overzicht Scenarios” the green boxes allow for easy adjustment of the entire case, this will adjust values in the relevant underlying sheets, see also snapshot F.3

Scenarios voor PF													
	PV (%)	Wind (%	Demand (GW	Conv Ge	IC import	IC expor	Electroly:	Case Type	Balance Gen-De	Import (-) Export (+)	final overschot	Electrolyser	Conventional
A0	0	87	16	N	N	N	N	base		0	164,60	0	0
B0	65,5	0	16	N	N	N	N	base		0	211,25	0	0
C0	18	90	21	N	N	N	N	base		0	177,00	0	0
A1-7	0	100	12	N	N	N	Y	elect	6580,00	0	80,00	6500,00	0
B1-7	91	0	12	N	N	N	Y	elect	10522,50	0	522,50	10000,00	0
C1-7	52	100	21	N	N	N	Y	elect	10450,00	0	450,00	10000,00	0
D1-7	15	80	16	N	N	N	Y	elect	2576,50	0	76,50	2500,00	0
E1-7	60	30	16	N	N	N	Y	elect	4424,00	0	224,00	4200,00	0
F1	0	0	12	Y	N	N	N	extreme	720,00	0	720,00	0	1,06
G1	0	0	21	Y	Y	N	N	extreme	-10596,00	-10800	204,00	0	1,02

Figure F.3: Input excel file snapshot

- The input file: ”Scenario Installed Cap”, contains the numbers for the different 2030 scenarios that can be used in simulations. For the case study only values for KA30 are used, therefore only these values are referenced to in python. For other installed capacities of scenarios FSI30 and AT30, adjusted the referenced column numbers in the capacities2030() command.
- For the output file: ”Scenario Output Data”, the sheets are arranged according to the scenario names. In each sheet results for power flow, contingency analysis and OPF are stored (from left to right). If you would like to add elements to the PowerFactory model, the sheets will need to be adjusted. This is because the python script checks the names of the elements and then inserts the results.

F.2. Python Code for Base Model Simulations

```
# -*- coding: utf-8 -*-
"""
Created on Wed May 26 14:11:09 2021
@author: Anouk de Roos

Script for Base Model Scenarios

Before running this script from PowerFactory, install the win32 package:
from the command line: "py -m pip install -pywin32". Check out this
website for troubleshooting: https://packaging.python.org/tutorials/installing-packages/#ensure-you-can-run-python-from-the-command-line.
(has to be installed in the python version that PowerFactory uses)

"""
# make sure the file is located in documents folder
input_excel = r'C:\Users\AdeRo\OneDrive\Documenten\Model Files\Scenario Input Data.xlsx'
installedcap_excel = r'C:\Users\AdeRo\OneDrive\Documenten\Model Files\Scenario Installed Cap.xlsx'
output_excel = r'C:\Users\AdeRo\OneDrive\Documenten\Model Files\Scenario Output Data.xlsx'
diagrams_path =  r'C:\Users\AdeRo\OneDrive\Documenten\Diagrams'

#Getting the Powerfactory Application
import sys
sys.path.append('C:\\Program Files\\DIgSILENT\\PowerFactory 2020 SP3\\Python\\3.8')

import powerfactory as pf

app=pf.GetApplication()
app.ActivateProject('EHVnetwork_NL_Final')
app.ResetCalculation()    # start always from the same PowerFactory state
app.ClearOutputWindow()    # clear Output Window (OPTIONAL)

import win32com.client as win32
excel=win32.gencache.EnsureDispatch('Excel.Application')
excel.Visible=True
import math

#open excelfile
wbin = excel.Workbooks.Open(input_excel)
wbout = excel.Workbooks.Open(output_excel)
wbcap = excel.Workbooks.Open(installedcap_excel)
excel.Visible = True

#studycase files
studycasefolder = app.GetProjectFolder('study')
studycases = studycasefolder.GetContents()

#other input values
Genstatmax = 1


#%% define function to set installed capacities to Base Model or KA2030 Values

def capacities_BM():
    wbcap1=wbcap.Worksheets("1) SymGen list")
    wbcap2 = wbcap.Worksheets("1) StatGen list BM")
    symgenlist = wbcap1.Range("B2:I28").Value
    trafolist = wbcap1.Range("K2:P12").Value
    statgenlist = wbcap2.Range("B2:D24").Value
    for row in symgenlist:
        name = row[0]+ '.ElmSym'
        variable = app.GetCalcRelevantObjects(name)[0]
        variable.ngnum = int(row[6])
        variable.outserv = 0
        variable.typ_id.sgn = float(row[2])/0.9
        variable.Pmax_ucPU = 1
        variable.Pmin_ucPU = 0

```

```
67
68      #reset amount of step up trafos needed for new gen capacities
69      for row in trafolist:
70          name = row[0]+'.ElmTr2'
71          variable = app.GetCalcRelevantObjects(name)[0]
72          variable.ntnum = math.ceil(row[2])
73
74      #reset stat gen capacities
75      for row in statgenlist:
76          name = row[0]+'.ElmGenstat'
77          variable = app.GetCalcRelevantObjects(name)[0]
78          if float(row[2])>0:
79              variable.sgn = float(row[2])
80              variable.Pmax_ucPU = 1
81              variable.Pmin_ucPU = 0
82
83  #%% define functions to set the dispatches using the excelfiles
84
85  def dispatches1_BM():
86      w1 = wbin.Worksheets(sheetname)
87      SymG_1 = w1.Range("A10:Z36").Value
88      StatG_1 = w1.Range("A41:Z63").Value
89      Load_1 = w1.Range("A69:Z86").Value
90      for row in SymG_1:
91          name = row[0]+ '.Elmsym'
92          variable = app.GetCalcRelevantObjects(name)[0]
93          variable.pgini = float(row[5])
94          variable.qgini = float(row[7])
95          variable.Pmax_ucPU = 1
96          variable.Pmin_ucPU = 0
97      for row in StatG_1:
98          name = row[0]+'.ElmGenstat'
99          variable = app.GetCalcRelevantObjects(name)[0]
100         variable.pgini = float(row[5])
101         variable.qgini = float(row[7])
102         variable.Pmax_ucPU = Genstatmax
103         variable.Pmin_ucPU = 0
104     for row in Load_1:
105         name = row[0]+'.ElmLod'
106         variable = app.GetCalcRelevantObjects(name)[0]
107         variable.plini = float(row[5])
108         variable.qlini = float(row[7])
109         variable.Pmax_ucPU = 1
110         variable.Pmin_ucPU = 0
111
112 def dispatches2_BM():
113     w1 = wbin.Worksheets(sheetname)
114     SymG_1 = w1.Range("A10:Z36").Value
115     StatG_1 = w1.Range("A41:Z63").Value
116     Load_1 = w1.Range("A69:Z86").Value
117     for row in SymG_1:
118         name = row[0]+ '.Elmsym'
119         variable = app.GetCalcRelevantObjects(name)[0]
120         variable.pgini = float(row[8])
121         variable.qgini = float(row[10])
122         variable.Pmax_ucPU = 1
123         variable.Pmin_ucPU = 0
124     for row in StatG_1:
125         name = row[0]+'.ElmGenstat'
126         variable = app.GetCalcRelevantObjects(name)[0]
127         variable.pgini = float(row[8])
128         variable.qgini = float(row[10])
129         variable.Pmax_ucPU = Genstatmax
130         variable.Pmin_ucPU = 0
131     for row in Load_1:
132         name = row[0]+'.ElmLod'
133         variable = app.GetCalcRelevantObjects(name)[0]
134         variable.plini = float(row[8])
135         variable.qlini = float(row[10])
136         variable.Pmax_ucPU = 1
137         variable.Pmin_ucPU = 0
```

```
138
139 def dispatches3_BM():
140     w1 = wbin.Worksheets(sheetname)
141     SymG_1 = w1.Range("A10:Z36").Value
142     StatG_1 = w1.Range("A41:Z63").Value
143     Load_1 = w1.Range("A69:Z86").Value
144     for row in SymG_1:
145         name = row[0]+ '.Elmsym'
146         variable = app.GetCalcRelevantObjects(name)[0]
147         variable.pgini = float(row[11])
148         variable.qgini = float(row[13])
149         variable.Pmax_ucPU = 1
150         variable.Pmin_ucPU = 0
151     for row in StatG_1:
152         name = row[0]+'.ElmGenstat'
153         variable = app.GetCalcRelevantObjects(name)[0]
154         variable.pgini = float(row[11])
155         variable.qgini = float(row[13])
156         variable.Pmax_ucPU = Genstatmax
157         variable.Pmin_ucPU = 0
158     for row in Load_1:
159         name = row[0]+'.ElmLod'
160         variable = app.GetCalcRelevantObjects(name)[0]
161         variable.plini = float(row[11])
162         variable.qlini = float(row[13])
163         variable.Pmax_ucPU = 1
164         variable.Pmin_ucPU = 0
165
166 def dispatches4_BM():
167     w1 = wbin.Worksheets(sheetname)
168     SymG_1 = w1.Range("A10:Z36").Value
169     StatG_1 = w1.Range("A41:Z63").Value
170     Load_1 = w1.Range("A69:Z86").Value
171     for row in SymG_1:
172         name = row[0]+ '.Elmsym'
173         variable = app.GetCalcRelevantObjects(name)[0]
174         variable.pgini = float(row[14])
175         variable.qgini = float(row[16])
176         variable.Pmax_ucPU = 1
177         variable.Pmin_ucPU = 0
178     for row in StatG_1:
179         name = row[0]+'.ElmGenstat'
180         variable = app.GetCalcRelevantObjects(name)[0]
181         variable.pgini = float(row[14])
182         variable.qgini = float(row[16])
183         variable.Pmax_ucPU = Genstatmax
184         variable.Pmin_ucPU = 0
185     for row in Load_1:
186         name = row[0]+'.ElmLod'
187         variable = app.GetCalcRelevantObjects(name)[0]
188         variable.plini = float(row[14])
189         variable.qlini = float(row[16])
190         variable.Pmax_ucPU = 1
191         variable.Pmin_ucPU = 0
192
193 #%% function for setting reactive power controls
194 # controlmode options: PV (only PV generation), Wind (only Wind generation), Both (both PV
      and Wind generation), Conv (conventional)
195     #selected WOZ and PV work also as STATCOMS providing reactive power support in all
      scenarios
196     #active power regulation for OPF: depends on if PV or wind was operational in loadflow
197
198 def reactivepowercontrol_BM(Controlmode):
199     w1 = wbin.Worksheets(sheetname)
200     SymG_1 = w1.Range("A10:Z36").Value
201     StatG_1 = w1.Range("A41:Z63").Value
202     if Controlmode == 'Conv':
203         for row in StatG_1:
204                     name = row[0]+'.ElmGenstat'
205                     variable = app.GetCalcRelevantObjects(name)[0]
```

```
206                     variable.av_mode = 'constq' #if wind, only active power regulations WOL
    and some WOZ not reactive
207                     variable.ictpg = 0
208                     variable.ictqg = 0
209                     variable.iOPFCPmin = 0
210                     variable.iOPFCPmax = 0
211                     variable.iOPFCQmin = 0
212                     variable.iOPFCQmax = 0
213          for row in SymG_1:
214                     name = row[0]+ '.ElmSym'
215                     variable = app.GetCalcRelevantObjects(name)[0]
216                     variable.av_mode = 'constv'
217                     variable.ictpg = 1
218                     variable.ictqg = 1
219                     variable.iOPFCPmin = 1
220                     variable.iOPFCPmax = 1
221                     variable.iOPFCQmin = 1
222                     variable.iOPFCQmax = 1
223
224 #%% Load flow functions for initialization and results
225
226 def loadflow():
227      Ldf = app.GetFromStudyCase('ComLdf')
228      Ldf.Execute()
229
230 def loadflowresults():
231     sheet = scen.loc_name[-2:]
232     w2 = wbout.Worksheets(sheet)
233     Line=app.GetCalcRelevantObjects('*.ElmLne') #getting the relevant results of all the
    lines
234     StatGenerators=app.GetCalcRelevantObjects('*.ElmGenstat')
235     SymGenerators=app.GetCalcRelevantObjects('*.ElmSym')
236     Zones=app.GetCalcRelevantObjects('*.ElmZone')
237     Loads = app.GetCalcRelevantObjects('*.ElmLod')
238     Boundaries=app.GetCalcRelevantObjects('*.ElmBoundary')
239     Trafos = app.GetCalcRelevantObjects('*.ElmTr2')
240     Phs = app.GetCalcRelevantObjects('*.ElmVoltreg')
241     Grid = app.GetCalcRelevantObjects('*.ElmNet')
242
243     for line in Line:
244         name=line.loc_name
245         if line.outserv == 0:
246             lineloading = line.GetAttribute('c:loading')
247         if line.outserv == 1:
248             lineloading = 0
249         for i in range (151,295):
250                 if w2.Cells(i,1).Value == name:
251                     w2.Cells(i,5).Value = lineloading
252     for statgen in StatGenerators:
253         name = statgen.loc_name
254         if statgen.outserv == 0:
255             statgen_P = str(statgen.GetAttribute('c:p'))
256             statgen_Q = str(statgen.GetAttribute('c:q'))
257             statgen_Preal = str(statgen.GetAttribute('m:P:bus1'))
258             statgen_Qreal = str(statgen.GetAttribute('m:Q:bus1'))
259             statgen_pf = str(statgen.GetAttribute('m:cosphi:bus1'))
260             statgen_loading=str(statgen.GetAttribute('c:loading'))
261         if statgen.outserv == 1:
262             statgen_P = 0
263             statgen_Q = 0
264             statgen_Preal = 0
265             statgen_Qreal = 0
266             statgen_pf = 0
267             statgen_loading = 0
268         for i in range (41,71):
269             if w2.Cells(i,1).Value == name:
270                 w2.Cells(i,5).Value = statgen_P
271                 w2.Cells(i,6).Value = statgen_Q
272                 w2.Cells(i,7).Value = statgen_Preal
273                 w2.Cells(i,8).Value = statgen_Qreal
274                 w2.Cells(i,9).Value = statgen_pf
```

```
                w2.Cells(i,10).Value = statgen_loading
    for symgen in SymGenerators:
        name = symgen.loc_name
        if symgen.outserv == 0:
            symgen_P = str(symgen.GetAttribute('c:p'))
            symgen_Q = str(symgen.GetAttribute('c:q'))
            symgen_Preal = str(symgen.GetAttribute('m:P:bus1'))
            symgen_Qreal = str(symgen.GetAttribute('m:Q:bus1'))
            symgen_pf = str(symgen.GetAttribute('m:cosphi:bus1'))
            symgen_loading=str(symgen.GetAttribute('c:loading'))
        if symgen.outserv == 1:
            symgen_P = 0
            symgen_Q = 0
            symgen_Preal = 0
            symgen_Qreal = 0
            symgen_pf = 0
            symgen_loading = 0
        for i in range (10,37):
            if w2.Cells(i,1).Value == name:
                w2.Cells(i,5).Value = symgen_P
                w2.Cells(i,6).Value = symgen_Q
                w2.Cells(i,7).Value = symgen_Preal
                w2.Cells(i,8).Value = symgen_Qreal
                w2.Cells(i,9).Value = symgen_pf
                w2.Cells(i,10).Value = symgen_loading
    for zone in Zones:
        name = zone.loc_name
        zone_P = str(zone.GetAttribute('c:GenP'))
        zone_Q = str(zone.GetAttribute('c:GenQ'))
        zone_Load = str(zone.GetAttribute('c:LoadP'))
        zone_Pint = str(zone.GetAttribute('c:InterP'))
        zone_Qint = str(zone.GetAttribute('c:InterQ'))
        for i in range (122,149):
            if w2.Cells(i,1).Value == name:
                w2.Cells(i,5).Value = zone_P
                w2.Cells(i,6).Value = zone_Q
                w2.Cells(i,7).Value = zone_Load
                w2.Cells(i,8).Value = zone_Pint
                w2.Cells(i,9).Value = zone_Qint
    for bound in Boundaries:
        name = bound.loc_name
        bound_Pint = str(bound.GetAttribute('c:Pinter'))
        bound_Qint = str(bound.GetAttribute('c:Qinter'))
        bound_Pex = str(bound.GetAttribute('c:ExportP'))
        bound_Qex = str(bound.GetAttribute('c:ExportQ'))
        bound_Pim = str(bound.GetAttribute('c:ImportP'))
        bound_Qim = str(bound.GetAttribute('c:ImportQ'))
        for i in range (101,121):
            if w2.Cells(i,1).Value == name:
                w2.Cells(i,5).Value = bound_Pint
                w2.Cells(i,6).Value = bound_Qint
                w2.Cells(i,7).Value = bound_Pex
                w2.Cells(i,8).Value = bound_Qex
                w2.Cells(i,9).Value = bound_Pim
                w2.Cells(i,10).Value = bound_Qim
    for load in Loads:
          name = load.loc_name
          if load.outserv == 0:
            load_P = str(load.GetAttribute('c:pini'))
            load_Q = str(load.GetAttribute('c:qini'))
            load_Preal = str(load.GetAttribute('m:P:bus1'))
            load_Qreal = str(load.GetAttribute('m:Q:bus1'))
            load_pf = str(load.GetAttribute('m:cosphi:bus1'))
          if load.outserv == 1:
            load_P = 0
            load_Q = 0
            load_Preal = 0
            load_Qreal = 0
            load_pf = 0
          for i in range (75,97):
            if w2.Cells(i,1).Value == name:
```

```
346                 w2.Cells(i,5).Value = load_P
347                 w2.Cells(i,6).Value = load_Q
348                 w2.Cells(i,7).Value = load_Preal
349                 w2.Cells(i,8).Value = load_Qreal
350                 w2.Cells(i,9).Value = load_pf
351     for trafo in Trafos:
352             name=trafo.loc_name
353             if trafo.outserv == 0:
354                 trafoloading = trafo.GetAttribute('c:loading')
355             if trafo.outserv == 1:
356                 trafoloading = 0
357             for i in range (296,371):
358                     if w2.Cells(i,1).Value == name:
359                         w2.Cells(i,5).Value = trafoloading
360     for phs in Phs:
361             name=phs.loc_name
362             if phs.outserv == 0:
363                 phsloading = phs.GetAttribute('c:loading')
364             if phs.outserv == 1:
365                 phsloading = 0
366             for i in range (372,379):
367                     if w2.Cells(i,1).Value == name:
368                         w2.Cells(i,5).Value = phsloading
369     for grid in Grid:
370             name=grid.loc_name
371             app.PrintPlain(name)
372             gridgenP = str(grid.GetAttribute('c:GenP'))
373             gridgenQ = str(grid.GetAttribute('c:GenQ'))
374             gridLoadP = str(grid.GetAttribute('c:LoadP'))
375             gridLoadQ = str(grid.GetAttribute('c:LoadQ'))
376             gridlossesP = str(grid.GetAttribute('c:LossP'))
377             gridlossesQ = str(grid.GetAttribute('c:LossQ'))
378             for i in range (3,5):
379                     if w2.Cells(i,4).Value == name:
380                       w2.Cells(i,5).Value = gridgenP
381                       w2.Cells(i,6).Value = gridgenQ
382                       w2.Cells(i,7).Value = gridLoadP
383                       w2.Cells(i,8).Value = gridLoadQ
384                       w2.Cells(i,9).Value = gridlossesP
385                       w2.Cells(i,10).Value = gridlossesQ
386
387 #%% Contingency analysis functions for initialization and results
388 def contingencyanalysis():
389     Ctg = app.GetFromStudyCase('ComSimoutage')
390     Ctg.Execute()
391
392 def contingencyresults():
393     sheet = scen.loc_name[-2:]
394     w2 = wbout.Worksheets(sheet)
395     Line=app.GetCalcRelevantObjects('*.ElmLne') #getting the relevant results of all the
        lines
396     StatGenerators=app.GetCalcRelevantObjects('*.ElmGenstat')
397     SymGenerators=app.GetCalcRelevantObjects('*.ElmSym')
398     Trafos = app.GetCalcRelevantObjects('*.ElmTr2')
399     Phs = app.GetCalcRelevantObjects('*.ElmVoltreg')
400
401     for line in Line:
402         name=line.loc_name
403         if line.outserv == 0:
404             linemaxloading = line.GetAttribute('c:maxLoading')
405             contingencynum = line.GetAttribute('c:maxCntcy')
406         if line.outserv == 1:
407             linemaxloading = 0
408             contingencynum = 0
409         for i in range (151,295):
410                 if w2.Cells(i,16).Value == name:
411                     w2.Cells(i,20).Value = linemaxloading
412                     w2.Cells(i,21).Value = contingencynum
413     for statgen in StatGenerators:
414         if statgen.outserv == 0:
415             name = statgen.loc_name
```

```
416             statgen_maxload = str(statgen.GetAttribute('c:maxLoading'))
417             statgen_contnum = str(statgen.GetAttribute('c:maxCntcy'))
418         if statgen.outserv == 1:
419             statgen_maxload = 0
420             statgen_contnum = 0
421         for i in range (41,71):
422             if w2.Cells(i,16).Value == name:
423                 w2.Cells(i,20).Value = statgen_maxload
424                 w2.Cells(i,21).Value = statgen_contnum
425     for symgen in SymGenerators:
426         name = symgen.loc_name
427         if symgen.outserv == 0:
428             symgen_maxload = str(symgen.GetAttribute('c:maxLoading'))
429             symgen_contnum = str(symgen.GetAttribute('c:maxCntcy'))
430         if symgen.outserv == 1:
431             symgen_maxload = 0
432             symgen_contnum = 0
433         for i in range (10,37):
434                 if w2.Cells(i,16).Value == name:
435                     w2.Cells(i,20).Value = symgen_maxload
436                     w2.Cells(i,21).Value = symgen_contnum
437     for trafo in Trafos:
438             name=trafo.loc_name
439             if trafo.outserv == 0:
440                 trafomaxloading = trafo.GetAttribute('c:maxLoading')
441                 trafocontingencynum = trafo.GetAttribute('c:maxCntcy')
442             if trafo.outserv == 1:
443                 trafomaxloading = 0
444                 trafocontingencynum = 0
445             for i in range (296,371):
446                     if w2.Cells(i,16).Value == name:
447                         w2.Cells(i,20).Value = trafomaxloading
448                         w2.Cells(i,21).Value = trafocontingencynum
449     for phs in Phs:
450             name=phs.loc_name
451             if phs.outserv == 0:
452                 phsmaxloading = phs.GetAttribute('c:maxLoading')
453                 phscontingencynum = phs.GetAttribute('c:maxCntcy')
454             if phs.outserv == 1:
455                 phsmaxloading = 0
456                 phscontingencynum = 0
457             for i in range (372,379):
458                     if w2.Cells(i,16).Value == name:
459                         w2.Cells(i,20).Value = phsmaxloading
460                         w2.Cells(i,21).Value = phscontingencynum
461
462 #%% Optimal Power flow functions for initialization and results
463 def optimalpowerflow():
464     OPF = app.GetFromStudyCase('ComOpf')
465     OPF.Execute()
466
467 def optimalpowerflowresults():
468     sheet = scen.loc_name[-2:]
469     w2 = wbout.Worksheets(sheet)
470     Line=app.GetCalcRelevantObjects('*.ElmLne') #getting the relevant results of all the
        lines
471     StatGenerators=app.GetCalcRelevantObjects('*.ElmGenstat')
472     SymGenerators=app.GetCalcRelevantObjects('*.ElmSym')
473     Zones=app.GetCalcRelevantObjects('*.ElmZone')
474     Loads = app.GetCalcRelevantObjects('*.ElmLod')
475     Boundaries=app.GetCalcRelevantObjects('*.ElmBoundary')
476     Trafos = app.GetCalcRelevantObjects('*.ElmTr2')
477     Phs = app.GetCalcRelevantObjects('*.ElmVoltreg')
478     Grid = app.GetCalcRelevantObjects('*.ElmNet')
479
480     for line in Line:
481         name=line.loc_name
482         if line.outserv == 0:
483             lineloading = line.GetAttribute('c:loading')
484         if line.outserv == 1:
485             lineloading = 0
```

```
        for i in range (151,295):
                if w2.Cells(i,23).Value == name:
                    w2.Cells(i,27).Value = lineloading
    for statgen in StatGenerators:
        name = statgen.loc_name
        if statgen.outserv == 0:
            statgen_P = str(statgen.GetAttribute('m:P:bus1'))
            statgen_Q = str(statgen.GetAttribute('m:Q:bus1'))
            statgen_loading=str(statgen.GetAttribute('c:loading'))
        if statgen.outserv == 1:
            statgen_P = 0
            statgen_Q = 0
            statgen_loading = 0
        for i in range (41,71):
            if w2.Cells(i,23).Value == name:
                w2.Cells(i,27).Value = statgen_P
                w2.Cells(i,28).Value = statgen_Q
                w2.Cells(i,29).Value = statgen_loading
    for symgen in SymGenerators:
        name = symgen.loc_name
        if symgen.outserv == 0:
            symgen_P = str(symgen.GetAttribute('m:P:bus1'))
            symgen_Q = str(symgen.GetAttribute('m:Q:bus1'))
            symgen_loading=str(symgen.GetAttribute('c:loading'))
        if symgen.outserv == 1:
            symgen_P = 0
            symgen_Q = 0
            symgen_loading = 0
        for i in range (10,37):
            if w2.Cells(i,23).Value == name:
                w2.Cells(i,27).Value = symgen_P
                w2.Cells(i,28).Value = symgen_Q
                w2.Cells(i,29).Value = symgen_loading
    for zone in Zones:
        name = zone.loc_name
        zone_P = str(zone.GetAttribute('c:GenP'))
        zone_Q = str(zone.GetAttribute('c:GenQ'))
        zone_Load = str(zone.GetAttribute('c:LoadP'))
        zone_Pint = str(zone.GetAttribute('c:InterP'))
        zone_Qint = str(zone.GetAttribute('c:InterQ'))
        for i in range (122,149):
            if w2.Cells(i,23).Value == name:
                w2.Cells(i,27).Value = zone_P
                w2.Cells(i,28).Value = zone_Q
                w2.Cells(i,29).Value = zone_Load
                w2.Cells(i,30).Value = zone_Pint
                w2.Cells(i,31).Value = zone_Qint
    for bound in Boundaries:
        name = bound.loc_name
        bound_Pint = str(bound.GetAttribute('c:Pinter'))
        bound_Qint = str(bound.GetAttribute('c:Qinter'))
        bound_Pex = str(bound.GetAttribute('c:ExportP'))
        bound_Qex = str(bound.GetAttribute('c:ExportQ'))
        bound_Pim = str(bound.GetAttribute('c:ImportP'))
        bound_Qim = str(bound.GetAttribute('c:ImportQ'))
        for i in range (101,121):
            if w2.Cells(i,23).Value == name:
                w2.Cells(i,27).Value = bound_Pint
                w2.Cells(i,28).Value = bound_Qint
                w2.Cells(i,29).Value = bound_Pex
                w2.Cells(i,30).Value = bound_Qex
                w2.Cells(i,31).Value = bound_Pim
                w2.Cells(i,32).Value = bound_Qim
    for load in Loads:
          name = load.loc_name
          if load.outserv == 0:
            load_P = str(load.GetAttribute('m:P:bus1'))
            load_Q = str(load.GetAttribute('m:Q:bus1'))
          if load.outserv == 1:
            load_P = 0
            load_Q = 0
```

```
            for i in range (75,97):
              if w2.Cells(i,23).Value == name:
                  w2.Cells(i,27).Value = load_P
                  w2.Cells(i,28).Value = load_Q
    for trafo in Trafos:
            name=trafo.loc_name
            if trafo.outserv == 0:
                trafoloading = trafo.GetAttribute('c:loading')
            if trafo.outserv == 1:
                trafoloading = 0
            for i in range (296,371):
                    if w2.Cells(i,23).Value == name:
                        w2.Cells(i,27).Value = trafoloading
    for phs in Phs:
            name=phs.loc_name
            if phs.outserv == 0:
                phsloading = phs.GetAttribute('c:loading')
            if phs.outserv == 1:
                phsloading = 0
            for i in range (372,379):
                    if w2.Cells(i,23).Value == name:
                        w2.Cells(i,27).Value = phsloading

    for grid in Grid:
            name=grid.loc_name
            app.PrintPlain(name)
            gridgenP = str(grid.GetAttribute('c:GenP'))
            gridgenQ = str(grid.GetAttribute('c:GenQ'))
            gridLoadP = str(grid.GetAttribute('c:LoadP'))
            gridLoadQ = str(grid.GetAttribute('c:LoadQ'))
            gridlossesP = str(grid.GetAttribute('c:LossP'))
            gridlossesQ = str(grid.GetAttribute('c:LossQ'))
            for i in range (3,5):
                    if w2.Cells(i,24).Value == name:
                      w2.Cells(i,25).Value = gridgenP
                      w2.Cells(i,26).Value = gridgenQ
                      w2.Cells(i,27).Value = gridLoadP
                      w2.Cells(i,28).Value = gridLoadQ
                      w2.Cells(i,29).Value = gridlossesP
                      w2.Cells(i,30).Value = gridlossesQ

#%% Define function to export diagrams from different simulations

def DiagramsLF():
    oDesk=app.GetFromStudyCase('SetDesktop')
    diagrams = app.GetProjectFolder('dia')
    diagramlist = diagrams.GetContents()
    for diagram in diagramlist:
        app.PrintPlain(diagram)
        diagramname = str(diagram.loc_name)
        oDesk.Show(diagramname)
        savename = diagrams_path + '\\' + scen.loc_name[-2:] + '_' + diagram.loc_name + '_LF'
        oDesk.WriteWMF(savename)

def diagramsOPF():
    oDesk=app.GetFromStudyCase('SetDesktop')
    diagrams = app.GetProjectFolder('dia')
    diagramlist = diagrams.GetContents()
    for diagram in diagramlist:
        app.PrintPlain(diagram)
        diagramname = str(diagram.loc_name)
        oDesk.Show(diagramname)
        savename =  diagrams_path + '\\' + scen.loc_name[-2:] + '_' + diagram.loc_name + '
    _OPF'
        oDesk.WriteWMF(savename)

def diagramsCA():
    oDesk=app.GetFromStudyCase('SetDesktop')
    diagrams = app.GetProjectFolder('dia')
    diagramlist = diagrams.GetContents()
    for diagram in diagramlist:
```

```
627         app.PrintPlain(diagram)
628         diagramname = str(diagram.loc_name)
629         oDesk.Show(diagramname)
630         savename =  diagrams_path + '\\' + scen.loc_name[-2:] + '_' + diagram.loc_name  + '
    _CA'
631         oDesk.WriteWMF(savename)
632
633 #%% Define whether simulations are run from python, and which results need to be exported
634
635 def simulations():
636         loadflow()                  #execute a load flow
637         # loadflowresults()           #write results to excelfile
638         # diagramsLF()                 #export diagrams
639
640         # optimalpowerflow()          #execute an optimal power flow
641         # optimalpowerflowresults()   #write results to excelfile
642         # diagramsOPF()                #export diagrams
643
644         # contingencyanalysis()       #execute a contingency analysis
645         # contingencyresults()        #write results to excelfile
646         # diagramsCA()                #export diagrams
647
648
649 #%% Scenarios for the Base Model
650 # Here the command is given to activate the study case for the base model, set the proper
    installed capacities, reactive power controls and dispatches
651
652 for StudyCase in studycases:
653     app.PrintPlain(StudyCase)
654     if StudyCase.loc_name == '2017-2019 Scenarios':
655         StudyCase.Activate()
656         capacities_BM()
657
658 OSfolder = app.GetProjectFolder('scen')
659 OS = OSfolder.GetContents()
660 for opscenfold in OS:
661     app.PrintPlain(opscenfold)
662     if opscenfold.loc_name == '2017-2019 Peak Demands':
663             sheetname = "2017-2019"
664             opscen = opscenfold.GetContents()
665             app.PrintPlain(opscen)
666             for scen in opscen:
667                 if scen.loc_name == 'Peak Demand 2017':
668                     scen.Activate()
669                     dispatches1_BM()
670                     reactivepowercontrol_BM('Conv')
671                     simulations()
672                 # if scen.loc_name == 'Peak Demand 2018':
673                 #     scen.Activate()
674                 #     dispatches2_BM()
675                 #     reactivepowercontrol_BM('Conv')
676                 #     simulations()
677                 # if scen.loc_name == 'Low Demand 2019':
678                 #     scen.Activate()
679                 #     dispatches3_BM()
680                 #     reactivepowercontrol_BM('Conv')
681                 #     simulations()
682                 # if scen.loc_name == 'DG - Peak Demand 2017':
683                 #     scen.Activate()
684                 #     dispatches4_BM()
685                 #     reactivepowercontrol_BM('Conv')
686                 #     simulations()
```

Listing F.1: Code for Base Model Simulations

F.3. Python Code for 2030 Simulations

```
# -*- coding: utf-8 -*-
"""
Created on Wed May 26 14:09:54 2021
@author: Anouk de Roos

Script for 2030 Scenarios

Before running this script from PowerFactory, install the win32 package:
from the command line: "py -m pip install -pywin32". Check out this
website for troubleshooting: https://packaging.python.org/tutorials/installing-packages/#ensure-you-can-run-python-from-the-command-line.
(has to be installed in the python version that PowerFactory uses)

"""
# make sure the file is located in documents folder
input_excel = r'C:\Users\AdeRo\OneDrive\Documenten\Model Files\Scenario Input Data.xlsx'
installedcap_excel = r'C:\Users\AdeRo\OneDrive\Documenten\Model Files\Scenario Installed Cap.xlsx'
output_excel = r'C:\Users\AdeRo\OneDrive\Documenten\Model Files\Scenario Output Data.xlsx'
diagrams_path =  r'C:\Users\AdeRo\OneDrive\Documenten\Diagrams'

#Getting the Powerfactory Application
import sys
sys.path.append('C:\\Program Files\\DIgSILENT\\PowerFactory 2020 SP3\\Python\\3.8')

import powerfactory as pf

app=pf.GetApplication()
app.ActivateProject('EHVnetwork_NL_Final')
app.ResetCalculation()    # start always from the same PowerFactory state
app.ClearOutputWindow()    # clear Output Window (OPTIONAL)

import win32com.client as win32
excel=win32.gencache.EnsureDispatch('Excel.Application')
excel.Visible=True
import math

#open excelfile
wbin = excel.Workbooks.Open(input_excel)
wbout = excel.Workbooks.Open(output_excel)
wbcap = excel.Workbooks.Open(installedcap_excel)
excel.Visible = True

#studycase files
studycasefolder = app.GetProjectFolder('study')
studycases = studycasefolder.GetContents()

#other input values
Genstatmax = 1


#%% define function to set installed capacities to Base Model or KA2030 Values

def capacities2030():
    wbcap1=wbcap.Worksheets("1) SymGen list")
    wbcap2 = wbcap.Worksheets("1) StatGen list")
    symgenlist = wbcap1.Range("B2:I28").Value
    trafolist = wbcap1.Range("K2:P12").Value
    statgenlist = wbcap2.Range("B2:G31").Value
    for row in symgenlist:
        name = row[0]+ '.ElmSym'
        variable = app.GetCalcRelevantObjects(name)[0]
        variable.ngnum = int(row[7])
        if float(row[3])>0:
            variable.typ_id.sgn = float(row[3])/0.9
            variable.Pmax_ucPU = 1
            variable.Pmin_ucPU = 0
        if float(row[3])==0:
```

```
67              variable.outserv = 1
68
69      #reset amount of step up trafos needed for new gen capacities
70      for row in trafolist:
71          name = row[0]+'.ElmTr2'
72          variable = app.GetCalcRelevantObjects(name)[0]
73          variable.ntnum = math.ceil(row[3])
74
75      #reset stat gen capacities
76      for row in statgenlist:
77          name = row[0]+'.ElmGenstat'
78          variable = app.GetCalcRelevantObjects(name)[0]
79          if float(row[3])>0:
80              variable.sgn = float(row[3])
81              variable.Pmax_ucPU = 1
82              variable.Pmin_ucPU = 0
83
84
85  #%% define functions to set the dispatches using the excelfiles
86
87  def dispatches1():
88      w1 = wbin.Worksheets(sheetname)
89      SymG_1 = w1.Range("A10:Z36").Value
90      StatG_1 = w1.Range("A41:Z70").Value
91      Load_1 = w1.Range("A76:Z96").Value
92      for row in SymG_1:
93          name = row[0]+ '.Elmsym'
94          variable = app.GetCalcRelevantObjects(name)[0]
95          variable.pgini = float(row[5])
96          variable.qgini = float(row[7])
97          variable.Pmax_ucPU = 1
98          variable.Pmin_ucPU = 0
99      for row in StatG_1:
100         name = row[0]+'.ElmGenstat'
101         variable = app.GetCalcRelevantObjects(name)[0]
102         variable.pgini = float(row[5])
103         variable.qgini = float(row[7])
104         variable.Pmax_ucPU = Genstatmax
105         variable.Pmin_ucPU = 0
106     for row in Load_1:
107         name = row[0]+'.ElmLod'
108         variable = app.GetCalcRelevantObjects(name)[0]
109         variable.plini = float(row[5])
110         variable.qlini = float(row[7])
111         variable.Pmax_ucPU = 1
112         variable.Pmin_ucPU = 0
113
114 def dispatches2():
115     w1 = wbin.Worksheets(sheetname)
116     SymG_1 = w1.Range("A10:Z36").Value
117     StatG_1 = w1.Range("A41:Z70").Value
118     Load_1 = w1.Range("A76:Z96").Value
119     for row in SymG_1:
120         name = row[0]+ '.Elmsym'
121         variable = app.GetCalcRelevantObjects(name)[0]
122         variable.pgini = float(row[8])
123         variable.qgini = float(row[10])
124         variable.Pmax_ucPU = 1
125         variable.Pmin_ucPU = 0
126     for row in StatG_1:
127         name = row[0]+'.ElmGenstat'
128         variable = app.GetCalcRelevantObjects(name)[0]
129         variable.pgini = float(row[8])
130         variable.qgini = float(row[10])
131         variable.Pmax_ucPU = Genstatmax
132         variable.Pmin_ucPU = 0
133     for row in Load_1:
134         name = row[0]+'.ElmLod'
135         variable = app.GetCalcRelevantObjects(name)[0]
136         variable.plini = float(row[8])
137         variable.qlini = float(row[10])
```

```
138         variable.Pmax_ucPU = 1
139         variable.Pmin_ucPU = 0
140
141 def dispatches3():
142     w1 = wbin.Worksheets(sheetname)
143     SymG_1 = w1.Range("A10:Z36").Value
144     StatG_1 = w1.Range("A41:Z70").Value
145     Load_1 = w1.Range("A76:Z96").Value
146     for row in SymG_1:
147         name = row[0]+ '.Elmsym'
148         variable = app.GetCalcRelevantObjects(name)[0]
149         variable.pgini = float(row[11])
150         variable.qgini = float(row[13])
151         variable.Pmax_ucPU = 1
152         variable.Pmin_ucPU = 0
153     for row in StatG_1:
154         name = row[0]+'.ElmGenstat'
155         variable = app.GetCalcRelevantObjects(name)[0]
156         variable.pgini = float(row[11])
157         variable.qgini = float(row[13])
158         variable.Pmax_ucPU = Genstatmax
159         variable.Pmin_ucPU = 0
160     for row in Load_1:
161         name = row[0]+'.ElmLod'
162         variable = app.GetCalcRelevantObjects(name)[0]
163         variable.plini = float(row[11])
164         variable.qlini = float(row[13])
165         variable.Pmax_ucPU = 1
166         variable.Pmin_ucPU = 0
167
168 def dispatches4():
169     w1 = wbin.Worksheets(sheetname)
170     SymG_1 = w1.Range("A10:Z36").Value
171     StatG_1 = w1.Range("A41:Z70").Value
172     Load_1 = w1.Range("A76:Z96").Value
173     for row in SymG_1:
174         name = row[0]+ '.Elmsym'
175         variable = app.GetCalcRelevantObjects(name)[0]
176         variable.pgini = float(row[14])
177         variable.qgini = float(row[16])
178         variable.Pmax_ucPU = 1
179         variable.Pmin_ucPU = 0
180     for row in StatG_1:
181         name = row[0]+'.ElmGenstat'
182         variable = app.GetCalcRelevantObjects(name)[0]
183         variable.pgini = float(row[14])
184         variable.qgini = float(row[16])
185         variable.Pmax_ucPU = Genstatmax
186         variable.Pmin_ucPU = 0
187     for row in Load_1:
188         name = row[0]+'.ElmLod'
189         variable = app.GetCalcRelevantObjects(name)[0]
190         variable.plini = float(row[14])
191         variable.qlini = float(row[16])
192         variable.Pmax_ucPU = 1
193         variable.Pmin_ucPU = 0
194
195 def dispatches5():
196     w1 = wbin.Worksheets(sheetname)
197     SymG_1 = w1.Range("A10:Z36").Value
198     StatG_1 = w1.Range("A41:Z70").Value
199     Load_1 = w1.Range("A76:Z96").Value
200     for row in SymG_1:
201         name = row[0]+ '.Elmsym'
202         variable = app.GetCalcRelevantObjects(name)[0]
203         variable.pgini = float(row[17])
204         variable.qgini = float(row[19])
205         variable.Pmax_ucPU = 1
206         variable.Pmin_ucPU = 0
207     for row in StatG_1:
208         name = row[0]+'.ElmGenstat'
```

```
209             variable = app.GetCalcRelevantObjects(name)[0]
210             variable.pgini = float(row[17])
211             variable.qgini = float(row[19])
212             variable.Pmax_ucPU = Genstatmax
213             variable.Pmin_ucPU = 0
214         for row in Load_1:
215             name = row[0]+'.ElmLod'
216             variable = app.GetCalcRelevantObjects(name)[0]
217             variable.plini = float(row[17])
218             variable.qlini = float(row[19])
219             variable.Pmax_ucPU = 1
220             variable.Pmin_ucPU = 0
221
222 def dispatches6():
223     w1 = wbin.Worksheets(sheetname)
224     SymG_1 = w1.Range("A10:Z36").Value
225     StatG_1 = w1.Range("A41:Z70").Value
226     Load_1 = w1.Range("A76:Z96").Value
227     for row in SymG_1:
228         name = row[0]+ '.Elmsym'
229         variable = app.GetCalcRelevantObjects(name)[0]
230         variable.pgini = float(row[20])
231         variable.qgini = float(row[22])
232         variable.Pmax_ucPU = 1
233         variable.Pmin_ucPU = 0
234     for row in StatG_1:
235         name = row[0]+'.ElmGenstat'
236         variable = app.GetCalcRelevantObjects(name)[0]
237         variable.pgini = float(row[20])
238         variable.qgini = float(row[22])
239         variable.Pmax_ucPU = Genstatmax
240         variable.Pmin_ucPU = 0
241     for row in Load_1:
242         name = row[0]+'.ElmLod'
243         variable = app.GetCalcRelevantObjects(name)[0]
244         variable.plini = float(row[20])
245         variable.qlini = float(row[22])
246         variable.Pmax_ucPU = 1
247         variable.Pmin_ucPU = 0
248
249 def dispatches7():
250     w1 = wbin.Worksheets(sheetname)
251     SymG_1 = w1.Range("A10:Z36").Value
252     StatG_1 = w1.Range("A41:Z70").Value
253     Load_1 = w1.Range("A76:Z96").Value
254     for row in SymG_1:
255         name = row[0]+ '.Elmsym'
256         variable = app.GetCalcRelevantObjects(name)[0]
257         variable.pgini = float(row[23])
258         variable.qgini = float(row[25])
259         variable.Pmax_ucPU = 1
260         variable.Pmin_ucPU = 0
261     for row in StatG_1:
262         name = row[0]+'.ElmGenstat'
263         variable = app.GetCalcRelevantObjects(name)[0]
264         variable.pgini = float(row[23])
265         variable.qgini = float(row[25])
266         variable.Pmax_ucPU = Genstatmax
267         variable.Pmin_ucPU = 0
268     for row in Load_1:
269         name = row[0]+'.ElmLod'
270         variable = app.GetCalcRelevantObjects(name)[0]
271         variable.plini = float(row[23])
272         variable.qlini = float(row[25])
273         variable.Pmax_ucPU = 1
274         variable.Pmin_ucPU = 0
275
276 def dispatches8():
277     w1 = wbin.Worksheets(sheetname)
278     SymG_1 = w1.Range("A10:AC36").Value
279     StatG_1 = w1.Range("A41:AC70").Value
```

```
    Load_1 = w1.Range("A76:AC96").Value
    for row in SymG_1:
        name = row[0]+ '.Elmsym'
        variable = app.GetCalcRelevantObjects(name)[0]
        variable.pgini = float(row[26])
        variable.qgini = float(row[28])
        variable.Pmax_ucPU = 1
        variable.Pmin_ucPU = 0
    for row in StatG_1:
        name = row[0]+'.ElmGenstat'
        variable = app.GetCalcRelevantObjects(name)[0]
        variable.pgini = float(row[26])
        variable.qgini = float(row[28])
        variable.Pmax_ucPU = Genstatmax
        variable.Pmin_ucPU = 0
    for row in Load_1:
        name = row[0]+'.ElmLod'
        variable = app.GetCalcRelevantObjects(name)[0]
        variable.plini = float(row[26])
        variable.qlini = float(row[28])
        variable.Pmax_ucPU = 1
        variable.Pmin_ucPU = 0

def dispatches9():
    w1 = wbin.Worksheets(sheetname)
    SymG_1 = w1.Range("A10:AF36").Value
    StatG_1 = w1.Range("A41:AF70").Value
    Load_1 = w1.Range("A76:AF96").Value
    for row in SymG_1:
        name = row[0]+ '.Elmsym'
        variable = app.GetCalcRelevantObjects(name)[0]
        variable.pgini = float(row[29])
        variable.qgini = float(row[31])
        variable.Pmax_ucPU = 1
        variable.Pmin_ucPU = 0
    for row in StatG_1:
        name = row[0]+'.ElmGenstat'
        variable = app.GetCalcRelevantObjects(name)[0]
        variable.pgini = float(row[29])
        variable.qgini = float(row[31])
        variable.Pmax_ucPU = Genstatmax
        variable.Pmin_ucPU = 0
    for row in Load_1:
        name = row[0]+'.ElmLod'
        variable = app.GetCalcRelevantObjects(name)[0]
        variable.plini = float(row[29])
        variable.qlini = float(row[31])
        variable.Pmax_ucPU = 1
        variable.Pmin_ucPU = 0

#%% function for setting reactive power controls
# controlmode options: PV (only PV generation), Wind (only Wind generation), Both (both PV
    and Wind generation), Conv (conventional)
    #selected WOZ and PV work also as STATCOMS providing reactive power support in all
    scenarios
    #active power regulation for OPF: depends on if PV or wind was operational in loadflow

def reactivepowercontrol(Controlmode):
    w1 = wbin.Worksheets(sheetname)
    SymG_1 = w1.Range("A10:Z36").Value
    StatG_1 = w1.Range("A41:Z70").Value
    if Controlmode == 'PV':
        for row in StatG_1:
            name = row[0]+'.ElmGenstat'
            variable = app.GetCalcRelevantObjects(name)[0]
            if variable.loc_name.startswith("DG_PV"):
                variable.av_mode = 'constv'
                variable.ictpg = 1
                variable.ictqg = 1
                variable.iOPFCPmin = 1
                variable.iOPFCPmax = 1
```

```
349                 variable.iOPFCQmin = 1
350                 variable.iOPFCQmax = 1
351             elif variable.loc_name == "Gen_WOZ_HKW" or variable.loc_name ==  "Gen_WOZ_IJMA"
    or variable.loc_name == "Gen_WOZ_IJMB" or variable.loc_name == "Gen_WOZ_TNW" or variable.
    loc_name ==  "Gen_WOZ_EOS380_2":
352                 variable.av_mode = 'constv' #if no wind, some WOZ only act as STATCOMS
353                 variable.ictpg = 0
354                 variable.ictqg = 1
355                 variable.iOPFCPmin = 0
356                 variable.iOPFCPmax = 0
357                 variable.iOPFCQmin = 1
358                 variable.iOPFCQmax = 1
359             else:
360                 variable.av_mode = 'constq'
361                 variable.ictpg = 0 #if no wind, no participation in OPF for other wind farms
362                 variable.ictqg = 0
363                 variable.iOPFCPmin = 0
364                 variable.iOPFCPmax = 0
365                 variable.iOPFCQmin = 0
366                 variable.iOPFCQmax = 0
367         for row in SymG_1:
368             name = row[0]+'.ElmSym'
369             variable = app.GetCalcRelevantObjects(name)[0]
370             if variable.loc_name == "Gen_GAS_MBT15":
371                 variable.av_mode = 'constv'
372                 variable.ictpg = 0
373                 variable.ictqg = 0
374                 variable.iOPFCPmin = 1
375                 variable.iOPFCPmax = 1
376                 variable.iOPFCQmin = 1
377                 variable.iOPFCQmax = 1
378             else:
379                 variable.av_mode = 'constv'
380                 variable.ictpg = 0
381                 variable.ictqg = 0
382                 variable.iOPFCPmin = 0
383                 variable.iOPFCPmax = 0
384                 variable.iOPFCQmin = 0
385                 variable.iOPFCQmax = 0
386
387     if ControlMode == 'Wind':
388         for row in StatG_1:
389             name = row[0]+'.ElmGenstat'
390             variable = app.GetCalcRelevantObjects(name)[0]
391             if variable.loc_name.startswith("DG_PV"):
392                     variable.av_mode = 'constv'
393                     variable.ictpg = 0
394                     variable.ictqg = 1
395                     variable.iOPFCPmin = 0
396                     variable.iOPFCPmax = 0
397                     variable.iOPFCQmin = 1
398                     variable.iOPFCQmax = 1
399             elif variable.loc_name == "Gen_WOZ_HKW" or variable.loc_name ==  "Gen_WOZ_IJMA"
    or variable.loc_name == "Gen_WOZ_IJMB" or variable.loc_name == "Gen_WOZ_TNW" or variable.
    loc_name ==  "Gen_WOZ_EOS380_2":
400                     variable.av_mode = 'constv' # if wind, active and reactive power
    regulation for these wind farms
401                     variable.ictpg = 1
402                     variable.ictqg = 1
403                     variable.iOPFCPmin = 1
404                     variable.iOPFCPmax = 1
405                     variable.iOPFCQmin = 1
406                     variable.iOPFCQmax = 1
407             else:
408                     variable.av_mode = 'constq' #if wind, only active power regulations WOL
    and some WOZ
409                     variable.ictpg = 1
410                     variable.ictqg = 0
411                     variable.iOPFCPmin = 1
412                     variable.iOPFCPmax = 1
413                     variable.iOPFCQmin = 0
```

```
414                     variable.iOPFCQmax = 0
415         for row in SymG_1:
416             name = row[0]+'.ElmSym'
417             variable = app.GetCalcRelevantObjects(name)[0]
418             if variable.loc_name == "Gen_GAS_MBT15":
419                     variable.av_mode = 'constv'
420                     variable.ictpg = 0
421                     variable.ictqg = 0
422                     variable.iOPFCPmin = 1
423                     variable.iOPFCPmax = 1
424                     variable.iOPFCQmin = 1
425                     variable.iOPFCQmax = 1
426             else:
427                     variable.av_mode = 'constv'
428                     variable.ictpg = 0
429                     variable.ictqg = 0
430                     variable.iOPFCPmin = 0
431                     variable.iOPFCPmax = 0
432                     variable.iOPFCQmin = 0
433                     variable.iOPFCQmax = 0
434
435     if ControlMode == 'Both':
436         for row in StatG_1:
437             name = row[0]+'.ElmGenstat'
438             variable = app.GetCalcRelevantObjects(name)[0]
439             if variable.loc_name.startswith("DG_PV"):
440                     variable.av_mode = 'constv' #PV operational as well as STATCOM
441                     variable.ictpg = 1
442                     variable.ictqg = 1
443                     variable.iOPFCPmin = 1
444                     variable.iOPFCPmax = 1
445                     variable.iOPFCQmin = 1
446                     variable.iOPFCQmax = 1
447             elif variable.loc_name == "Gen_WOZ_HKW" or variable.loc_name ==  "Gen_WOZ_IJMA"
    or variable.loc_name == "Gen_WOZ_IJMB" or variable.loc_name == "Gen_WOZ_TNW" or variable.
    loc_name ==  "Gen_WOZ_EOS380_2":
448                     variable.av_mode = 'constv' # if wind, active and reactive power
    regulation for these wind farms
449                     variable.ictpg = 1
450                     variable.ictqg = 1
451                     variable.iOPFCPmin = 1
452                     variable.iOPFCPmax = 1
453                     variable.iOPFCQmin = 1
454                     variable.iOPFCQmax = 1
455             else:
456                     variable.av_mode = 'constq' #if wind, only active power regulations WOL
    and some WOZ not reactive
457                     variable.ictpg = 1
458                     variable.ictqg = 0
459                     variable.iOPFCPmin = 1
460                     variable.iOPFCPmax = 1
461                     variable.iOPFCQmin = 0
462                     variable.iOPFCQmax = 0
463         for row in SymG_1:
464             name = row[0]+'.ElmSym'
465             variable = app.GetCalcRelevantObjects(name)[0]
466             if variable.loc_name == "Gen_GAS_MBT15":
467                     variable.av_mode = 'constv'
468                     variable.ictpg = 0
469                     variable.ictqg = 0
470                     variable.iOPFCPmin = 1
471                     variable.iOPFCPmax = 1
472                     variable.iOPFCQmin = 1
473                     variable.iOPFCQmax = 1
474             else:
475                     variable.av_mode = 'constv'
476                     variable.ictpg = 0
477                     variable.ictqg = 0
478                     variable.iOPFCPmin = 0
479                     variable.iOPFCPmax = 0
480                     variable.iOPFCQmin = 0
```

```
481                     variable.iOPFCQmax = 0
482
483     if ControlMode == 'Conv':
484         for row in StatG_1:
485                     name = row[0]+'.ElmGenstat'
486                     variable = app.GetCalcRelevantObjects(name)[0]
487                     if variable.loc_name == "Gen_WOZ_HKW" or variable.loc_name == "
        Gen_WOZ_IJMA" or variable.loc_name == "Gen_WOZ_IJMB" or variable.loc_name == "Gen_WOZ_TNW
        " or variable.loc_name == "Gen_WOZ_EOS380_2":
488                             variable.av_mode = 'constv' # if wind, active and reactive power
        regulation for these wind farms
489                             variable.ictpg = 0
490                             variable.ictqg = 1
491                             variable.iOPFCPmin = 0
492                             variable.iOPFCPmax = 0
493                             variable.iOPFCQmin = 1
494                             variable.iOPFCQmax = 1
495                     else:
496                             variable.av_mode = 'constq' #if wind, only active power
        regulations WOL and some WOZ not reactive
497                             variable.ictpg = 0
498                             variable.ictqg = 0
499                             variable.iOPFCPmin = 0
500                             variable.iOPFCPmax = 0
501                             variable.iOPFCQmin = 0
502                             variable.iOPFCQmax = 0
503         for row in SymG_1:
504                     name = row[0]+ '.Elmsym'
505                     variable = app.GetCalcRelevantObjects(name)[0]
506                     variable.av_mode = 'constv'
507                     variable.ictpg = 1
508                     variable.ictqg = 1
509                     variable.iOPFCPmin = 1
510                     variable.iOPFCPmax = 1
511                     variable.iOPFCQmin = 1
512                     variable.iOPFCQmax = 1
513
514 #%% Load flow functions for initialization and results
515
516 def loadflow():
517      Ldf = app.GetFromStudyCase('ComLdf')
518      Ldf.Execute()
519
520 def loadflowresults():
521     sheet = scen.loc_name[9::]
522     w2 = wbout.Worksheets(sheet)
523     Line=app.GetCalcRelevantObjects('*.ElmLne') #getting the relevant results of all the
        lines
524     StatGenerators=app.GetCalcRelevantObjects('*.ElmGenstat')
525     SymGenerators=app.GetCalcRelevantObjects('*.ElmSym')
526     Zones=app.GetCalcRelevantObjects('*.ElmZone')
527     Loads = app.GetCalcRelevantObjects('*.ElmLod')
528     Boundaries=app.GetCalcRelevantObjects('*.ElmBoundary')
529     Trafos = app.GetCalcRelevantObjects('*.ElmTr2')
530     Phs = app.GetCalcRelevantObjects('*.ElmVoltreg')
531     Grid = app.GetCalcRelevantObjects('*.ElmNet')
532
533     for line in Line:
534         name=line.loc_name
535         if line.outserv == 0:
536             lineloading = line.GetAttribute('c:loading')
537         if line.outserv == 1:
538             lineloading = 0
539         for i in range (151,295):
540                 if w2.Cells(i,1).Value == name:
541                     w2.Cells(i,5).Value = lineloading
542     for statgen in StatGenerators:
543         name = statgen.loc_name
544         if statgen.outserv == 0:
545             statgen_P = str(statgen.GetAttribute('c:p'))
546             statgen_Q = str(statgen.GetAttribute('c:q'))
```

```
547             statgen_Preal = str(statgen.GetAttribute('m:P:bus1'))
548             statgen_Qreal = str(statgen.GetAttribute('m:Q:bus1'))
549             statgen_pf = str(statgen.GetAttribute('m:cosphi:bus1'))
550             statgen_loading=str(statgen.GetAttribute('c:loading'))
551         if statgen.outserv == 1:
552             statgen_P = 0
553             statgen_Q = 0
554             statgen_Preal = 0
555             statgen_Qreal = 0
556             statgen_pf = 0
557             statgen_loading = 0
558         for i in range (41,71):
559             if w2.Cells(i,1).Value == name:
560                 w2.Cells(i,5).Value = statgen_P
561                 w2.Cells(i,6).Value = statgen_Q
562                 w2.Cells(i,7).Value = statgen_Preal
563                 w2.Cells(i,8).Value = statgen_Qreal
564                 w2.Cells(i,9).Value = statgen_pf
565                 w2.Cells(i,10).Value = statgen_loading
566     for symgen in SymGenerators:
567         name = symgen.loc_name
568         if symgen.outserv == 0:
569             symgen_P = str(symgen.GetAttribute('c:p'))
570             symgen_Q = str(symgen.GetAttribute('c:q'))
571             symgen_Preal = str(symgen.GetAttribute('m:P:bus1'))
572             symgen_Qreal = str(symgen.GetAttribute('m:Q:bus1'))
573             symgen_pf = str(symgen.GetAttribute('m:cosphi:bus1'))
574             symgen_loading=str(symgen.GetAttribute('c:loading'))
575         if symgen.outserv == 1:
576             symgen_P = 0
577             symgen_Q = 0
578             symgen_Preal = 0
579             symgen_Qreal = 0
580             symgen_pf = 0
581             symgen_loading = 0
582         for i in range (10,37):
583             if w2.Cells(i,1).Value == name:
584                 w2.Cells(i,5).Value = symgen_P
585                 w2.Cells(i,6).Value = symgen_Q
586                 w2.Cells(i,7).Value = symgen_Preal
587                 w2.Cells(i,8).Value = symgen_Qreal
588                 w2.Cells(i,9).Value = symgen_pf
589                 w2.Cells(i,10).Value = symgen_loading
590     for zone in Zones:
591         name = zone.loc_name
592         zone_P = str(zone.GetAttribute('c:GenP'))
593         zone_Q = str(zone.GetAttribute('c:GenQ'))
594         zone_Load = str(zone.GetAttribute('c:LoadP'))
595         zone_Pint = str(zone.GetAttribute('c:InterP'))
596         zone_Qint = str(zone.GetAttribute('c:InterQ'))
597         for i in range (122,149):
598             if w2.Cells(i,1).Value == name:
599                 w2.Cells(i,5).Value = zone_P
600                 w2.Cells(i,6).Value = zone_Q
601                 w2.Cells(i,7).Value = zone_Load
602                 w2.Cells(i,8).Value = zone_Pint
603                 w2.Cells(i,9).Value = zone_Qint
604     for bound in Boundaries:
605         name = bound.loc_name
606         bound_Pint = str(bound.GetAttribute('c:Pinter'))
607         bound_Qint = str(bound.GetAttribute('c:Qinter'))
608         bound_Pex = str(bound.GetAttribute('c:ExportP'))
609         bound_Qex = str(bound.GetAttribute('c:ExportQ'))
610         bound_Pim = str(bound.GetAttribute('c:ImportP'))
611         bound_Qim = str(bound.GetAttribute('c:ImportQ'))
612         for i in range (101,121):
613             if w2.Cells(i,1).Value == name:
614                 w2.Cells(i,5).Value = bound_Pint
615                 w2.Cells(i,6).Value = bound_Qint
616                 w2.Cells(i,7).Value = bound_Pex
617                 w2.Cells(i,8).Value = bound_Qex
```

```
618                 w2.Cells(i,9).Value = bound_Pim
619                 w2.Cells(i,10).Value = bound_Qim
620     for load in Loads:
621           name = load.loc_name
622           if load.outserv == 0:
623             load_P = str(load.GetAttribute('c:pini'))
624             load_Q = str(load.GetAttribute('c:qini'))
625             load_Preal = str(load.GetAttribute('m:P:bus1'))
626             load_Qreal = str(load.GetAttribute('m:Q:bus1'))
627             load_pf = str(load.GetAttribute('m:cosphi:bus1'))
628           if load.outserv == 1:
629             load_P = 0
630             load_Q = 0
631             load_Preal = 0
632             load_Qreal = 0
633             load_pf = 0
634           for i in range (75,97):
635             if w2.Cells(i,1).Value == name:
636                 w2.Cells(i,5).Value = load_P
637                 w2.Cells(i,6).Value = load_Q
638                 w2.Cells(i,7).Value = load_Preal
639                 w2.Cells(i,8).Value = load_Qreal
640                 w2.Cells(i,9).Value = load_pf
641     for trafo in Trafos:
642             name=trafo.loc_name
643             if trafo.outserv == 0:
644                 trafoloading = trafo.GetAttribute('c:loading')
645             if trafo.outserv == 1:
646                 trafoloading = 0
647             for i in range (296,371):
648                     if w2.Cells(i,1).Value == name:
649                         w2.Cells(i,5).Value = trafoloading
650     for phs in Phs:
651             name=phs.loc_name
652             if phs.outserv == 0:
653                 phsloading = phs.GetAttribute('c:loading')
654             if phs.outserv == 1:
655                 phsloading = 0
656             for i in range (372,379):
657                     if w2.Cells(i,1).Value == name:
658                         w2.Cells(i,5).Value = phsloading
659     for grid in Grid:
660             name=grid.loc_name
661             app.PrintPlain(name)
662             gridgenP = str(grid.GetAttribute('c:GenP'))
663             gridgenQ = str(grid.GetAttribute('c:GenQ'))
664             gridLoadP = str(grid.GetAttribute('c:LoadP'))
665             gridLoadQ = str(grid.GetAttribute('c:LoadQ'))
666             gridlossesP = str(grid.GetAttribute('c:LossP'))
667             gridlossesQ = str(grid.GetAttribute('c:LossQ'))
668             for i in range (3,5):
669                     if w2.Cells(i,4).Value == name:
670                       w2.Cells(i,5).Value = gridgenP
671                       w2.Cells(i,6).Value = gridgenQ
672                       w2.Cells(i,7).Value = gridLoadP
673                       w2.Cells(i,8).Value = gridLoadQ
674                       w2.Cells(i,9).Value = gridlossesP
675                       w2.Cells(i,10).Value = gridlossesQ
676
677 #%% Contingency analysis functions for initialization and results
678 def contingencyanalysis():
679     Ctg = app.GetFromStudyCase('ComSimoutage')
680     Ctg.Execute()
681
682 def contingencyresults():
683     sheet = scen.loc_name[9::]
684     w2 = wbout.Worksheets(sheet)
685     Line=app.GetCalcRelevantObjects('*.ElmLne') #getting the relevant results of all the
        lines
686     StatGenerators=app.GetCalcRelevantObjects('*.ElmGenstat')
687     SymGenerators=app.GetCalcRelevantObjects('*.ElmSym')
```

```
    Trafos = app.GetCalcRelevantObjects('*.ElmTr2')
    Phs = app.GetCalcRelevantObjects('*.ElmVoltreg')

    for line in Line:
        name=line.loc_name
        if line.outserv == 0:
            linemaxloading = line.GetAttribute('c:maxLoading')
            contingencynum = line.GetAttribute('c:maxCntcy')
        if line.outserv == 1:
            linemaxloading = 0
            contingencynum = 0
        for i in range (151,295):
                if w2.Cells(i,16).Value == name:
                    w2.Cells(i,20).Value = linemaxloading
                    w2.Cells(i,21).Value = contingencynum
    for statgen in StatGenerators:
        if statgen.outserv == 0:
            name = statgen.loc_name
            statgen_maxload = str(statgen.GetAttribute('c:maxLoading'))
            statgen_contnum = str(statgen.GetAttribute('c:maxCntcy'))
        if statgen.outserv == 1:
            statgen_maxload = 0
            statgen_contnum = 0
        for i in range (41,71):
            if w2.Cells(i,16).Value == name:
                w2.Cells(i,20).Value = statgen_maxload
                w2.Cells(i,21).Value = statgen_contnum
    for symgen in SymGenerators:
        name = symgen.loc_name
        if symgen.outserv == 0:
            symgen_maxload = str(symgen.GetAttribute('c:maxLoading'))
            symgen_contnum = str(symgen.GetAttribute('c:maxCntcy'))
        if symgen.outserv == 1:
            symgen_maxload = 0
            symgen_contnum = 0
        for i in range (10,37):
                if w2.Cells(i,16).Value == name:
                    w2.Cells(i,20).Value = symgen_maxload
                    w2.Cells(i,21).Value = symgen_contnum
    for trafo in Trafos:
            name=trafo.loc_name
            if trafo.outserv == 0:
                trafomaxloading = trafo.GetAttribute('c:maxLoading')
                trafocontingencynum = trafo.GetAttribute('c:maxCntcy')
            if trafo.outserv == 1:
                trafomaxloading = 0
                trafocontingencynum = 0
            for i in range (296,371):
                    if w2.Cells(i,16).Value == name:
                        w2.Cells(i,20).Value = trafomaxloading
                        w2.Cells(i,21).Value = trafocontingencynum
    for phs in Phs:
            name=phs.loc_name
            if phs.outserv == 0:
                phsmaxloading = phs.GetAttribute('c:maxLoading')
                phscontingencynum = phs.GetAttribute('c:maxCntcy')
            if phs.outserv == 1:
                phsmaxloading = 0
                phscontingencynum = 0
            for i in range (372,379):
                    if w2.Cells(i,16).Value == name:
                        w2.Cells(i,20).Value = phsmaxloading
                        w2.Cells(i,21).Value = phscontingencynum

#%% Optimal Power flow functions for initialization and results
def optimalpowerflow():
    OPF = app.GetFromStudyCase('ComOpf')
    OPF.Execute()

def optimalpowerflowresults():
    sheet = scen.loc_name[9::]
```

```
759     w2 = wbout.Worksheets(sheet)
760     Line=app.GetCalcRelevantObjects('*.ElmLne') #getting the relevant results of all the
        lines
761     StatGenerators=app.GetCalcRelevantObjects('*.ElmGenstat')
762     SymGenerators=app.GetCalcRelevantObjects('*.ElmSym')
763     Zones=app.GetCalcRelevantObjects('*.ElmZone')
764     Loads = app.GetCalcRelevantObjects('*.ElmLod')
765     Boundaries=app.GetCalcRelevantObjects('*.ElmBoundary')
766     Trafos = app.GetCalcRelevantObjects('*.ElmTr2')
767     Phs = app.GetCalcRelevantObjects('*.ElmVoltreg')
768     Grid = app.GetCalcRelevantObjects('*.ElmNet')
769
770     for line in Line:
771         name=line.loc_name
772         if line.outserv == 0:
773             lineloading = line.GetAttribute('c:loading')
774         if line.outserv == 1:
775             lineloading = 0
776         for i in range (151,295):
777                 if w2.Cells(i,23).Value == name:
778                     w2.Cells(i,27).Value = lineloading
779     for statgen in StatGenerators:
780         name = statgen.loc_name
781         if statgen.outserv == 0:
782             statgen_P = str(statgen.GetAttribute('m:P:bus1'))
783             statgen_Q = str(statgen.GetAttribute('m:Q:bus1'))
784             statgen_loading=str(statgen.GetAttribute('c:loading'))
785         if statgen.outserv == 1:
786             statgen_P = 0
787             statgen_Q = 0
788             statgen_loading = 0
789         for i in range (41,71):
790             if w2.Cells(i,23).Value == name:
791                 w2.Cells(i,27).Value = statgen_P
792                 w2.Cells(i,28).Value = statgen_Q
793                 w2.Cells(i,29).Value = statgen_loading
794     for symgen in SymGenerators:
795         name = symgen.loc_name
796         if symgen.outserv == 0:
797             symgen_P = str(symgen.GetAttribute('m:P:bus1'))
798             symgen_Q = str(symgen.GetAttribute('m:Q:bus1'))
799             symgen_loading=str(symgen.GetAttribute('c:loading'))
800         if symgen.outserv == 1:
801             symgen_P = 0
802             symgen_Q = 0
803             symgen_loading = 0
804         for i in range (10,37):
805             if w2.Cells(i,23).Value == name:
806                 w2.Cells(i,27).Value = symgen_P
807                 w2.Cells(i,28).Value = symgen_Q
808                 w2.Cells(i,29).Value = symgen_loading
809     for zone in Zones:
810         name = zone.loc_name
811         zone_P = str(zone.GetAttribute('c:GenP'))
812         zone_Q = str(zone.GetAttribute('c:GenQ'))
813         zone_Load = str(zone.GetAttribute('c:LoadP'))
814         zone_Pint = str(zone.GetAttribute('c:InterP'))
815         zone_Qint = str(zone.GetAttribute('c:InterQ'))
816         for i in range (122,149):
817             if w2.Cells(i,23).Value == name:
818                 w2.Cells(i,27).Value = zone_P
819                 w2.Cells(i,28).Value = zone_Q
820                 w2.Cells(i,29).Value = zone_Load
821                 w2.Cells(i,30).Value = zone_Pint
822                 w2.Cells(i,31).Value = zone_Qint
823     for bound in Boundaries:
824         name = bound.loc_name
825         bound_Pint = str(bound.GetAttribute('c:Pinter'))
826         bound_Qint = str(bound.GetAttribute('c:Qinter'))
827         bound_Pex = str(bound.GetAttribute('c:ExportP'))
828         bound_Qex = str(bound.GetAttribute('c:ExportQ'))
```

```
829         bound_Pim = str(bound.GetAttribute('c:ImportP'))
830         bound_Qim = str(bound.GetAttribute('c:ImportQ'))
831         for i in range (101,121):
832             if w2.Cells(i,23).Value == name:
833                 w2.Cells(i,27).Value = bound_Pint
834                 w2.Cells(i,28).Value = bound_Qint
835                 w2.Cells(i,29).Value = bound_Pex
836                 w2.Cells(i,30).Value = bound_Qex
837                 w2.Cells(i,31).Value = bound_Pim
838                 w2.Cells(i,32).Value = bound_Qim
839     for load in Loads:
840       name = load.loc_name
841       if load.outserv == 0:
842         load_P = str(load.GetAttribute('m:P:bus1'))
843         load_Q = str(load.GetAttribute('m:Q:bus1'))
844       if load.outserv == 1:
845         load_P = 0
846         load_Q = 0
847       for i in range (75,97):
848         if w2.Cells(i,23).Value == name:
849             w2.Cells(i,27).Value = load_P
850             w2.Cells(i,28).Value = load_Q
851     for trafo in Trafos:
852             name=trafo.loc_name
853             if trafo.outserv == 0:
854                 trafoloading = trafo.GetAttribute('c:loading')
855             if trafo.outserv == 1:
856                 trafoloading = 0
857             for i in range (296,371):
858                     if w2.Cells(i,23).Value == name:
859                         w2.Cells(i,27).Value = trafoloading
860     for phs in Phs:
861             name=phs.loc_name
862             if phs.outserv == 0:
863                 phsloading = phs.GetAttribute('c:loading')
864             if phs.outserv == 1:
865                 phsloading = 0
866             for i in range (372,379):
867                     if w2.Cells(i,23).Value == name:
868                         w2.Cells(i,27).Value = phsloading
869
870     for grid in Grid:
871             name=grid.loc_name
872             app.PrintPlain(name)
873             gridgenP = str(grid.GetAttribute('c:GenP'))
874             gridgenQ = str(grid.GetAttribute('c:GenQ'))
875             gridLoadP = str(grid.GetAttribute('c:LoadP'))
876             gridLoadQ = str(grid.GetAttribute('c:LoadQ'))
877             gridlossesP = str(grid.GetAttribute('c:LossP'))
878             gridlossesQ = str(grid.GetAttribute('c:LossQ'))
879             for i in range (3,5):
880                     if w2.Cells(i,24).Value == name:
881                       w2.Cells(i,25).Value = gridgenP
882                       w2.Cells(i,26).Value = gridgenQ
883                       w2.Cells(i,27).Value = gridLoadP
884                       w2.Cells(i,28).Value = gridLoadQ
885                       w2.Cells(i,29).Value = gridlossesP
886                       w2.Cells(i,30).Value = gridlossesQ
887
888 #%% Define function to export diagrams from different simulations
889
890 def diagramsLF():
891     oDesk=app.GetFromStudyCase('SetDesktop')
892     diagrams = app.GetProjectFolder('dia')
893     diagramlist = diagrams.GetContents()
894     for diagram in diagramlist:
895         app.PrintPlain(diagram)
896         diagramname = str(diagram.loc_name)
897         oDesk.Show(diagramname)
898         savename = diagrams_path + '\\' + scen.loc_name[9::] + '_' + diagram.loc_name + '_LF'
899         oDesk.WriteWMF(savename)
```

```
900
901 def diagramsOPF():
902     oDesk=app.GetFromStudyCase('SetDesktop')
903     diagrams = app.GetProjectFolder('dia')
904     diagramlist = diagrams.GetContents()
905     for diagram in diagramlist:
906         app.PrintPlain(diagram)
907         diagramname = str(diagram.loc_name)
908         oDesk.Show(diagramname)
909         savename =  diagrams_path + '\\' + scen.loc_name[9::] + '_' + diagram.loc_name + '
    _OPF'
910         oDesk.WriteWMF(savename)
911
912 def diagramsCA():
913     oDesk=app.GetFromStudyCase('SetDesktop')
914     diagrams = app.GetProjectFolder('dia')
915     diagramlist = diagrams.GetContents()
916     for diagram in diagramlist:
917         app.PrintPlain(diagram)
918         diagramname = str(diagram.loc_name)
919         oDesk.Show(diagramname)
920         savename =  diagrams_path + '\\' + scen.loc_name[9::] + '_' + diagram.loc_name  + '
    _CA'
921         oDesk.WriteWMF(savename)
922
923
924 #%% Define whether simulations are run from python, and which results need to be exported
925
926 def simulations():
927         loadflow()                  #execute a load flow
928         # loadflowresults()           #write results to excelfile
929         # diagramsLF()                 #export diagrams
930
931         # optimalpowerflow()          #execute an optimal power flow
932         # optimalpowerflowresults()   #write results to excelfile
933         # diagramsOPF()                #export diagrams
934
935         # contingencyanalysis()       #execute a contingency analysis
936         # contingencyresults()        #write results to excelfile
937         # diagramsCA()                #export diagrams
938
939 #%%% Simulations for 2030
940 # Here the command is given to activate the study case for 2030, set the proper installed
    capacities, reactive power controls and dispatches
941
942 for StudyCase in studycases:
943     if StudyCase.loc_name == '2030 Scenarios':
944         StudyCase.Activate()
945         capacities2030() #set capacities
946
947 OSfolder = app.GetProjectFolder('scen')
948 OS = OSfolder.GetContents()
949 for opscenfold in OS:
950     app.PrintPlain(opscenfold)
951     if opscenfold.loc_name == '2030 Base ABC':
952         sheetname = "Base A,B,C"
953         opscen = opscenfold.GetContents()
954         for scen in opscen:
955             if scen.loc_name == 'Scenario A0':
956                 scen.Activate()
957                 dispatches1()
958                 reactivepowercontrol('Wind')
959                 simulations()
960             if scen.loc_name == 'Scenario B0':
961                 scen.Activate()
962                 dispatches2()
963                 reactivepowercontrol('PV')
964                 simulations()
965             if scen.loc_name == 'Scenario C0':
966                 scen.Activate()
967                 dispatches3()
```

```
                reactivepowercontrol('Both')
                simulations()
    if opscenfold.loc_name == '2030 A1-7':
            sheetname = "A1-7"
            opscen = opscenfold.GetContents()
            app.PrintPlain(opscen)
            for scen in opscen:
                if scen.loc_name == 'Scenario A1':
                    scen.Activate()
                    dispatches1()
                    reactivepowercontrol('Wind')
                    simulations()
                if scen.loc_name == 'Scenario A2':
                    scen.Activate()
                    dispatches2()
                    reactivepowercontrol('Wind')
                    simulations()
                if scen.loc_name == 'Scenario A3':
                    scen.Activate()
                    dispatches3()
                    reactivepowercontrol('Wind')
                    simulations()
                if scen.loc_name == 'Scenario A4':
                    scen.Activate()
                    dispatches4()
                    reactivepowercontrol('Wind')
                    simulations()
                if scen.loc_name == 'Scenario A5':
                    scen.Activate()
                    dispatches5()
                    reactivepowercontrol('Wind')
                    simulations()
                if scen.loc_name == 'Scenario A6':
                    scen.Activate()
                    dispatches6()
                    reactivepowercontrol('Wind')
                    simulations()
                if scen.loc_name == 'Scenario A7':
                    scen.Activate()
                    dispatches7()
                    reactivepowercontrol('Wind')
                    simulations()
    if opscenfold.loc_name == '2030 B1-7':
            sheetname = "B1-7"
            opscen = opscenfold.GetContents()
            app.PrintPlain(opscen)
            for scen in opscen:
                if scen.loc_name == 'Scenario B1':
                    scen.Activate()
                    dispatches1()
                    reactivepowercontrol('PV')
                    simulations()
                if scen.loc_name == 'Scenario B2':
                    scen.Activate()
                    dispatches2()
                    reactivepowercontrol('PV')
                    simulations()
                if scen.loc_name == 'Scenario B3':
                    scen.Activate()
                    dispatches3()
                    reactivepowercontrol('PV')
                    simulations()
                if scen.loc_name == 'Scenario B4':
                    scen.Activate()
                    dispatches4()
                    reactivepowercontrol('PV')
                    simulations()
                if scen.loc_name == 'Scenario B5':
                    scen.Activate()
                    reactivepowercontrol('PV')
                    simulations()
```

```
                if scen.loc_name == 'Scenario B6':
                    scen.Activate()
                    dispatches6()
                    reactivepowercontrol('PV')
                    simulations()
                if scen.loc_name == 'Scenario B7':
                    scen.Activate()
                    dispatches7()
                    reactivepowercontrol('PV')
                    simulations()
    if opscenfold.loc_name == '2030 C1-7':
            sheetname = "C1-7"
            opscen = opscenfold.GetContents()
            app.PrintPlain(opscen)
            for scen in opscen:
                if scen.loc_name == 'Scenario C1':
                    scen.Activate()
                    dispatches1()
                    reactivepowercontrol("Both")
                    simulations()
                if scen.loc_name == 'Scenario C2':
                    scen.Activate()
                    dispatches2()
                    reactivepowercontrol("Both")
                    simulations()
                if scen.loc_name == 'Scenario C3':
                    scen.Activate()
                    dispatches3()
                    reactivepowercontrol("Both")
                    simulations()
                if scen.loc_name == 'Scenario C4':
                    scen.Activate()
                    dispatches4()
                    reactivepowercontrol("Both")
                    simulations()
                if scen.loc_name == 'Scenario C5':
                    scen.Activate()
                    dispatches5()
                    reactivepowercontrol("Both")
                    simulations()
                if scen.loc_name == 'Scenario C6':
                    scen.Activate()
                    dispatches6()
                    reactivepowercontrol("Both")
                    simulations()
                if scen.loc_name == 'Scenario C7':
                    scen.Activate()
                    dispatches7()
                    reactivepowercontrol("Both")
                    simulations()
    if opscenfold.loc_name == '2030 D1-7':
            sheetname = "D1-7"
            opscen = opscenfold.GetContents()
            app.PrintPlain(opscen)
            for scen in opscen:
                if scen.loc_name == 'Scenario D1':
                    scen.Activate()
                    dispatches1()
                    reactivepowercontrol("Both")
                    simulations()
                if scen.loc_name == 'Scenario D2':
                    scen.Activate()
                    dispatches2()
                    reactivepowercontrol("Both")
                    simulations()
                if scen.loc_name == 'Scenario D3':
                    scen.Activate()
                    dispatches3()
                    reactivepowercontrol("Both")
                    simulations()
                if scen.loc_name == 'Scenario D4':
```

```
                    scen.Activate()
                    dispatches4()
                    reactivepowercontrol("Both")
                    simulations()
                if scen.loc_name == 'Scenario D5':
                    scen.Activate()
                    dispatches5()
                    reactivepowercontrol("Both")
                    simulations()
                if scen.loc_name == 'Scenario D6':
                    scen.Activate()
                    dispatches6()
                    reactivepowercontrol("Both")
                    simulations()
                if scen.loc_name == 'Scenario D7':
                    scen.Activate()
                    dispatches7()
                    reactivepowercontrol("Both")
                    simulations()
    if opscenfold.loc_name == '2030 E1-7':
            sheetname = "E1-7"
            opscen = opscenfold.GetContents()
            app.PrintPlain(opscen)
            for scen in opscen:
                if scen.loc_name == 'Scenario E1':
                    scen.Activate()
                    dispatches1()
                    reactivepowercontrol("Both")
                    simulations()
                if scen.loc_name == 'Scenario E2':
                    scen.Activate()
                    dispatches2()
                    reactivepowercontrol("Both")
                    simulations()
                if scen.loc_name == 'Scenario E3':
                    scen.Activate()
                    dispatches3()
                    reactivepowercontrol("Both")
                    simulations()
                if scen.loc_name == 'Scenario E4':
                    scen.Activate()
                    dispatches4()
                    reactivepowercontrol("Both")
                    simulations()
                if scen.loc_name == 'Scenario E5':
                    scen.Activate()
                    dispatches5()
                    reactivepowercontrol("Both")
                    simulations()
                if scen.loc_name == 'Scenario E6':
                    scen.Activate()
                    dispatches6()
                    reactivepowercontrol("Both")
                    simulations()
                if scen.loc_name == 'Scenario E7':
                    scen.Activate()
                    dispatches7()
                    reactivepowercontrol("Both")
                    simulations()
    if opscenfold.loc_name == '2030 F1 G1':
            sheetname = "F1 and G1"
            opscen = opscenfold.GetContents()
            app.PrintPlain(opscen)
            for scen in opscen:
                if scen.loc_name == 'Scenario F1':
                    scen.Activate()
                    dispatches1()
                    reactivepowercontrol("Conv")
                    simulations()
                if scen.loc_name == 'Scenario G1':
                    scen.Activate()
```

```
                    dispatches2()
                    reactivepowercontrol("Conv")
                    simulations()
    if opscenfold.loc_name == '2030 Transit X1-7':
            sheetname = "X1-7"
            opscen = opscenfold.GetContents()
            app.PrintPlain(opscen)
            for scen in opscen:
                if scen.loc_name == 'Scenario X1':
                    scen.Activate()
                    dispatches1()
                    reactivepowercontrol("Both")
                    simulations()
                if scen.loc_name == 'Scenario X2':
                    scen.Activate()
                    dispatches2()
                    reactivepowercontrol("Both")
                    simulations()
                if scen.loc_name == 'Scenario X3':
                    scen.Activate()
                    dispatches3()
                    reactivepowercontrol("Both")
                    simulations()
                if scen.loc_name == 'Scenario X4':
                    scen.Activate()
                    dispatches4()
                    reactivepowercontrol("Both")
                    simulations()
                if scen.loc_name == 'Scenario X5':
                    scen.Activate()
                    dispatches5()
                    reactivepowercontrol("Both")
                    simulations()
                if scen.loc_name == 'Scenario X6':
                    scen.Activate()
                    dispatches6()
                    reactivepowercontrol("Both")
                    simulations()
                if scen.loc_name == 'Scenario X7':
                    scen.Activate()
                    dispatches7()
                    reactivepowercontrol("Both")
                    simulations()
    if opscenfold.loc_name == '2030 Transit NZ1-7':
            sheetname = "NZ1-7"
            opscen = opscenfold.GetContents()
            app.PrintPlain(opscen)
            for scen in opscen:
                if scen.loc_name == 'Scenario NZ1':
                    scen.Activate()
                    dispatches1()
                    reactivepowercontrol("Both")
                    simulations()
                if scen.loc_name == 'Scenario NZ2':
                    scen.Activate()
                    dispatches2()
                    reactivepowercontrol("Both")
                    simulations()
                if scen.loc_name == 'Scenario NZ3':
                    scen.Activate()
                    dispatches3()
                    reactivepowercontrol("Both")
                    simulations()
                if scen.loc_name == 'Scenario NZ4':
                    scen.Activate()
                    dispatches4()
                    reactivepowercontrol("Both")
                    simulations()
                if scen.loc_name == 'Scenario NZ5':
                    scen.Activate()
                    dispatches5()
```

```
                    reactivepowercontrol("Both")
                    simulations()
                if scen.loc_name == 'Scenario NZ6':
                    scen.Activate()
                    dispatches6()
                    reactivepowercontrol("Both")
                    simulations()
                if scen.loc_name == 'Scenario NZ7':
                    scen.Activate()
                    dispatches7()
                    reactivepowercontrol("Both")
                    simulations()
    if opscenfold.loc_name == '2030 Transit WE1-7':
            sheetname = "WE1-7"
            opscen = opscenfold.GetContents()
            app.PrintPlain(opscen)
            for scen in opscen:
                if scen.loc_name == 'Scenario WE1':
                    scen.Activate()
                    dispatches1()
                    reactivepowercontrol("Both")
                    simulations()
                # if scen.loc_name == 'Scenario WE2':
                #     scen.Activate()
                #     dispatches2()
                #     reactivepowercontrol("Both")
                #     simulations()
                if scen.loc_name == 'Scenario WE3':
                    scen.Activate()
                    dispatches3()
                    reactivepowercontrol("Both")
                    simulations()
                if scen.loc_name == 'Scenario WE4':
                    scen.Activate()
                    dispatches4()
                    reactivepowercontrol("Both")
                    simulations()
                if scen.loc_name == 'Scenario WE5':
                    scen.Activate()
                    dispatches5()
                    reactivepowercontrol("Both")
                    simulations()
                if scen.loc_name == 'Scenario WE6':
                    scen.Activate()
                    dispatches6()
                    reactivepowercontrol("Both")
                    simulations()
                if scen.loc_name == 'Scenario WE7':
                    scen.Activate()
                    dispatches7()
                    reactivepowercontrol("Both")
                    simulations()
    if opscenfold.loc_name == '2030 Transit ALL1-7':
            sheetname = "ALL1-7"
            opscen = opscenfold.GetContents()
            app.PrintPlain(opscen)
            for scen in opscen:
                if scen.loc_name == 'Scenario ALL1':
                    scen.Activate()
                    dispatches1()
                    reactivepowercontrol("Both")
                    simulations()
                if scen.loc_name == 'Scenario ALL2':
                    scen.Activate()
                    dispatches2()
                    reactivepowercontrol("Both")
                    simulations()
                if scen.loc_name == 'Scenario ALL3':
                    scen.Activate()
                    dispatches3()
                    reactivepowercontrol("Both")
```

```
                    simulations()
                if scen.loc_name == 'Scenario ALL4':
                    scen.Activate()
                    dispatches4()
                    reactivepowercontrol("Both")
                    simulations()
                if scen.loc_name == 'Scenario ALL5':
                    scen.Activate()
                    dispatches5()
                    reactivepowercontrol("Both")
                    simulations()
                if scen.loc_name == 'Scenario ALL6':
                    scen.Activate()
                    dispatches6()
                    reactivepowercontrol("Both")
                    simulations()
                if scen.loc_name == 'Scenario ALL7':
                    scen.Activate()
                    dispatches7()
                    reactivepowercontrol("Both")
                    simulations()
                if scen.loc_name == 'Scenario ALLX':
                    scen.Activate()
                    dispatches8()
                    reactivepowercontrol("Both")
                    simulations()
    if opscenfold.loc_name == '2030 Transit ALLR1-7':
            sheetname = "ALLR1-7"
            opscen = opscenfold.GetContents()
            app.PrintPlain(opscen)
            for scen in opscen:
                if scen.loc_name == 'Scenario ALLR1':
                    scen.Activate()
                    dispatches1()
                    reactivepowercontrol("Both")
                    simulations()
                # if scen.loc_name == 'Scenario ALLR2':
                #     scen.Activate()
                #     dispatches2()
                #     reactivepowercontrol("Both")
                #     simulations()
                if scen.loc_name == 'Scenario ALLR3':
                    scen.Activate()
                    dispatches3()
                    reactivepowercontrol("Both")
                    simulations()
                if scen.loc_name == 'Scenario ALLR4':
                    scen.Activate()
                    dispatches4()
                    reactivepowercontrol("Both")
                    simulations()
                if scen.loc_name == 'Scenario ALLR5':
                    scen.Activate()
                    dispatches5()
                    reactivepowercontrol("Both")
                    simulations()
                if scen.loc_name == 'Scenario ALLR6':
                    scen.Activate()
                    dispatches6()
                    reactivepowercontrol("Both")
                    simulations()
                if scen.loc_name == 'Scenario ALLR7':
                    scen.Activate()
                    dispatches7()
                    reactivepowercontrol("Both")
                    simulations()
                if scen.loc_name == 'Scenario ALLRX':
                    scen.Activate()
                    dispatches8()
                    reactivepowercontrol("Both")
                    simulations()
```

```
1394    if opscenfold.loc_name == '2030 Transit EW1-7':
1395            sheetname = "EW1-7"
1396            opscen = opscenfold.GetContents()
1397            app.PrintPlain(opscen)
1398            for scen in opscen:
1399                if scen.loc_name == 'Scenario EW1':
1400                    scen.Activate()
1401                    dispatches1()
1402                    reactivepowercontrol("Both")
1403                    simulations()
1404                # if scen.loc_name == 'Scenario EW2':
1405                #     scen.Activate()
1406                #     dispatches2()
1407                #     reactivepowercontrol("Both")
1408                #     simulations()
1409                if scen.loc_name == 'Scenario EW3':
1410                    scen.Activate()
1411                    dispatches3()
1412                    reactivepowercontrol("Both")
1413                    simulations()
1414                if scen.loc_name == 'Scenario EW4':
1415                    scen.Activate()
1416                    dispatches4()
1417                    reactivepowercontrol("Both")
1418                    simulations()
1419                if scen.loc_name == 'Scenario EW5':
1420                    scen.Activate()
1421                    dispatches5()
1422                    reactivepowercontrol("Both")
1423                    simulations()
1424                if scen.loc_name == 'Scenario EW6':
1425                    scen.Activate()
1426                    dispatches6()
1427                    reactivepowercontrol("Both")
1428                    simulations()
1429                if scen.loc_name == 'Scenario EW7':
1430                    scen.Activate()
1431                    dispatches7()
1432                    reactivepowercontrol("Both")
1433                    simulations()
1434    if opscenfold.loc_name == '2030 Transit ZN1-7':
1435            sheetname = "ZN1-7"
1436            opscen = opscenfold.GetContents()
1437            app.PrintPlain(opscen)
1438            for scen in opscen:
1439                if scen.loc_name == 'Scenario ZN1':
1440                    scen.Activate()
1441                    dispatches1()
1442                    reactivepowercontrol("Both")
1443                    simulations()
1444                # if scen.loc_name == 'Scenario ZN2':
1445                #     scen.Activate()
1446                #     dispatches2()
1447                #     reactivepowercontrol("Both")
1448                #     simulations()
1449                if scen.loc_name == 'Scenario ZN3':
1450                    scen.Activate()
1451                    dispatches3()
1452                    reactivepowercontrol("Both")
1453                    simulations()
1454                if scen.loc_name == 'Scenario ZN4':
1455                    scen.Activate()
1456                    dispatches4()
1457                    reactivepowercontrol("Both")
1458                    simulations()
1459                if scen.loc_name == 'Scenario ZN5':
1460                    scen.Activate()
1461                    dispatches5()
1462                    reactivepowercontrol("Both")
1463                    simulations()
1464                if scen.loc_name == 'Scenario ZN6':
```

```
                    scen.Activate()
                    dispatches6()
                    reactivepowercontrol("Both")
                    simulations()
                if scen.loc_name == 'Scenario ZN7':
                    scen.Activate()
                    dispatches7()
                    reactivepowercontrol("Both")
                    simulations()
    if opscenfold.loc_name == '2030 Proposal 1-9':
            sheetname = "Prop1-9"
            opscen = opscenfold.GetContents()
            app.PrintPlain(opscen)
            for scen in opscen:
                if scen.loc_name == 'Scenario P1':
                    scen.Activate()
                    dispatches1()
                    reactivepowercontrol("Both")
                    simulations()
                if scen.loc_name == 'Scenario P2':
                    scen.Activate()
                    dispatches2()
                    reactivepowercontrol("Both")
                    simulations()
                if scen.loc_name == 'Scenario P3':
                    scen.Activate()
                    dispatches3()
                    reactivepowercontrol("Both")
                    simulations()
                if scen.loc_name == 'Scenario P4':
                    scen.Activate()
                    dispatches4()
                    reactivepowercontrol("Both")
                    simulations()
                if scen.loc_name == 'Scenario P5':
                    scen.Activate()
                    dispatches5()
                    reactivepowercontrol("Both")
                    simulations()
                if scen.loc_name == 'Scenario P6':
                    scen.Activate()
                    dispatches6()
                    reactivepowercontrol("Both")
                    simulations()
                if scen.loc_name == 'Scenario P7':
                    scen.Activate()
                    dispatches7()
                    reactivepowercontrol("Both")
                    simulations()
                if scen.loc_name == 'Scenario P8':
                    scen.Activate()
                    dispatches8()
                    reactivepowercontrol("Both")
                    simulations()
                if scen.loc_name == 'Scenario P9':
                    scen.Activate()
                    dispatches9()
                    reactivepowercontrol("Both")
                    simulations()
    if opscenfold.loc_name == '2030 Proposal 10-18':
            sheetname = "Prop10-18"
            opscen = opscenfold.GetContents()
            app.PrintPlain(opscen)
            for scen in opscen:
                if scen.loc_name == 'Scenario P10':
                    scen.Activate()
                    dispatches1()
                    reactivepowercontrol("Both")
                    simulations()
                if scen.loc_name == 'Scenario P11':
                    scen.Activate()
```

```
                dispatches2()
                reactivepowercontrol("Both")
                simulations()
            if scen.loc_name == 'Scenario P12':
                scen.Activate()
                dispatches3()
                reactivepowercontrol("Both")
                simulations()
            if scen.loc_name == 'Scenario P13':
                scen.Activate()
                dispatches4()
                reactivepowercontrol("Both")
                simulations()
            if scen.loc_name == 'Scenario P14':
                scen.Activate()
                dispatches5()
                reactivepowercontrol("Both")
                simulations()
            if scen.loc_name == 'Scenario P15':
                scen.Activate()
                dispatches6()
                reactivepowercontrol("Both")
                simulations()
            if scen.loc_name == 'Scenario P16':
                scen.Activate()
                dispatches7()
                reactivepowercontrol("Both")
                simulations()
            if scen.loc_name == 'Scenario P17':
                scen.Activate()
                dispatches8()
                reactivepowercontrol("Both")
                simulations()
            if scen.loc_name == 'Scenario P18':
                scen.Activate()
                dispatches9()
                reactivepowercontrol("Both")
                simulations()
```

Listing F.2: Code for 2030 Model Simulations