FLEXPOSTS

FLEXIBLE ENERGY POSITIVITY DISTRICTS

Report:

Analyzing the electricity grid around de Zwette Leeuwarden to understand grid congestion and research possible solutions

Deliverable 4.1, 4.2, 4.4, and 4.6

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Disclaimer

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Deliverable D.4: Summary lessons learned from technical perspective in de Zwette demo site

Within this report and the FLEXPOSTS project, the focus is placed on analyzing the Zwette case to better understand grid congestion now and in future growth scenarios, and to analyze the impact of potential solutions. First, the focus will be on potential methodologies and tools that can be used for analyzing current and future grid congestion, as well as the impact of potential solutions, task T3.1. Next, these tools will be used to model the De Zwette area in Leeuwarden to perform a current state analysis, followed by future PED scenarios as part of task T4.1. One of the future PED scenarios will be further developed by adding flexibility to lower the impact on the electricity grid and increase balance, as part of task T4.4. Additionally, the PowerNodes model will be made available for stakeholders and used in stakeholder sessions, as part of task T4.6. Finally, results and conclusions from the scenarios will be discussed, and a general tool will be proposed for performing high-level analysis of grid-congested areas.

D4.1 Local energy balance assessment

Within the energy balance assessment three main scenarios are worked out namely; the reference scenario, describing the current situation; the autonomic growth scenario, projecting current developments towards a future PED; and the planned scenario, where the municipality actively steers the development of the PED.

In the **Reference scenario,** the resulting NLS, and more specifically the fluctuations within it, are not only caused by industry but also in equal measure by the residential areas connected to the Schenkenschans area. Therefore, results indicate that households play a significant role in both creating grid congestion and providing solutions. However, currently there are very few line loading congestion events, and the severity of the congestion is not extreme. Due to the uncertainty in the simulated profiles over this large network, it is probable that there is currently no physical line loading congestion occurring. Which seems logical as line overloading would mean loss of electricity or local blackouts, which would not escape the attention of both Liander and the municipality of Leeuwarden.

However, in the **Autonomous Growth Scenario,** where there is an expected growth in solar PV on rooftops of 400 MW combined with heat pumps, the maximum production of the combined PV installations easily surpasses the capacity of the main station's transformers, leading to grid congestion. Additionally, energy demand throughout the year increases due to the introduction of electric cars and green gas production, leading to grid congestion on the demand side even in summer. This creates situations where, over the course of a single day, there can be congestion on both the production and demand sides. The range of maximum line loading observed is around 0-350% above our physical limit for the solved timesteps, looking at specific components (e.g. Line or power cable loading). The non-converged or unsolvable timesteps by the Pandapower model are likely worse. Timesteps with maximum solar production coincide with the timesteps during which most lines experience congestion. This is likely because within this scenario PV capacity is distributed throughout the entire network. Consequently, all this capacity feeds in simultaneously from all levels of the grid, causing widespread congestion. Therefore, the lines in the network with the worst observed congestion would need to have at least 4,5 times the current capacity.

Within the **Planned Growth Scenario,** there is an expected growth in wind energy to achieve PED and heat is produced using a heat grid. Results indicate that the impact on the electricity grid is less substantial than for the Autonomous Growth Scenario. Still, the increased demand from electric cars substantially increases the demand peaks compared to the Reference Scenario. However, unlike the Autonomous Growth Scenario, for this scenario Pandapower found a solution for every timestep, indicating that the extreme conditions in this system are less severe than in the Autonomous Growth Scenario. During these timesteps, the planned scenario performs relatively well in terms of congestion, whereas the autonomous growth scenario experiences high congestion. The range of maximum line loading observed is around 0-180% above our physical limit and thus less severe than the Autonomous Growth Scenario. For the Planned Growth Scenario, this is the confirmed worst condition, indicating that the capacity of some specific lines should be increased by a factor of approximately 3. Congestion likely occurs during timesteps with relatively lower demand and high wind production or relatively high demand and low wind production. In both cases, congestion mainly occurs in the higher-level lines. The lower-level lines also have relatively higher capacity to handle it due to higher simultaneity assumed at lower levels of the grid. As power flows upward into the network, the higher-level lines, designed with a lower level of simultaneity in mind, experience congestion. The effect of the heat grid and smart EV charging limits the increase in peak electricity demand. Furthermore, in the Planned Growth Scenario, dispersed wind production leads to significantly less congestion. The congestion is concentrated in specific strings that could be reinforced, requiring much less network-wide reinforcement. Without smart charging and a heat network, demand will increase, and there will be times with no wind and high demand, leading to congestion. Results show that the highest number of lines undergoing congestion in one timestep in the Planned Growth Scenario is 14, in contrast to 100 lines in the Autonomous Growth Scenario. One reason for this difference is the way wind is integrated into the network, dispersed through the network in the middle of each string, allowing power to flow in both directions. However, wind generally aligns better with demand than solar, so congestion will likely be less severe than in the Autonomous Growth Scenario. In this case, grid reinforcement or sufficient storage to store wind production and discharge it later to meet demand will be necessary. Ultimately, the chosen system must be based on multiple criteria, considering stakeholder preferences and tolerances.

D4.2 Barriers for implementing PED’s in the Netherlands

Within this report, only the technical barriers for implementing a PED are explored. Other influencing factors including spatial, economic, legal, and social are discussed in other deliverables of the FlexPosts project. Below the main barriers encountered during the Zwette case are listed.

Technical grid capacity: The most obvious barrier for PEDs in the Zwette case is the technical capacity of the electricity grid. The grid was designed based on projected electricity use without considering electric heating and transport options, resulting in the following main barriers:

- The energy transition indicates electrification as a potential solution, increasing demand.
- When increasing local demand and renewable production (e.g. Solar PV, Electric transport, heat pump, electrification of processes) grid capacity at all levels needs reinforcement, from high voltage, middle voltage, to low voltage.
- Grid reinforcements are unlikely to keep pace with the timeline of the energy transition.

Simultaneity factor: Both on the demand and production side, renewable options have a high simultaneity factor, meaning they often operate or are active at the same time. Grid operators used the simultaneity factor to design electricity grids, resulting in the following main barriers:

- Electrification and renewable production often come with a high simultaneity factor.
- The simultaneity factor only occurs at specific times, leading to overdesigning the system for the highest peaks in load.
- High loads originate at the lowest level of the electricity grid, due to the simultaneity factor.

Dunkelflaute: This term requires some explanation, which essentially refers to periods throughout the year when there is almost no solar irradiation or wind available for renewable energy production, combined with potential moments of high demand (e.g., low temperatures) , resulting in the following main barriers:

- Dunkelflautes are difficult to manage as technical options are often already exhausted.
- To manage Dunkelflautes, high capacities of backup power are required.
- With high rates of electrification, the impact of Dunkelflautes will be more substantial.

- Grid congestion will most likely occur during Dunkelflautes as all the demand will need to be transported in from central production or storage facilities (currently often central fossil power plants).

D4.4. Flexibility assessment analysis

Flexibility scenarios: Within the flexibility assessment two future scenarios are explored, where additional storage, smart charging, and peak power production is added to the Planned Growth Scenario. In the **FLEX scenario** energy storage, smart charging, curtailment, and peak power using locally produced biogas will be integrated in the Planed Growth scenario. Additionally in the **FLEX++ Scenario,** Energy savings (e.g. insulation of housing stock) will be included combined with bi-directional charging, thereby using electric transport in the region as local batteries.

Within the Flex scenarios results indicate that using wind production, heat grids, and storage options can ensure almost 80% self-consumption of locally produced electricity, significantly reducing the strain on the central high voltage transportation grid of the Netherlands. While local grid congestion is greatly reduced, it cannot be entirely prevented in some bottlenecks, necessitating grid reinforcement in parts of the electricity grid. However, despite this, there remains a considerable imbalance between the set limits, where grid congestion at lower levels in the electricity system below the main switching station can still occur. This indicates that further research is needed to identify local grid congestion points and plan grid reinforcements or the placement of flexible power sources nearby to mitigate the issue.

Both this scenario and the Flex++ scenario will require an emergency power system to absorb peak demand, which will be necessary for approximately 66 full load hours per year. Additionally, these scenarios anticipate that car owners will charge their vehicles over an extended period, thereby mostly avoiding fast charging.

Flexibility assessment scenario: This analyses focusses on freeing up capacity at the high voltage connection with TenneT for the reference scenario. Within this analysis multiple combinations of batteries/peaking generators and curtailment will be simulated, to determine how much capacity can be freed on the demand or production side and the associated costs per asset/operation.

Results indicate that, battery systems can be effectively utilized throughout the year for both overproduction and demand management. The cost of freeing up capacity at the high voltage connection with TenneT per MW of capacity was around €900K/MW for the production side and €1.46M/MW for the demand side.

The following main lessons learned could be extracted from the reference scenario flexibility analysis:

- It is easier to free up production-side capacity than demand-side capacity. For the same energy project, more capacity is unlocked on the production side than on the demand side, and the cost per MW is lower for the production side.

- Generally, combining technologies leads to lower costs than using only storage. The cost per MW is higher for storage-only projects. This is likely because the usage rate of the additional installed storage capacity to meet the last peak demands is much less cost-effective compared to the initial units of installed storage capacity. Using a different technology to handle the last few peaks of demand makes the first few units of the other technology more cost-effective than the last few units of the storage technology. The system can be incrementally sized to achieve the optimal mix of technologies to free up the most capacity at the lowest cost.

And for the future scenario flexibility analysis:

- Heat grids can help solve grid congestion in the mid to lower voltage grid.

- Using the potential of electric cars as batteries holds great promise; however, there are no guarantees of availability at every moment of the day.

D4.6: Stakeholder engagement

Engaging and including stakeholders in the technical phase of PED design and analysis is not often integrated and utilized, however, it is becoming more and more important, as solutions are often not manageable by one stakeholder. For strong solutions interdisciplinary collaboration is required over multiple disciplines. Also, collaboration and mutual understanding in the beginning of the process will help the continuation of the process. From the process of stakeholder engagement within this technical analysis, vital information was gathered from both the grid operator and the municipality, required for more accurately modelling the Zwette case. Furthermore, stakeholder engagement can broaden as well as deepen the discussion on the topic as new viewpoints are integrated in the analysis itself.

Within the technical scenarios two main process where utilised:

1) For the validation of both the PowerNodes and Pandapower models interactive workshops where organized between the Hanze, Municipality of Leeuwarden and Liander. During this workshops we did a walkthrough the modelling approaches and data used in the analysis.
2) For further understanding of the results from the analysis in the Zwette case and for using the knowledge gained in other potential cases a general model was produced that can be used by third parties. This model was handed over to the municipality of Leeuwarden together with train the trainer sessions.

Project experience indicates that, stakeholder engagement should (also) be part of the technical analysis right from the very beginning, which is advised for all other PED projects or technical analysis in general.

1 Introduction

Positive Energy Districts (PEDs) can play a crucial role in the energy transition for urban areas. Implementing PEDs requires the integration of energy planning into urban planning processes, as well as a committed network of stakeholders from both the public and private sectors. The aim of FLEXPOSTS (FLEXible energy POSitivity districTS) is to develop effective and repliline strategies to enhance the process of establishing PEDs. A major emphasis is placed on engaging stakeholders and developing innovative business models for flexible energy systems. FLEXPOSTS will apply an interdisciplinary approach to integrating energy and urban planning. This approach is demonstrated in two demo sites: Zwette VI (Leeuwarden, the Netherlands) and Aalborg East (Aalborg, Denmark). In these demos, the lessons learned and new insights from research will be translated into practice and vice versa. The specific stakeholders included in this report for the Zwette case include the municipality of Leeuwarden, the grid operator Liander, and the companies active in the Zwette area organized in a buisiness assosiation.

More specifically, Zwette VI focuses on energy system planning issues that hinder further urban development and the application of flexibility. Within this context, the integration of renewable energy and the shift toward electrification in industry, housing, and transport have given rise to grid congestion, where the electricity grid is unable to ensure sufficient capacity for the expansion of demand or new connections for both demand and production. This situation can halt the development of new housing projects, companies, and the growth of existing businesses.

Definition of Positive Energy District (PED): A PED is a complicated definition or approuch where the goal is technically "a defined urban area that generates more energy, particularly from renewable sources, than it consumes on an annual basis" (JPI Urban Europe). From this main definition the folowing elelemns are added to the definition used in this report:

1) A PED is a defined urban area that generates more energy, particularly from renewable sources, than it consumes on an annual basis
2) Within a PED the electricity system is balanced and managed such that peaks in demand or production do not exceed the current or future limits of the electricity grid.
3) Within a PED individual as wel as group efforts are combined to maximise the effective use of the electricity grid.

This definition will be tested in a virtual dynamic system based on realistic data from the Zwette case

Currently, the electricity grid is organized top-down through the use of large electricity plants and a well-developed grid, which, for instance in the Netherlands, largely operates on fossil energy sources (e.g., coal, natural gas) [1], [2]. However, the growing presence of intermittent renewable technologies (I-RE) and the increase in demand in the electricity system necessitate regulatory and reserve capacity and transport capacity to handle variability and limited predictability [1]. Furthermore, studies indicate that load balancing requirements are expected to increase proportionally with growing I-RE production and additional demand [3], [4], [5], [6]. Therefore, the question arises whether it is necessary to adjust the current load balancing system, for instance, from a more central to a more decentralized system, where balance is achieved at a decentralized level close to I-RE production, thereby reducing the impact on the central electricity grid and lowering transport requirements.

It is indicated that decentralized load balancing can help integrate I-RE production, avoid grid expansion, decrease the need for central balancing systems, and reduce dependency on fossil fuels, using three main options: flexible RE production, demand and production side management, and storage. Additionally, the electricity grid can be expanded. **Local flexible RE** production (F-RE) can include biogas from Anaerobic Digestion (AD), where the produced biogas is used for producing electricity on demand. Studies have indicated the possibility of F-RE production, where on-farm biogas storage can provide biogas supply for the generation of balancing capacity [7], [8], [9], [10]. **Demand Side Management** (DSM) is the process of managing energy consumption to [1]optimize availability and planned generation resources, for instance, by shutting off demand in times of low production and vice versa, thereby shifting demand to periods of high production. Power curtailment (PC), or **Production Side Management**, can be used to manage decentralized I-RE overproduction by curtailing peak loads in the grid [11], [12], [13]. Power curtailment is currently only allowed as a measure of last resort to ensure power security. However, curtailment can be a very effective technique to manage voltage rise, and it is deemed necessary with extremely high levels of PV penetration. The **storage of energy** (ST) can be implemented through multiple technologies (e.g., batteries, flywheels, hydrogen), which can store decentralized overproduction from intermittent sources and be utilized in times of demand. Specific storage systems can also absorb fast changes in either demand or intermittent RE production (e.g., clouds passing over solar panels) [14], [15]. Finally, with **grid expansion**, the capacity of the electricity grid (GC) can be increased (capacity of the lines and transformers) to handle higher loads. Currently, this is the most selected option in the Netherlands, as it falls under the legal responsibilities of the DSO [16]. Unfortunately, this option is often expensive, time-consuming, and merely shifts the problem to the national or even international electricity grid.

To determine the potential of a decentralized approach for balancing and reducing grid congestion, the properties of grid congestion must first be better understood from a system perspective, as well as potential solutions for local balancing. Therefore, within this report and the FLEXPOSTS project, the focus is placed on analyzing the Zwette case to better understand grid congestion now and in future growth scenarios, and to analyze the impact of potential solutions. First, the focus will be on potential methodologies and tools that can be used for analyzing current and future grid congestion, as well as the impact of potential solutions, task T3.1.

WP 3: Process innovation, business models and circularity
T3.1: Developing methodologies for implementing PEDs
T3.2: Developing business models and PED implementation strategies
T3.3: Replication Toolkit

Next, these tools will be used to model the De Zwette area in Leeuwarden to perform a current state analysis, followed by future PED scenarios as part of task T4.1. One of the future PED scenarios will be further developed by adding flexibility to lower the impact on the electricity grid and increase balance, as part of task T4.4. Additionally, the PowerNodes model will be made available for stakeholders and used in stakeholder sessions, as part of task T4.6. Finally, results and conclusions from the scenarios will be discussed, and a general tool will be proposed for performing high-level analysis of grid-congested areas.

WP 4: Demo Site Zwette VI, Leeuwarden
T4.1: Assessment of energy demand, generation profiles, and local energy balance
T4.2: Identifying regulatory, structural and technical barriers
T4.3: Identifying existing partnerships and networks at Zwette VI
T4.4: Assessment of the quality of flexibility
T4.5: Developing business models
T4.6: Developing a strategy for implementing PED

Traditionally, the intervention by the electricity grid system operator has been to reinforce or expand the grid. However, other options such as flexible production, demand and production side management, and storage have not been studied in depth. This raises the question:

What are the optimal interventions or combinations of interventions to manage grid congestion, considering different technological options?

This main challenge is being analyzed at the De Zwette demo site, where we aim to quantify the techno-economic impact of various solutions to alleviate grid congestion, while considering regulatory, structural, and technical barriers.

To achieve this, close collaboration is required between local and regional stakeholders. Key stakeholders in this process include the municipality of Leeuwarden, the local grid operator Liander, businesses located in the De Zwette area, and the Energy Campus. The municipality of Leeuwarden acts as the linking pin within this network, actively engaging stakeholders, supporting ideas, and coordinating projects. The DSO Liander is openly collaborating with the FLEXPOSTS partners in the search for solutions to local grid congestion. Additionally, companies in De Zwette are proactively following developments that can create more room on the electricity grid for business growth or new companies to settle in De Zwette.

Furthermore, a better understanding of the dynamics of grid congestion and potential solutions within De Zwette can provide insights into the national problem of grid congestion. This is crucial as the integration of renewable technologies is hampered by a lack of capacity, slowing progress towards the overall goals set for 2050, not only in the Netherlands but potentially in other countries in Europe and beyond. To prevent this, smart and cost-effective solutions must be developed.

2 The Zwette demo site

De Zwette business and shopping park is located on the southwestern side of Leeuwarden (see figure 2.1). It is the largest business park in Friesland, with approximately 400 companies providing around 6,000 jobs. The industrial sectors in De Zwette range from production industry, wholesale, retail, and business services to kitchen stores, hardware stores, and offices. De Zwette is a spacious business park with plenty of water and greenery, centrally located directly on the N31, near the A32.

A special project in De Zwette is the WTC area development, which includes the new FC Cambuur soccer stadium: the Eleven Cities Park. This development will transform the area, creating more dynamics with the addition of shops, catering, offices, and indoor leisure activities. Two new supermarkets have been established, and the new Cambuur Stadium will also house educational facilities (ROC Friese Poort).

The business park is divided into different zones (De Zwette I to VI), each with its own specifications and conditions. There are various locations available in Zwette IV and V. Zwette VI is currently in development (see figure 2.1). There are currently no companies located in De Zwette VI, but construction is expected to begin on this new site in a few years.

(Source: Ondernemend Leeuwarden: https://ondernemendleeuwarden.nl/locatie/bedrijventerrein-de-zwette/).

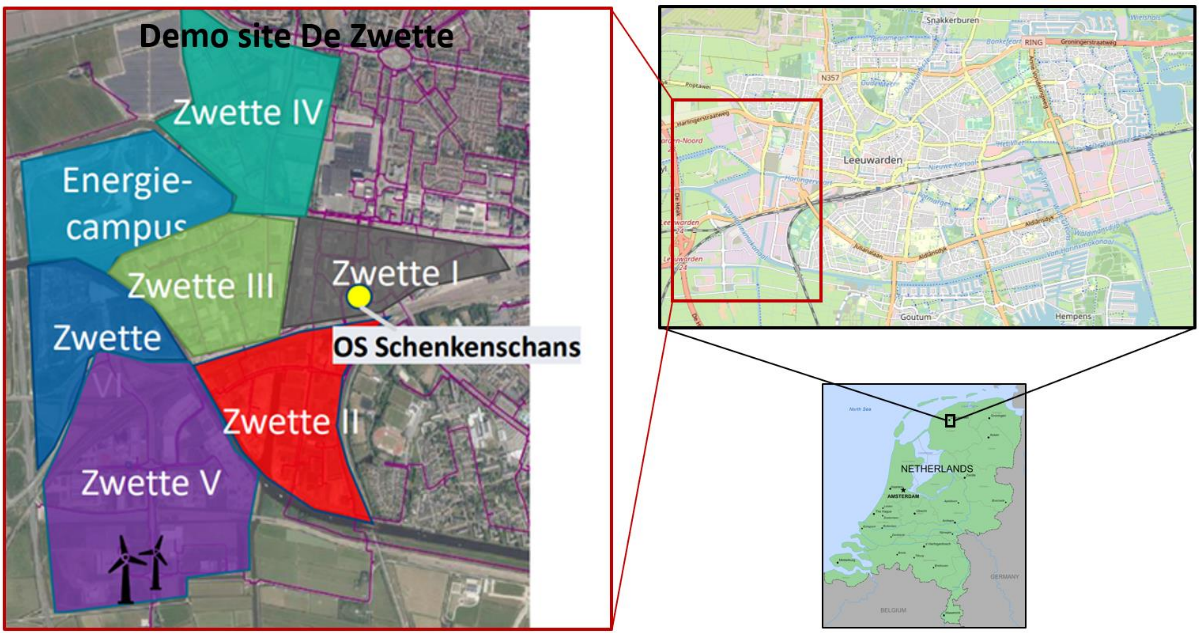

Figure 2.1: Location of the demo site De Zwette

De Zwette also has a sustainability ambition and intends to be an energy-neutral and circular business park by 2035. The Energy Campus has been located in De Zwette since 2019. Here, organizations collaborate on the energy transition through smart cross-pollination between companies, knowledge institutions, and government. There are companies that produce sustainable energy, startups focused on innovations, and close collaboration with knowledge institutions.

The site consists mainly of light, medium, and heavy industry, with mostly small to medium enterprises and a few large consumers of electricity (connections of >400 kW). There is also renewable energy production in the area, with currently 4 MW of installed solar PV capacity on the roofs of the companies. Additionally, solar parks are situated close to De Zwette and connected to the same electricity grid, along with two wind turbines of 0.9 MW each (see Figure 2.2).

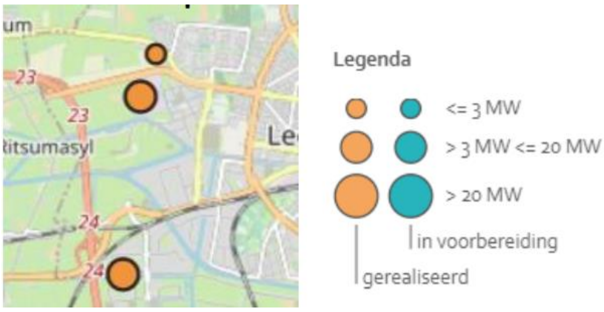

Figure 2.2: Location of large solar parks at the demo site De Zwette

For the future, there are plans to further expand De Zwette, creating space for more industrial development and renewable production. However, recent developments in the area have resulted in congestion of the electricity grid, leaving no room for adding production (or feed-in) and/or demand. Simply put, within an electricity system, electricity can flow in two ways: 1) demand, where electricity flows to a location of demand (e.g., turning on a washing machine, computer, etc.); or 2) feed-in, where electricity flows from a location of production (e.g., overproduction from solar PV on the roof of a house).

In the De Zwette demo site, the specific issue is electricity grid congestion. This local grid congestion is partly caused by the large increase in demand and the non-dispatchable nature coupled with the decentralized production capabilities of solar and wind, which at times result in a large surplus in production and local congestion. This can raise issues such as limits on the number of newly distributed intermittent energy resource projects that can be integrated, the number of new consumers/businesses that can be connected to the grid, and/or the ability of existing consumers/businesses to switch from fossil fuel energy to (renewable) electricity sources. These local constraints can stifle the energy transition.

The electricity system, including De Zwette, starts at the TenneT level or high voltage transport connection at the Schenkenschans substation (see Figure 4). Here, 110 kV is lowered to a mid-voltage distribution system operating at 10 kV and transported to mid-voltage switching systems. From the switching stations, companies can be directly connected at 10 kV, or the electricity is further distributed to low-voltage transformers that finally feed the low-voltage grid used in residential areas at 230 V (see section 3.1 for additional explanation).

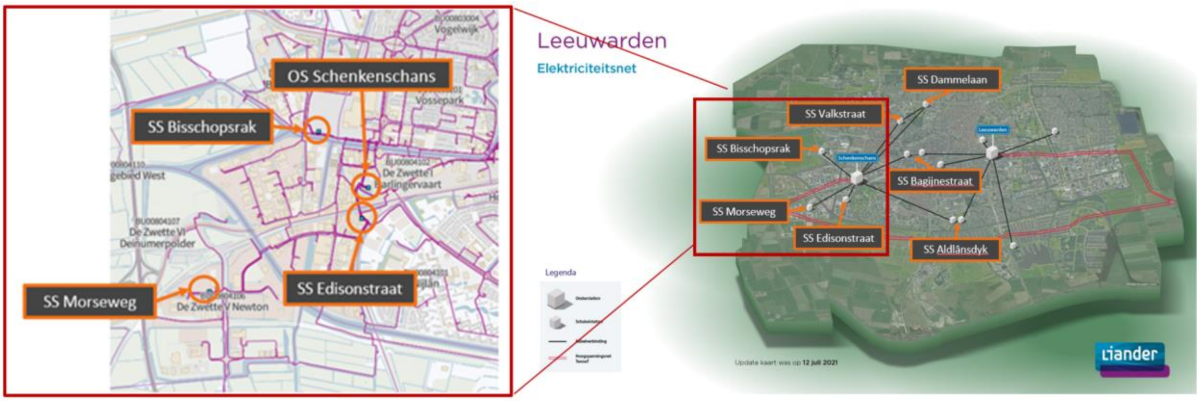

Figure 2.3: Map of de Zwette area with electricity grid and main electricity grid transformation and switching stations in Leeuwarden [16]

3 Deliverable D3.2 Methodology for implementing PEDs

This section will outline the methodologies used for implementing PEDs in FLEXPOSTS (T3.1). The task of developing methodologies for implementing PEDs in the two demo sites has been divided into five sub-tasks that will guide the analyses in the two demo sites. These sub-tasks are:

WP 3: Process innovation, business models and circularity
T3.1: Developing methodologies for implementing PEDs

- **T3.1.1:** Methodology for analyzing the existing energy system and energy balance at the neighborhood level.
- **T3.1.2:** Methodology for developing future energy scenarios.
- **T3.1.3:** Methodology for identifying regulatory, structural and technical barriers for implementing PEDs
- **T3.1.4:** Interdisciplinary and transdisciplinary methodology for synergising energy and urban planning processes at neighbourhood scale.
- **T3.1.5:** Methodology for local stakeholder engagement and establishing local partnerships and networks to support the establishment of public-private partnerships.

In accordance with the comparative approach outlined above, the analyses in each demo site will follow the same methodological guide, while allowing some flexibility in terms of how the analyses are conducted. In this section, we outline the overall methodological approach that will be applied in the Zwette demo site.

Below is an overview (figure 3.1) of the overall approach used within the Zwette demo site, with the main focus on the technical aspects. The first phase is focused on gathering data on the current situation at the Zwette demo site, primarily looking at energy use patterns and the state of the infrastructure. This is followed by the definition of scenarios and the programming of the model. In the final phase, the model is validated, and the outcomes of the scenarios are communicated with the stakeholders in several sessions. This section further discusses the specific methods and expressions used for the Zwette demo site.

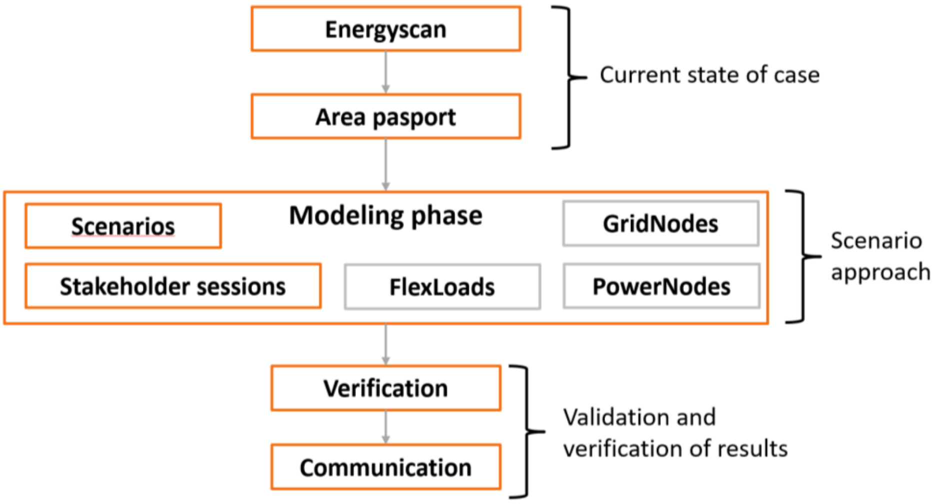

Figure 3.1: The main approach for developing energy scenarios

3.1 System boundary

When looking at the Zwette area from an electricity grid perspective, there is no distinction between industrial and residential areas. Therefore, the main connection to the high voltage grid is taken as the system boundary.

The Zwette is connected to the main switching station of Schenkenschans, also referred to as "onderstation" in figure 3.2, which transforms high voltage (110 kV) to mid voltage (10 kV) for distribution to switching stations, called "schakelstations" in figure 3.2. These switching stations feed the low voltage transformers for domestic use (230 V).

Industries and businesses can be connected directly to the mid voltage grid via a switching station at 10 kV or to a low voltage system at 230 V, depending on the needs of the company. The area indicated by the dotted black line marked with number 1 in figure 3.2 represents the system boundary for this study, including all switching stations, companies, and neighborhoods connected to the main station of Schenkenschans. The area marked with number 2 in figure 3.2 is a planned new industrial area that will need to be connected to Schenkenschans.

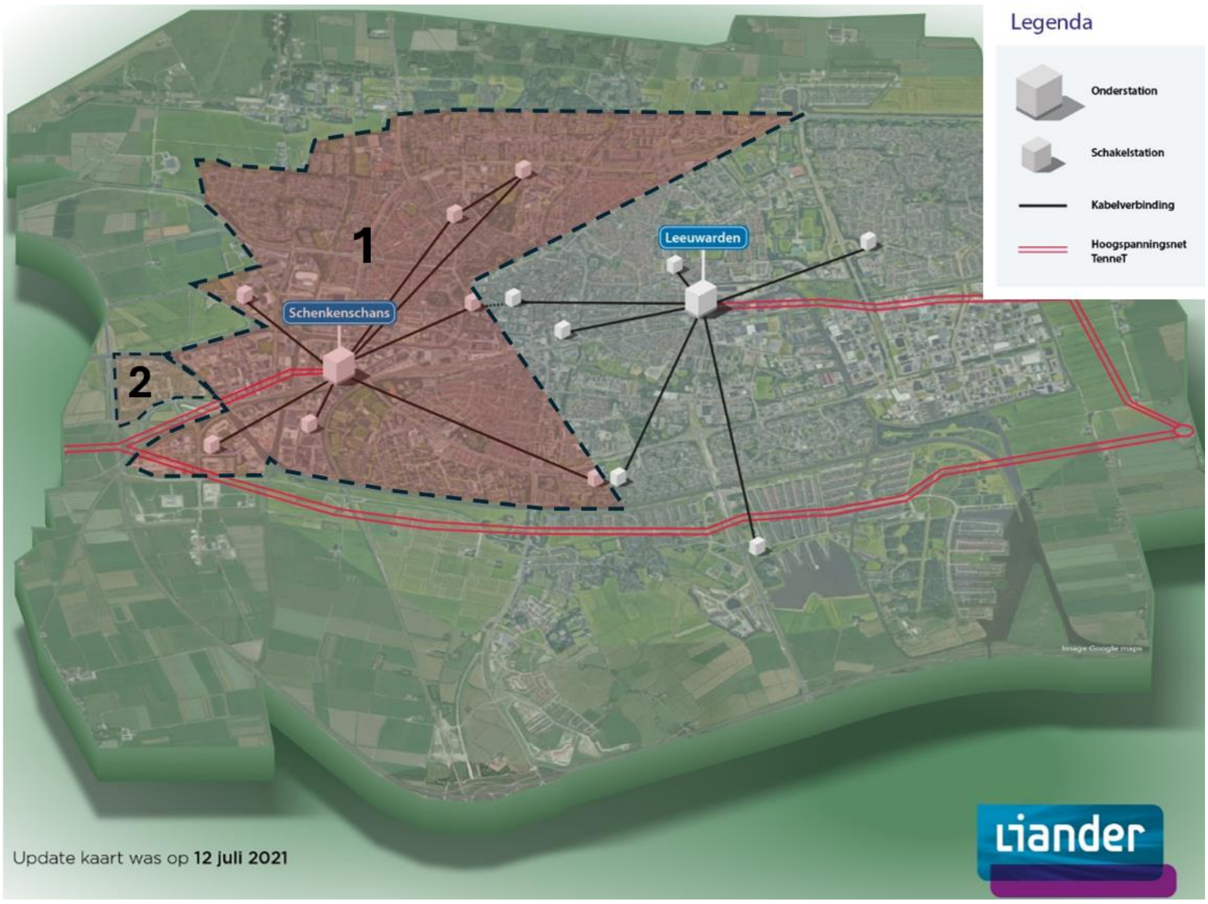

Figure 3.2: The service area of the Schenkenschans station for the city of Leeuwarden [16]

Within the system boundary, the main station of Schenkenschans has three main transformers, of which two are active and one is in reserve (see figure 3.3). The main station supplies multiple substations ("Schakelstations") around the west side of Leeuwarden, including De Zwette. The transformers have a combined capacity of around 62 MVA. However, the connection to the high voltage grid (TenneT) is limited to a lower capacity, as transformers are often over-dimensioned. This limitation is currently one of the reasons for grid congestion in the region. TenneT is currently working on an additional high voltage line and connection to increase the capacity of the high voltage grid. This grid expansion is not included in this research at the moment.

Within this study, two models will be used to analyze the impact of PEDs and possible grid congestion solutions on the electricity grid at two levels: First, the PowerNodes model will focus on the connection point with the high voltage grid, modeling the impact on a specific point in the electricity grid (see figure 3.3). Second, the Panda Power model will focus on the electricity grid below the main connection with the high voltage grid, modeling the strain on the electricity grid (see figure 3.3).

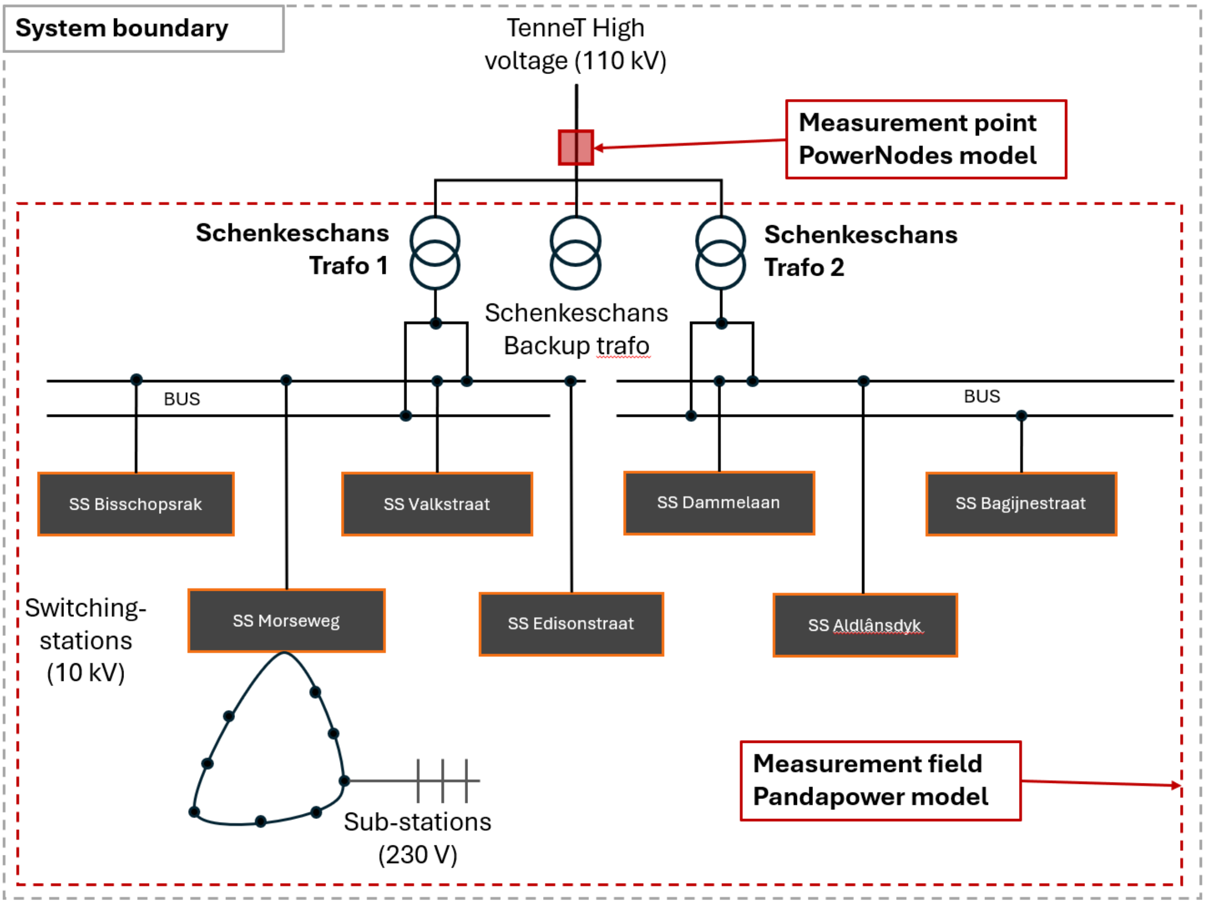

Figure 3.3: The electricity grid structure below the Schenkenschans station

3.2 Method 1: Assessing the current state: the energy scan

In order to develop future scenarios, the current situation within the demo sites must be clearly defined. For this purpose, two methods are used: the Energy Scan method, to map the current energy system, and the Area Passport method, to provide a clear picture of the current energy system.

Energy Scan Method: When developing future PED scenarios, the current situation in terms of energy use, efficiency, and renewable energy production or potentials must be clear and accurate. The Energy Scan (nulmeting in Dutch) collects data on the current situation in a specific area regarding energy transition-related topics, such as energy use, building stock, energy labels, and electricity grid capacity. A clear picture of the current energy system is required to create strong scenarios. The Energy Scan method uses a structured approach for performing a baseline measurement, contributing to the comparability, transparency, and reliability of baseline measurements. The proposed approach consists of five steps, which will be performed mainly through literature study and stakeholder interviews (see Figure 3.4).

1. **Determine the Goal:** Focus on determining the goal of the energy scan and the following scenarios to create a clear picture of the required data and knowledge.
2. **Divide Data into Elements:** Divide the required data into clear elements that can be individually researched or measured, such as current renewable energy production or electricity demand.
3. **Select Methods and Sources:** Select the methods, databases, and sources for gathering data for each element to ensure a transparent data collection process.

4. **Indicate Units:** Clearly indicate the units used to avoid confusion, for instance, between cubic meters of gas, gigajoules of heat, and kilowatt-hours of electricity.

5. **Execute Data Collection:** After defining all previous steps, divide and execute the tasks for collecting the specific elements.

By following this procedure, every Energy Scan will be comparable, transparent, and reliable.

Figure 3.4: The five main steps in the energy scan method for performing a baseline measurement

3.3 Method 2: PowerNodes model

To find possible options for managing grid congestion, a new approach called PowerNodes is used (see Figure 3.5). This approach schematically represents an energy system in an area through a collection of nodes, each representing a specific element (e.g., solar PV park, wind turbine, demand village, etc.). The model can simulate a specific section of an energy grid and calculate the impact on the energy system at a specific point, such as an electricity transformer or a gas hub supplying a business area or neighborhood, based on research (Pierie et al., 2021).

Behind this connection point, a selection of technologies can be simulated, represented by individual Power Nodes. In a Power Node, a separate technology (e.g., wind turbine, solar PV) is described in terms of technical, economic, environmental, and spatial aspects (e.g., energy production per hour, NPV over 25 years, kgCO2eq/kWh, and ha space used) (see Figure 3.5). Each of these individual nodes is a model by itself and can operate independently if desired (e.g., for calculating the business case of a single solar park). This approach allows for adding, removing, or turning off a node without redesigning the model, enhancing flexibility and transparency, as models can be verified individually per node.

The Power Nodes method works on an hourly basis for the energy demand and production elements to include variations in demand and production, such as solar or wind production and demand for electricity and heat over a period of one year. The result of this hourly pattern for a whole year is called the Net Load Signal (NLS), which is the main connection between the nodes in the model (similar to connecting technologies to an electricity line). By combining all sub-modules, the Net Load Signal (NLS) will be the result. If the demand signal is negative, there is still a demand from the national grid at that hour. If the demand signal is positive, there is overproduction, and this overproduction (electricity, natural gas) can be stored or sold.

This model will be integrated into the Excel modeling environment to generate results regarding production, planet, profit, and balance. This method will be used in the demo site De Zwette (T4.1) and the demo site Aalborg East (T5.1).

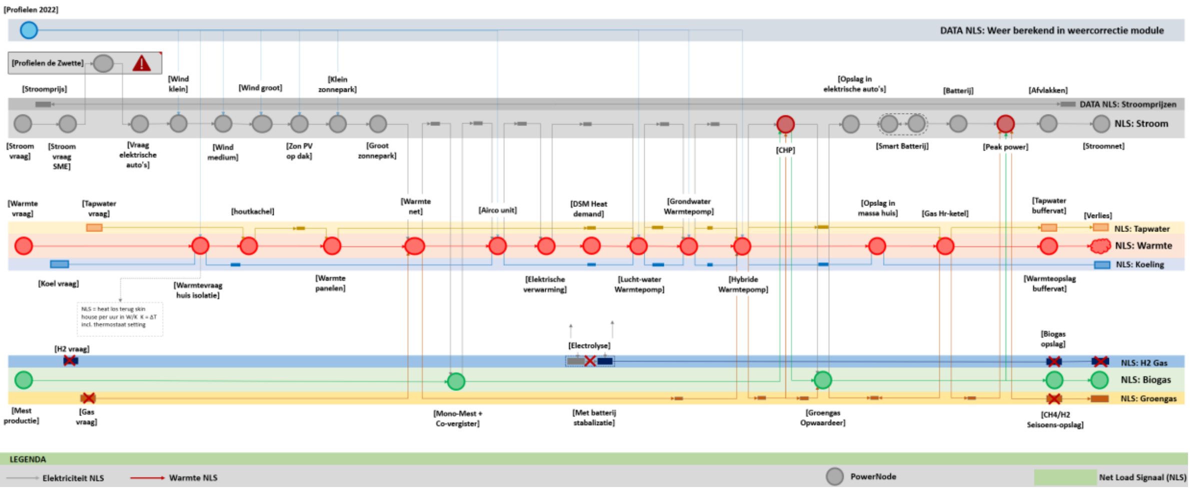

Figure 3.5: Main overview (conceptual model) of a PowerNodes model including legend of elements

3.4 Method 3: Pandapower model

Grid congestion can be a very localized problem that occurs on an object-level basis. To identify where exactly grid congestion occurs in the system, it is necessary to model the specific electricity grid where congestion is happening. For this purpose, the project uses Pandapower.

Electricity grids are complex networks consisting of different component types that are all connected and influence each other. To model such a complex system on an hourly to 15-minute basis and incorporate multiple technological options such as decentralized electricity production, storage, curtailment, and power-to-X, specialist programs are needed to reduce manual work and increase computational speed. The open-source Python module Pandapower is used for this detailed modeling. This program was developed to bridge the gap between commercial and open-source power system analysis tools. The open-source nature is desirable because it allows stakeholders to learn and use the program, ensuring no paywall or entry barrier.

Pandapower is designed to perform static analysis of three-phase power systems, allowing the modeling of transmission, subtransmission, and three-phase distribution systems. Pandapower was validated by comparing all its element and power flow results against DIgSILENT PowerFactory and PSS Sincal, which are high-level commercial packages that ensure high professional standards are met. For more information on Pandapower, see Thurner et al. (2018). This method will be used in the demo site De Zwette (T4.1).

3.5 Methodology for local stakeholder engagement

Local stakeholders will play an active role in developing future energy scenarios for their neighborhoods. To explore future energy scenarios and their different impacts on the demo sites, a spatial approach is proposed. For instance, in Figure 3.6, three possible spatial representations are indicated. First, on the left, the We-Energy Region Tool combined with the We-Energy Game map interface shows the spatial impacts on a physical map using small playing cards that indicate a technology and the space used on the map. On the screen, the model itself indicates the results of the selected scenario.

Additionally, during the technical modeling phase, the Municipality of Leeuwarden and the DSO Liander were actively involved in developing the models and scenarios. These activities can also be seen as specific validation techniques, which are further discussed in section 3.5 of this report.

Figure 3.6: Proposed spatial representation of scenarios

3.6 Expressions used in the methods

From the perspective of Positive Energy Districts, insight in the most important elements require clear and transparent expressions which are comparable between models and scenarios. Within the demo site De Zwette (4.1) the following main indicators are used:

3.6.1 Demand and production indicators (PowerNodes)

- **Demand Mix:** The share of demand types within the area on a yearly basis, indicated as percentages of the total electricity demand of the area (Figure 3.7a).
- **Production Mix:** The share of renewable energy within the area on a yearly basis, indicated as percentages of the total electricity demand of the area (Figure 3.7b).
- **Self-Sufficiency (SS):** Indicates on a yearly base how much demand is filled in by local renewable prodeced electrcity. If SS is 100% this means that on a yearly basis local demand and production are equal see Figure 3.7c. **Self-Consumption (SC)** indicates the amount of locally produced electricity consued directly by local demand Figure 3.7c green part and the electricity exported to the national grd Figure 3.7c grey part.

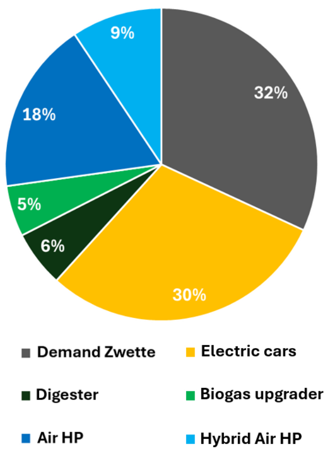

Figure 3.7a: Demand mix

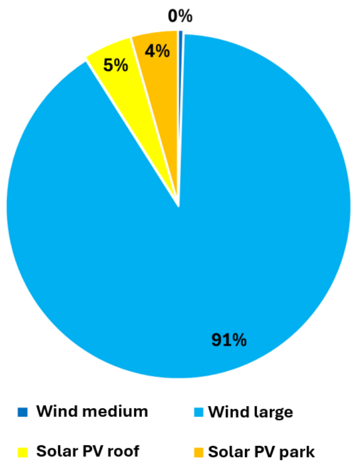

Figure 3.7b: Production mix

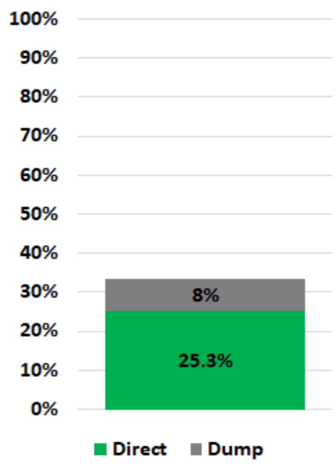

Figure 3.7c: Self consumption and self sufficiency

3.6.2 Net Load Signal (PowerNodes)

The indicator for grid strain is the Net Load Signal (NLS), which indicates the amplitude of the demand (in kW) per hour over a year [3,4]. To indicate both demand and overproduction in the Net Load Signal, the local demand (PD) is subtracted from renewable energy production (PI-RE) per hour, which indicates either overproduction or underproduction (see Equation (3) from Ueckerdt et al., 2015). When the NLS is positive, there is overproduction; when negative, there is demand; and when zero, local production is equal to demand (Figure 3.8).

$$NLS = P_{I-RE} - P_D \quad (\mathrm{kW}) \tag{3.1}$$

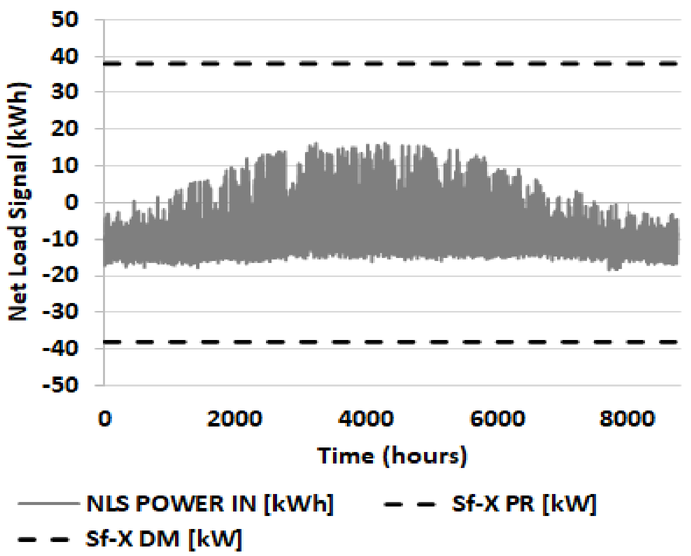

Figure 3.8: Net Load Signal

3.6.3 Net Load Duration Curve (PowerNodes)

The indicator for (im)balance is the Net Load Duration Curve (NLDC), which is based on the Load Duration Curve (NLS). By ordering the NLS from the highest amplitude (overproduction) to the lowest amplitude (demand), an NLDC curve will take shape (Figure 3.9) that indicates overproduction and demand in kW per hour as a function of time, distributed over a year [17]. The NLDC includes multiple indicators:

- *The amount of overproduction or remaining demand as the area above or below zero.*
- *The maximum peak loads and the time in hours per year this occurs.*
- *The hours per year that demand and supply are met.*

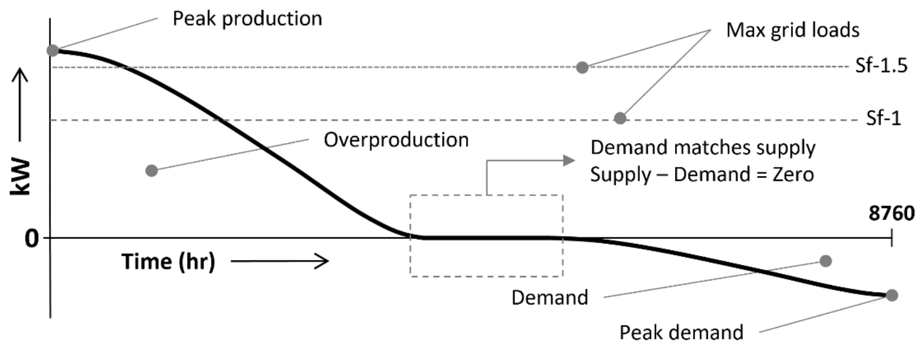

Figure 3.9: Example of NLDC and maximum grid loads based on Sf factors.

3.6.4 Max grid load indicator (Sf) (PowerNodes)

Within the average area, the maximum grid load is defined as "the maximum amount of electricity load that can be accommodated without impacting system operation (reliability, power quality, thermal limits, spatial placement, etc.) under existing control and infrastructure configurations." This is determined by the Distribution System Operator (DSO) using a simultaneity factor (Sf) multiplied by the number of households. The Sf factors are based on historical data and the experience of the local DSO (see Table 3.1) [18].

Definition: The simultaneity factor is a value that represents the fraction of connected electrical loads that are actually drawing power at any given time. It's used to estimate the maximum demand of a group of loads, accounting for the fact that not all devices are operating at their maximum power simultaneously. This factor helps in designing electrical systems by ensuring they are not oversized or undersized, as it considers the realistic load conditions rather than the theoretical maximum.

Additionally, the contracted power rating of the electricity connections from industry can be summed up in a specific area to indicate the required capacity of the electricity grid. When the NLS exceeds the set grid capacity within a section of the grid, steps are required to safeguard the electricity grid, such as shutting down or expanding the grid.

Table 3.1: Simultaneity factors grid.

	Simultaneity Factor (Sf)	Unit	Abbreviation	Source
Old grid pre 1990	1.0	kW/household	L-Sf	[18]
New grid 2012	1.5	kW/household	H-Sf	[18]

3.6.5 Heat map grid congestion (Pandapower)

Grid congestion is a problem that occurs at certain locations in the grid and at specific time periods with varying severity. The indicators used for identifying grid congestion thus have these characteristics.

Location: Each grid component in our model has a name attached to it, indicating its location in the grid.

Time Periods: Congestion occurs at specific times. The model results keep track of the timestamps, identifying the periods when congestion occurs most frequently.

Severity: The output depends on the type of component being considered. Severity can be given for three types of components:

1. **Buses:** The model output is the voltage levels at each bus. Severity is indicated by voltage levels above or below the maximum and minimum allowable voltage levels, given in per unit (pu). The nominal voltage level is 1.0 pu, with an overvoltage limit set at 1.1 pu and an undervoltage limit set at 0.9 pu. Congestion occurs if the power flow results show voltage levels above 1.1 pu or below 0.9 pu. For example, if a bus has a voltage level of 1.13 pu, the severity of the congestion is 0.03 pu. If a bus has a voltage level of 0.88 pu, the severity is 0.02 pu. These values can also be expressed as percentages, with 3% above and 2% below the nominal value, respectively. While voltage indicators are available for all grid simulations, this research focuses more on the current loading of components.

2. **Lines/Lines:** The model output is the current flowing through the line. In Pandapower, each line has a maximum current limit. Severity is given in terms of the percentage of line loading above the maximum current limit. For example, if the line loading is 130%, the severity is 30%.

3. **Transformers:** The model output is the current flowing through the transformer. In Pandapower, each transformer has a maximum current limit. Severity is given in terms of the percentage of transformer

loading above the maximum current limit. For example, if the transformer loading is 130%, the severity is 30%.

Given the relatively large network being modeled, there are many components. To get an overview of the time element of congestion frequency and severity, heat maps are used as indicators of grid congestion. The heat map covers a whole year, with the day of the year on the x-axis and the hour of the day on the y-axis. The intensity of the heat map depends on the chosen characteristic. It can show either the average severity of congestion for a specific day-hour combination or the count of specific components undergoing congestion for each day-hour combination. The heat map can also filter by the types of components and whether the component is feeding into the grid, taking from the grid, or is neutral. To get a complete overview of the severity and frequency, both heat maps need to be considered together.

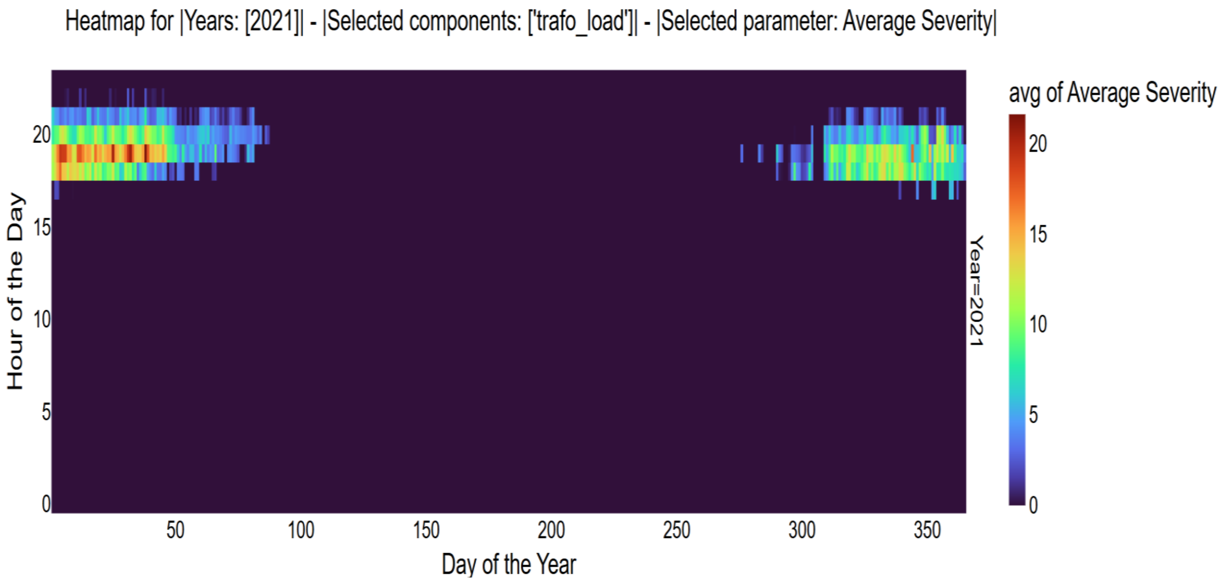

Figure 3.10: Heatmap indicating transformer congestion severity for transformers taking energy from the grid, year 2021.

Figure 3.10 provides an example of a heatmap for 2021. The heatmap show the average congestion severity for each day-hour combination for all known transformers in the network that take electricity from the grid. The colored bar on the side indicates the range of congestion severity by color in percentages. The heatmap indicates that congestion occurs primarily in the first and last two months of the year, around the afternoon/evening.

However, the frequency plot should also be examined to see how often congestion occurs at these time steps. This is shown in Figure 3.11, where the count of congestion events for each day-hour combination is given.

These figures give a summary of the time element of congestion in terms of frequency and severity but not location. For this we use the figures in section 3.6.6.

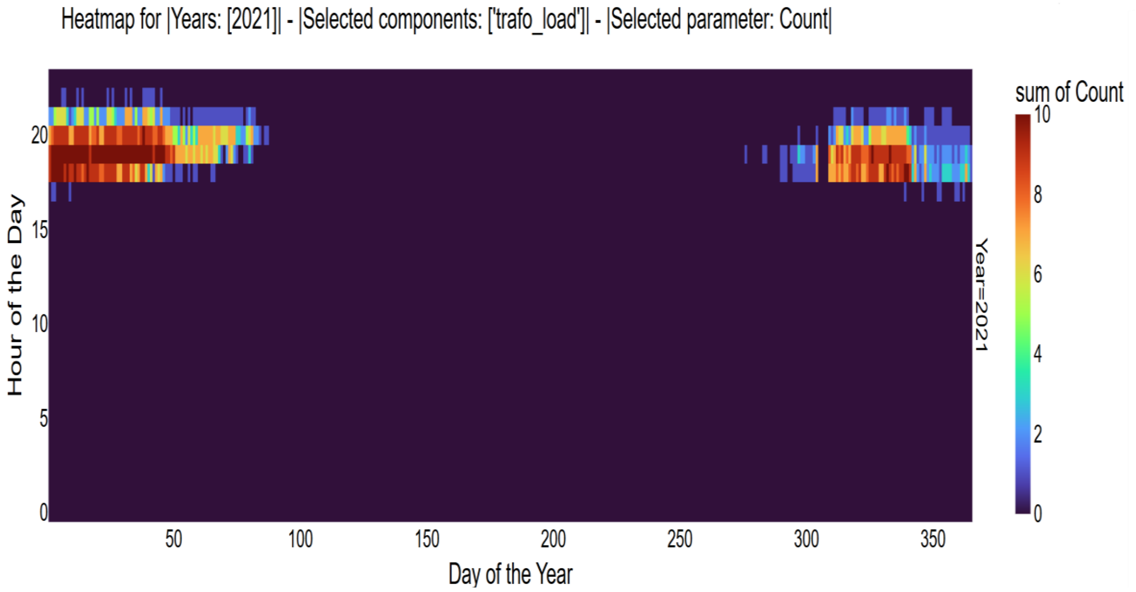

Figure 3.11: Heatmap indicating transformer congestion frequency for transformers taking energy from the grid, year 2021.

3.6.6 Severity and locational grid congestion plots (Pandapower)

The grid model performs a power flow calculation for each timestep in the dataset. Using a network plot, the locational results can be visualized for each timestep based on the power flow results and GIS coordinates in the dataset. This is shown in Figure 3.12 for one timestep. The colored bars on the side indicate the power flow results. Similar to the heatmaps, the results are indicated in terms of voltage or current. For voltage, this is in per unit (pu), and for current, this is in loading percentage. Buses are represented by dots in the network, and transformers and lines are represented by lines in the network. In the dashboard, the network plots are interactive, and information per component is available by hovering over a specific component. The darker red the dots are, the more overvoltage there is, and the darker blue the dots are, the more undervoltage there is. For the lines, the same applies but for current loading percentage. For current loading, there can only be overloading.

The network plot is useful for visualizing congestion for one specific timestep, but when modeling a large dataset, not all timesteps will be examined. To summarize the locational element of congestion severity and frequency, box plots and bar plots are used.

The box plot is shown in Figure 3.13. On the x-axis are the names of the specific components where congestion is taking place over each modeled year. The y-axis shows the percentage loading over the physical limit. The shape of the box plots indicates the distribution of congestion severity for each component. To identify certain sections of the grid where there is more congestion than others, the boxes are colored. The colors represent groupings based on the zone in the grid where the component is located. For Figure 3.13, it indicates most of the congestion occurring in the zone Aldlansdyk (ALDDK), shown in the legend.

As with the heatmaps, the box plot indicating severity must be combined with the bar plots indicating frequency to get a complete overview of congestion. Figure 3.14 provides the bar plot that should be used in conjunction with the box plot in Figure 3.13. The ordering and names on the x-axis are the same as the box plot. To best use the plots, they should be stacked on each other. The y-axis in the bar plot indicates the congestion event count for each component that experienced congestion for each modeled year. These figures show that zone ALDDK had the most different components undergoing congestion. The other two zones have only one component of this specific type undergoing congestion.

These plots provide temporal and locational insights into congestion severity and frequency. Simulating possible interventions and comparing the same plots of those scenarios with a base case can indicate grid congestion relief.

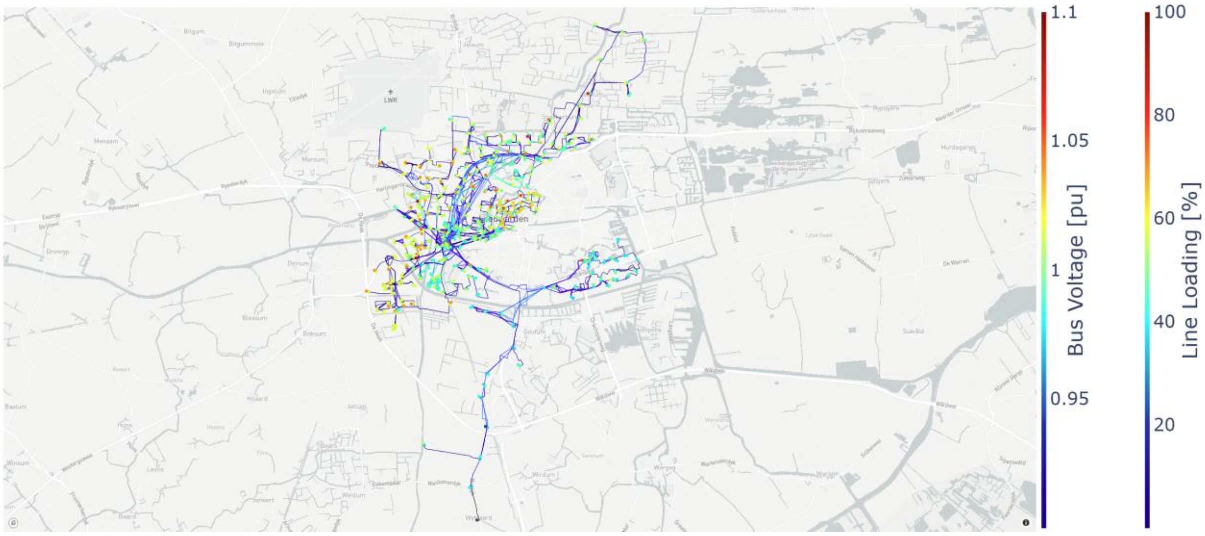

Figure 3.12: Network plot of the part of the electricity grid modelled in this research.

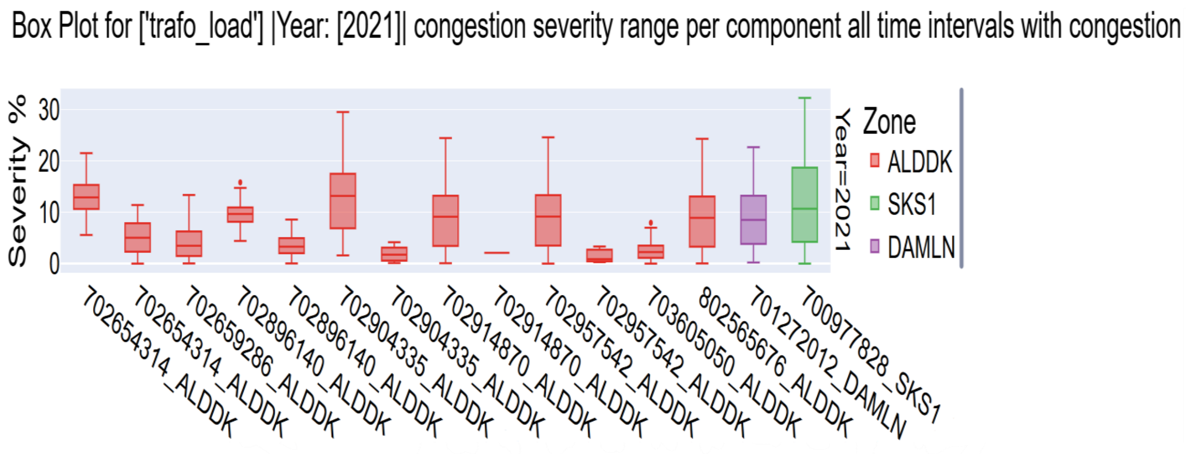

Figure 3.13: Box plots used to indicate the grid congestion severity distribution per component for each year modelled for a certain component type (transformers taking electricity from the grid).

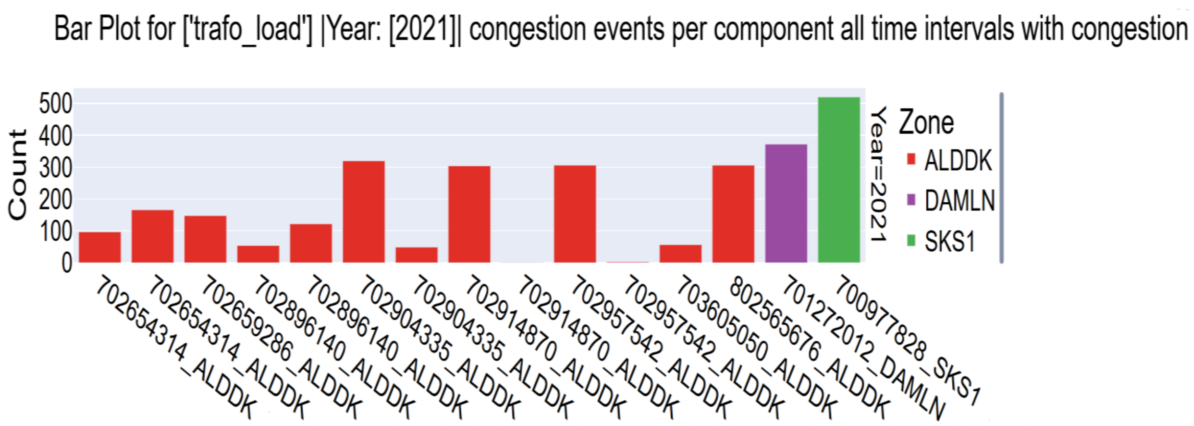

Figure 3.14: Bar plots used to indicate the grid congestion frequency per component for each year modelled for a certain component type (transformers taking electricity from the grid).

3.7 Validation methods

In the validation phase the new modelling methodologies will be verified using multiple validation techniques, retrieved from Sargent, 2013 [19]. The focus points are separated into two main parts. First, the validation will focus on the goal of the model, in order to identify whether the correct model was built for answering the main research questions (*Did I build the right thing?*). Second, the model itself will be verified, through a testing structure, in order to assess transparency and correctness. (*Did I build the thing right?*). The validation and verification (V&V) process will be performed with the help of multiple verification techniques addressing the concept, the overall model, or a particular area of the model.

Definition of validation and verification: Validation confirms that the realized system complies with stakeholder requirements (the right system was built); defined as the 'substantiation that a model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model' [19]. Verification confirms that all elements of the system meet technical requirements (the product was built right) [19] defined as 'ensuring that the computer program, the computerized model, and its implementation are correct' [19].

Validation of concept: Did I build the right thing?: The first step in the overall V&V process will be focusing on the problem entity (Figure) and the conceptual model. When building a model, it is important to keep in mind that most models have the purpose of providing answers to complex issues. From this perspective it is important to start with the right question, and verify your question, or in short: Did I build the right model? To validate this, the concept must comply with the following statements. Does/is the model:

1) Add to scientific understanding or add to societal benefit?
2) Refer to clear answers which can be provided through modelling?
3) Reviewed (e.g., literature review etc.) and verified by experts in the field (e.g., professors, researchers)?

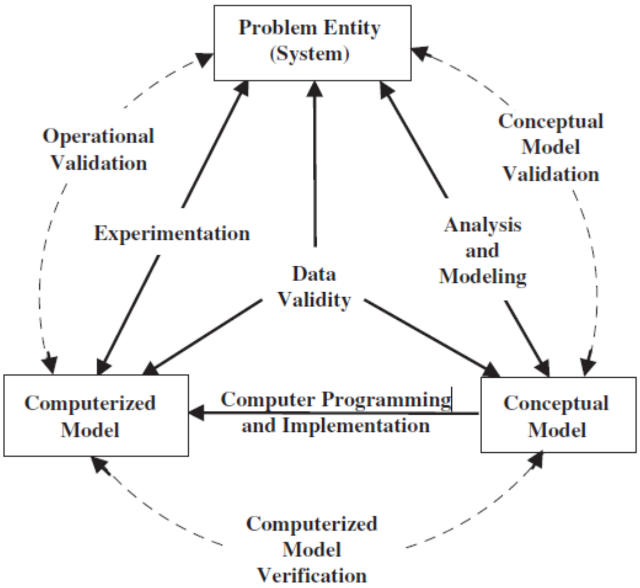

Figure 3.15: Main list of subjects used in the V&V process [20]

Model Verification: Did I build the thing right?

The V&V techniques selected for the models used in both the demo site De Zwette (T4.1) and the demo site Aalborg East (T5.1) are discussed. Most of the techniques described here are found in literature, although some may be described slightly differently to specifically fit the used models. The V&V techniques can be used either subjectively or objectively. Subjectively means common reasoning by the modeler and experts in the field, while objectively means using some type of mathematical procedure or statistical test, e.g., hypothesis tests or confidence intervals (Sargent, 2013b) [19]. A combination of techniques is used within the V&V process, which can be applied to verify individual components within the model and the complete model. The following list of verification techniques is retrieved from Sargent (2013b) [19] for use in this article and in the V&V process of the PowerNodes and Pandapower model:

- Comparison to Other Models: Various results (e.g., outputs) of the simulation model being validated are compared to results of other (valid) models. For example, simple cases of a simulation model are compared to known results of analytic models, and the simulation model is compared to other validated simulation models. Specifically, in this research, the models used in the De Zwette demo site and the Aalborg East demo site with similar functions will be compared with similar inputs, e.g., the PowerNodes and EnergyPlan model, and Pandapower model.

- Data Relationship Correctness: Data relationship correctness requires data to have the proper values regarding relationships that occur within a type of data, and between and among different types of data. For example, are the values of data collected on a system or model correct for some known relationship within some type of data such as an inventory balance relationship or a dollar relationship? The first step is to separate the model from the data and treat data as a separate entity for verification. The data will be checked with similar data and reviewed by experts in the field, e.g., the DSO or municipality.

- Event Validity: The ‘events’ or occurrences of the simulation model are compared to those of the real system to determine whether they are similar. For example, comparing the outcomes of models simulating the electricity grid in the demo site De Zwette (T4.1) and the demo site Aalborg East (T5.1) with real measurements from the DSO or energy-producing companies.

- Face Validity: Individuals knowledgeable about the system are asked whether the model and/or its behavior are reasonable. For example, is the logic in the conceptual model correct, and are the model’s input–output relationships reasonable? The consortium of the FLEXPOSTS project and other JPI-PED project partners, including the expert facility, can provide professional feedback or input on our modeling process and/or used data.

- Parameter Variability–Sensitivity Analysis: This technique consists of changing parameters in the model to determine the effect upon the model's behavior or output. The same relationships should occur in the model as in the real system. This technique can be used qualitatively—directions only of outputs—and quantitatively—both directions and (precise) magnitudes of outputs. Those parameters which are deemed sensitive because of significant changes in the model's behavior or output should be made sufficiently accurate prior to using the model. (This may require iterations in model development.) This technique will be continuously used during the scenario modeling process in the demo site De Zwette (T4.1) and the demo site Aalborg East (T5.1) to verify outcomes of the models and indicate sensitive variables or data requiring additional scrutiny.

4 Data used in research Zwette case

For the methods and models used in the research, certain data inputs are needed. The sections below provide an overview of the different types of data and the specific data used in the research.

4.1 Weather data

As we are modeling a system in the city of Leeuwarden, weather data from the weather station in Leeuwarden (station number 270) of the Royal Dutch Meteorological Institute (KNMI) was used. The data includes Global Horizontal Irradiance (GHI) (W/m²), ambient temperature (°C), and wind speed (m/s). The data is provided at an hourly resolution and is primarily used to simulate solar and wind energy production. The data used corresponds to the years for which other data was acquired, namely 2021 and 2022.

4.2 Liander data

As the DSO, Liander is responsible for the functional operation of the medium voltage electricity grid in De Zwette and possesses all the data pertaining to the grid's operation. Liander provided some of this data for the research. For the power flow simulations, the most important data included the network configuration of the part of the grid under study, along with the specific technical details of all the important components in the grid.

The network configuration essentially details which component is connected to which component in the network. The technical details varied per component type. For example, lines required details such as lengths, resistances, reactances, capacitances, and maximum thermal currents. Other components, such as transformers and buses, required different levels of detail. Aside from the network configuration and component technical details, Liander's network data also included other information. Based on stakeholder meetings with Liander, it was determined that they use this additional data in their grid modeling simulations. Thus, this data was also used in the simulations for this research. This data included details per node in the network, such as peak active power (MW), peak reactive power (MVAR), peak apparent power (MVA), power factor, simultaneity factor, the amount of production capacity per technology type installed at the node (kW), the contracted capacity to consume from the grid (kW), and the contracted capacity to feed into the grid (kW).

Other data provided by Liander included the aggregated net load signal of certain components in the grid. These included the net load signal of the large transformers (medium voltage to high voltage) in the system OSSKS1 and OSSKS2, as well as the net load signals of certain switching stations (MRSWG, BSSRK, BAGYN, and EDSON) and certain routes (a route is a connection of multiple nodes and strings that connect to a switching station) in the grid. This data covered the two years modeled and was provided with a 15-minute resolution.

4.3 Company data

De Zwette is an industrial business park with a wide variety of business types. For modeling and simulation, using actual company data is desirable because it minimizes uncertainty in modeling. Different business types can have very different energy use profiles depending on their characteristics and the processes they operate, which can be difficult to model accurately. As a first principle, the research was carried out to be as data-driven as possible, with modeling and simulation employed only when no data was available.

Kenter, the metering subsidiary of Liander, has the energy profile data of all the businesses with a large user connection (GVB) and their own transformer. For this research, the company had to give Kenter permission to deliver their data for use in the research. The municipality of Leeuwarden undertook this task and collected permission from all the GVB companies willing to contribute their data to this research. Out of a total of 114 GVB connections, 26 gave permission. The data was provided at a 15-minute resolution and covered the years 2021 and 2022.

4.4 Energy profiles and patterns

For users in the grid without measured data, their profiles needed to be simulated. For users with small user connections (KVB), it was assumed that these are mostly residential users. Generally, residential users have comparable energy consumption profiles. Therefore, the generalized residential profiles for the Netherlands for the specific modeled years were used to generate profiles for all KVB connections, specifically the MFFBAS profiles [1]. These profiles are based on multiple years of data for different types of consumers and are temperature-corrected for the specific years.

In addition to the generalized residential profiles, one of the modeled scenarios included the implementation of a heat grid in the system. For the energy consumption of the heat grid, the consumption profile of a heat grid in Groningen was used.

Within this report, the residential electricity demand within the Zwette area per year is determined by the number of houses in the region (Nh) and the average electricity consumption per household (Q_{Ave}). Hourly fluctuations in demand are incorporated using an hourly profile for households based on MFFBAS (Home - MFFBAS). This pattern includes seasonal changes in demand, such as the availability of natural light, weather conditions, and national holidays, based on historical data over the past years. The yearly demand for electricity (P_D) is calculated by multiplying the number of households by the consumption per household (Q_{use}). The load profile is calculated by multiplying the yearly demand for electricity (P_D) by the hourly profile (pAve) (Eqs. 4.1).

$$P_D = Q_{Use} \times N_H \ (kWh/a) \quad \textit{Where} \quad P_{Load\,(0-8760)} = P_D \times p_{Ave\,(0-8760)} \ (kW) \qquad (4.1)$$

5 Models used in research Zwette case

To model the energy system of the Zwette case, two specific models were used. Namely Pandapower and PowerNodes The following sections details the procedure followed when using these models.

5.1 Pandapower

See Section 3.2, Method 2: Electricity Grid Simulator Pandapower, for a general overview of the Pandapower model or refer to the package documentation for specific details (pandapower - pandapower). This section provides an overview of the process used in this research to identify possible congestion using Pandapower. The starting point is to generate a base case using the data collected as outlined in Section 3.1, Method 1: Assessing the Current State: The Energy Scan. Figures 5.1 and 5.2 highlight the process to determine congestion and simulate future scenarios/possible solutions. Figure 5.1 illustrates the process for determining the base case, while Figure 5.2 shows the process for running a new scenario. The process can be divided into three parts, indicated by the blue arrows on the left in the figures:

1. **Database**: In this part, all the nodal energy profiles needed to run a power flow simulation are prepared based on the acquired data. The quality of the profiles is divided into different categories based on the uncertainty of the profile, as indicated by colors in Figure 5.1. Dark green represents the highest quality profiles, which are based on measured data. These are the measured profiles of companies acquired by the municipality and require no simulation.
   The light green category includes simulated profiles with a lower uncertainty factor due to the characteristics of the profile. These include the KVB connections, which are assumed to be mostly residential consumption and thus follow the generalized residential profile. Other profiles in this category include distributed renewable energy production at nodes where the installed capacity is known based on Liander data. For example, the PV capacity at certain nodes with no measured data is known, so the PV production is modeled using irradiance data and the PowerNodes model. This modeled production is allocated to the node. As the models in PowerNodes have been validated, the uncertainty is deemed low. The same applies to wind production.
   The yellow category includes the remaining profiles for which there is no measured data and no simulation possibility that can be considered to have low uncertainty due to their characteristics. These are mostly the consumption profiles of GVB connections. These profiles are allocated based on energy balances set up over different components higher up in the network, such as switching stations and HV-MV transformers. This is shown in the figures as all profile categories equal the measured profiles' total power grid. By subtracting the measured and simulated profile categories from the aggregated higher-level profiles, a 'rest profile' is obtained. This aggregated rest profile is allocated over all remaining nodes for each energy balance in the network according to a ratio based on data attributed to each node by Liander. There is a ratio for the net consumption and net production of the aggregated profile. For example, the ratio for the consumption part of the profile is determined as follows:

$$ratio\ consumption_i = \frac{simultaneity\ factor_i \times peak\ apparent\ power_i}{\sum_i^n simultaneity\ factor_i \times peak\ apparent\ power_i} \quad \text{[eq. 5.1]}$$

   With the subscript indicating a certain node i and n being the total number of nodes, the fraction is then multiplied by the aggregated rest profile to allocate the consumption part of the specific node. The same procedure is repeated for the production part of the rest profile. Here, the ratio is determined based on the installed production capacity at the node over the total non-simulated installed production capacity within the energy balance. In this case, certain nodes had CHPs installed. If there is still production in the rest profile after accounting for all intermittent production via simulations, the production is attributed to the CHPs, up to their installed capacity limits. If all production is accounted for up to their limits, then the unknown production is allocated over all nodes based on their consumption ratio. This is done to evenly distribute the uncertainty over the network.

The red category indicates faulty data points in profiles, which are filtered from the dataset. These are mostly measured data that have been analyzed and identified as measurement errors. All timestamps for which such measurements have been detected are removed from every nodal profile in the dataset.

All the individual nodal profiles are saved in the same file, indicated by the blue diagonal block, and are part of the input for the next part.

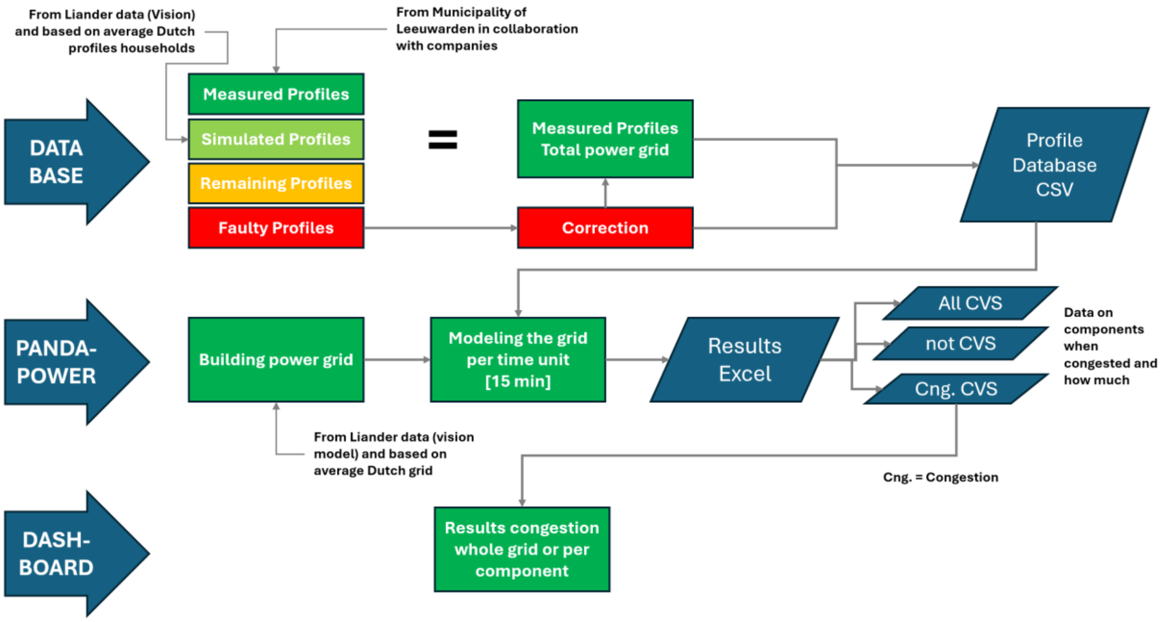

Figure 5.1: The process of generating a powerflow simulation using the Pandapower model for the base case scenario.

2. **Pandapower:** In this part, the grid is built in Pandapower using the network configuration data and component technical details provided by Liander. For the base case, a simulation is conducted for the entire time series, which spans two years and is corrected for measurement errors with a 15-minute resolution. The Pandapower grid, indicated by the dark green block, is fed with the nodal profile data generated in the previous step. For each timestep, a power flow result file is generated in Excel and CSV formats. The results are grouped into time steps with congestion and without congestion, indicated by 'cng.CSV' and 'not.CSV' on the right side in the middle of the figures.

3. **Dashboard:** From all the power flow results, the expressions indicated in Section 3.5.5 (Heat Map Grid Congestion) and Section 3.5.6 (Severity and Locational Grid Congestion Plots) are generated based on inputs chosen on an interactive dashboard. These provide the temporal and locational elements of the congestion severity and frequency in our system.

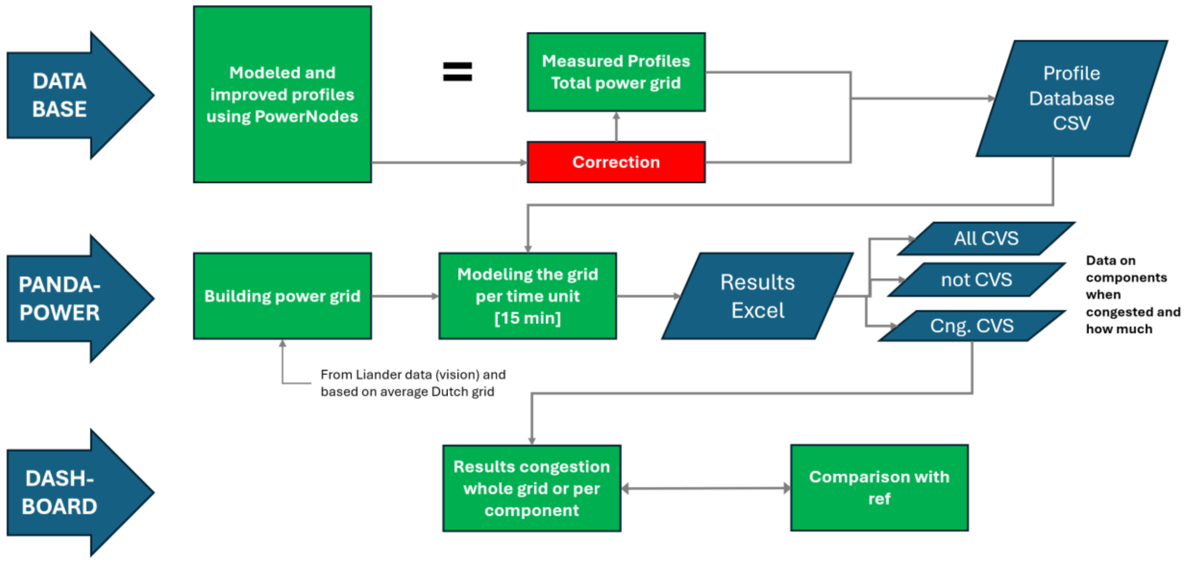

Figure 5.2: The process of generating a powerflow simulation for a new scenario using pandapower and comparing with our reference scenario.

Figure 5.2 shows the process when running a scenario that is not the base case. The steps are the same, but with two slight modifications:

1. **Input Profiles**: The input profiles are changed based on the type of scenario. These changes are simulated using PowerNodes. For example, in a scenario where it is assumed that all houses install solar panels to become PED, the production of the panels is simulated in PowerNodes. The production profiles are then added to the base case nodal profiles, leading to a profile database specific to the scenario. Each new scenario thus has its own profile database, depending on the technologies added in the scenario. The Pandapower step remains the same.
2. **Dashboard**: In this part, the expressions of the new scenario are compared to the base case scenario to see how the changes implemented in the scenario affect the grid. If there are more congestion events, the scenario leads to more problems. Conversely, if there are fewer congestion events, the scenario can contribute to congestion relief.

5.2 PowerNodes

PowerNodes is an Excel-based "what-if" model that allows for the analysis of an energy system on an hourly level. The model can be compared to a multimeter, which measures current or voltage at a specific point in the electricity grid. PowerNodes can measure the energy of a multi-commodity energy system (e.g., power, heat, green gas, biogas) at a specific point (Figure 5.3). Often, this point is geographically selected, such as a transformer or gas delivery station for a neighborhood or village.

In the case of the De Zwette demo site, the specific measuring point is the connection of the Zwette region to the high voltage transformers (10 kV to 110 or 280 kV). At this specific measurement point, the PowerNodes model can simulate current and future energy demand for multiple energy carriers (e.g., power, green gas, heat) by using relative patterns (e.g., MFFBAS, Section 4.3) or actual measurements (e.g., Section 4.2). Furthermore, the model can include renewable production (e.g., solar and wind based on weather data, Section 4.1), flexible production (e.g., biogas CHP), storage options, and demand and production side management. Within this context, the model provides insights into future developments and their impact on the energy system.

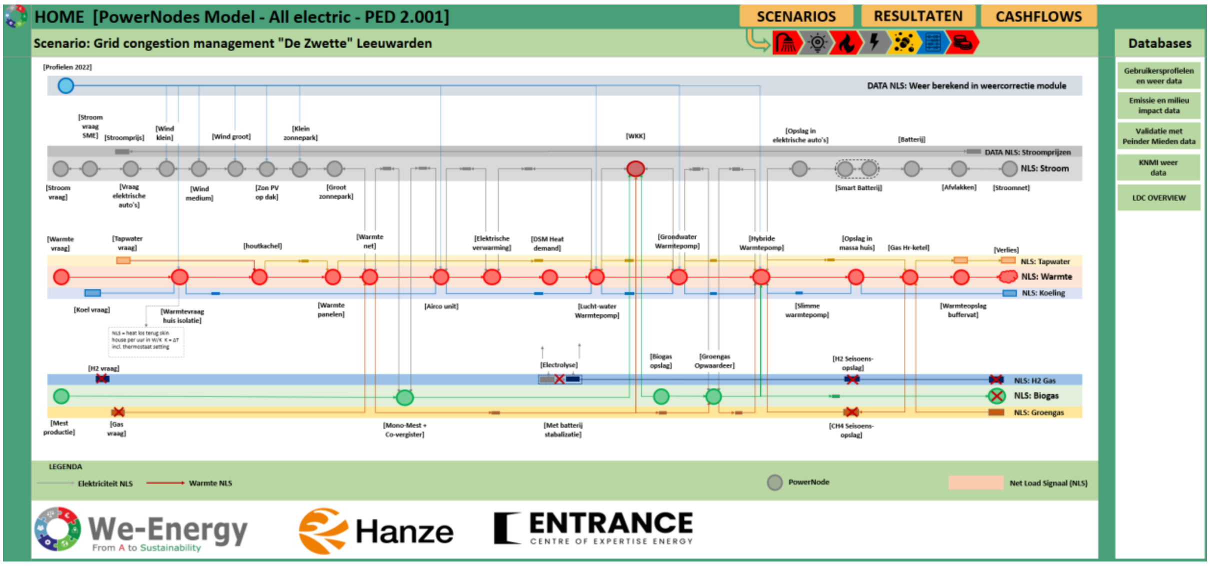

Figure 5.3: An overview of the PowerNodes model layout, with the specific measuring points of the energy system as the right most block.

5.2.1 PowerNodes scenario planner

The PowerNodes model includes a scenario planner that guides users through the process of entering the necessary information step by step. The required information includes:

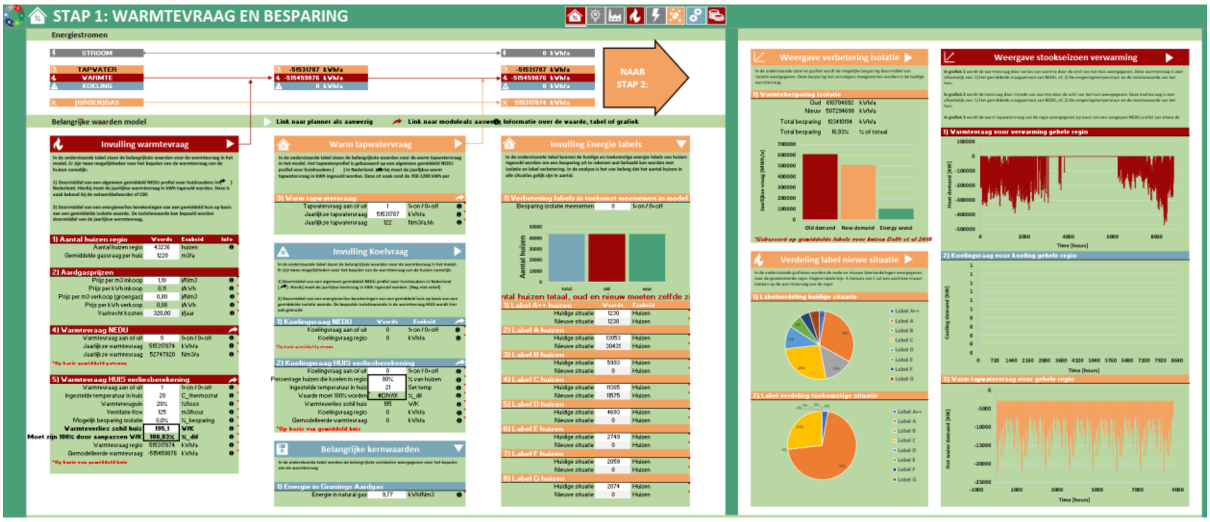

Figure 5.4: An overview of a PowerNodes scenario planner, specifically the heat demand planner.

1. **Heat Demand Planner**

- **Yearly Heat Demand in the Region:** Enter the total yearly heat demand in the region into the model. This demand is transformed into an hourly profile using an energy loss calculation that considers the average insulation value of houses and local outside temperature data.
- **Yearly Hot Water Demand in the Region:** Enter the total yearly hot water demand in the region into the model. This demand is transformed into an hourly profile using an average hot water demand profile based on MFFBAS (section 4.4).
- **Yearly Cooling Demand in the Region (Not Used):** Determine the total yearly cooling demand in the region using an energy loss calculation that considers the average insulation value of houses and local outside

temperature data. By setting an inside temperature, the model calculates the required cooling demand to maintain the set temperature.

2. **Power Demand Planner**

- **Yearly Domestic Power Use:** Enter the total yearly electricity demand in the region into the model. This demand is transformed into an hourly profile using an average electricity demand profile based on MFFBAS (section 4.4).

- **DSO / Measured Data:** Fill in measured profiles of actual transformers or stations within the model (section 4.2). Correctly measured data is generally more accurate than average modeled profiles like MFFBAS.

- **Electric Cars:** Integrate electric cars into the model by entering the total number of cars in the region. The model uses average E-laad profiles to generate a charging pattern, which is not managed to lower the impact on the electricity grid.

3. **Heat Production Planner**

- **Heat Production:** Indicate the percentage of heat demand met by specific technologies in the model. For the Zwette case, these technologies include a heat grid (based on Warmtestad Groningen, including heat pumps, waste heat, ATOS, solar thermal, and backup gas boiler and CHP), air source heat pumps, hybrid air source heat pumps, and high-efficiency gas boilers. Fuel sources for heat production include electricity (e.g., heat pumps) or green gas/biogas (e.g., boilers).

- **Heat Storage:** Integrate a more stable production option for heat pumps combined with floor heating, based on a 12-hour average production balanced with the storage capacity of the floor heating system.

4. **Power Production Planner**

- **Power Production:** Fill in power production by specific technologies in the model. For the Zwette case, these technologies include solar PV roofs, large PV parks, medium and large wind turbines, and peak power production using CHP and biogas. The model uses weather data to calculate the output of solar and wind technologies. Additionally, peak power can be programmed to activate at certain demand loads in the grid.

- **Storage:** Include multiple storage systems in the model, ranging from normal storage (focusing on matching demand and supply), congestion storage (safeguarding the electricity grid and preventing overcapacity on lines), and electric car storage (using part of the capacity of available electric cars to aid in other storage options). The options are defined by storage capacity and charge/discharge power, with the model determining storage utilization based on the power demand profile.

- **Curtailment:** Switch off specific energy sources during overproduction or grid congestion periods. The curtailment option allows production to be switched off by setting a specific load above which production is halted.

5. **Green Gas Production Planner**

- **Biogas Production:** Fill in biogas production using anaerobic digestion in the model. For the Zwette case, these technologies include mono manure or waste materials. The produced biogas is determined by the number of cows in the area or the availability of waste materials (e.g., roadside grass, natural grass).

- **Combined Heat and Power (CHP):** Use biogas directly in a CHP unit for producing heat and power or for producing power during high electricity demand or local grid congestion. Enter the specific capacity of the unit in the model, and program the CHP to run constantly or adjust to current power demand.

- **Green Gas:** Upgrade biogas to green gas (or gas with natural gas quality) to replace current or future gas demand (e.g., high-efficiency boilers, hybrid heat pumps, or CHP units). Indicate the percentage of biogas converted to green gas in the model (often the remaining biogas is upgraded to avoid losses).

6 Scenario's used in research Zwette case

For the De Zwette demo site, the main approach outlined in section 3.1 will be followed, incorporating a variety of approaches, methods, and tools (Figure 3.1). First, the current state of the De Zwette demo site will be analyzed using the Energy Scan and Area Passport methods. Next, scenarios will be developed to understand current grid congestion, assess the impact of future PED implementation on the grid, and explore ways to alleviate existing grid congestion. Throughout the research process, the main scenarios will be further refined in collaboration with the stakeholders connected to the De Zwette demo site. The following main scenarios have been identified:

6.1 Energy balance reference scenario

The reference scenario will map the current situation of the electricity grid in De Zwette demo site using the Current state analysis, PowerNodes and Pandapower methodologies. This scenario is linked to task T4.1 Assessment of energy demand, generation profiles, and local energy balance. The area will be mapped looking at general features using the Energy Scan and Area passport e.g. number of companies, households, installed RE production, available infrastructure etc. PowerNodes will be used for simulations of renewable energy production and energy demand profiles. The electricity grid will be visualized indicating locations of possible grid congestion using Pandapower. The reference scenario is simulated using the process detailed in Figure . A description of the reference scenario is given in Table 6.1.

Table 6.1: The reference scenario and its description.

Scenario	Description
Reference scenario **Model used** PowerNodes, Pandapower	This is the current scenario for De Zwette, based on collected measured data and simulations using known installed production capacities, peak demands, and simultaneity factors. The procedure described in section 5.1 (Pandapower) is used to establish a nodal energy balance over the electricity grid. Key inputs to the scenario are provided in Tables 6.2 and 6.3. It is assumed that household heat and hot tap water demand is primarily met by natural gas. Heat demand from companies is not included, as their profiles can vary significantly and nodal gas demand data was not available. The heat demand is determined using the neighborhood passport, which indicates average gas use for heating and hot tap water.

Table 6.2: The main values for determining energy demand in the reference scenario.

Description	Value	Unit	Source
Total amount of houses	43236	amount	Wijkpaspoort*
Average gas use per household	1220	Nm³/a	Wijkpaspoort*
Heat use Zwette total residential	515317874	kWh/a	Wijkpaspoort*
Hot tapwater use Zwette total residential	51531787	kWh/a	Wijkpaspoort*
Electricity use Zwette total (based on NLS)	151798660	kWh/a	Liander
Electricity use Zwette total (corrected for production sources)	175036253	kWh/a	Liander PowerNodes
Electricity use from residential in Pandapower	105245244	kWh/a	Liander + MFFBAS
Electricity use from industry in Pandapower	69791009	kWh/a	Liander

*Wijkpasport is a public data platform Datavoorziening Wijkpaspoort energietransitie - VNG realisatie

Table 6.3: The main values for determining energy production in the reference scenario.

Description	Value	Unit	Source
Installed capacity solar PV rooftops	19896	kW	Liander
Installed capacity solar PV parks	18460	kW	Liander
Installed capacity wind turbines	1800	kW	Liander
Installed capacity CHP	1017	kW	Liander

6.2 Energy balance PED scenario's

Energy balance PED scenarios will explore the impact of potential PED implementations on the current electricity grid. These scenarios will identify locations in the medium voltage grid that could pose barriers to achieving PED. Profile simulations are conducted using the PowerNodes methodology, while grid impact is assessed using the PandaPower methodology. The two scenarios were developed during stakeholder meetings, utilizing different technologies that result in the system being a PED. Table 6.4 provides the energy balance PED scenarios and their descriptions and figure 6.1 gives an overvieuw of the used renewable energy systems in the electricity system.

Table 6.4: Energy balance PED scenario's and their descriptions.

Scenario	Description
Autonomous growth; Expected growth based on current policies NL with no limitations (2040) **Model used** PowerNodes, Pandapower	The Autonomous Growth Scenario begins with the heat, hot water, and power demand within the REF scenario. This scenario for De Zwette is based on the continuation of trends observed over the past decade, projected into the future. It includes the integration of 50% hybrid heat pumps and 50% all-electric heat pumps for heat and hot water production. Insulation improvements and cooling demand are not included. Electric transport is considered, assuming one car per household, with 50% of the vehicles being electric. These electric cars charge using an unmanaged charging pattern based on E-laad. Other forms of transport are not taken into account. For electricity production, within this scenario an additional 400 MW of solar PV on roofs is installed. This amount of solar PV is necessary to make De Zwette a PED, excluding industrial heat demand. The distribution of PV capacity throughout the network is based on nodal peak demands; for example, nodes with higher demand receive more PV allocation. The current installed capacity of solar PV and wind is also included. Finally, biogas production from mono manure digestion is incorporated (using PowerNodes) to meet the remaining green gas demand.
Planned growth; Expected growth based on current policies NL with no limitations (2040) **Model used** PowerNodes, Pandapower	The Planned Growth Scenario begins with the heat, hot water, and power demand within the REF scenario. This scenario for De Zwette is based on a more strategic approach to optimize balance and minimize grid congestion. It includes the integration of district heating based on waste heat, solar thermal, and ground and ATOS-fed heat pump systems for heat and hot water production. Insulation improvements and cooling demand are not included.

	Electric transport is considered, assuming one car per household, with 50% of the vehicles being electric. These electric cars charge with smart charging behavior aimed at relieving grid strain. Other forms of transport are not taken into account. For electricity production within this scenario, an additional 144 MW of wind power is installed using 1 MW turbines. This amount of wind power is necessary to make De Zwette a PED, excluding industrial heat demand. The turbines are distributed across De Zwette, taking into account grid capacity constraints and demand. The current installed capacity of solar PV and wind is also included. Finally, biogas production from mono manure digestion is incorporated to meet the remaining green gas demand.

6.3 Flexibility assesment future scenario's

Within the flexibility assessment two future scenarios are explored, where additional storage, smart charging, and peak power production is added to the Planned Growth Scenario. In the **FLEX scenario** energy storage, smart charging, curtailment, and peak power using locally produced biogas will be integrated in the Planed Growth scenario (Table 6.5). Additionally in the **FLEX++ Scenario,** Energy savings (e.g. insulation of housing stock) will be included combined with bi-directional charging, thereby using electric transport in the region as local batteries (Table 6.5). In figure 6.1 an overview is given of the used flexibility options in the electricity system.

Table 6.5: Flexibility scenario's and their descriptions.

Scenario	**Description**
FLEX scenario With a range of flexibility assests/operations (primarily battery electricity storage /peaking generators and curtailment.) **Model used** PowerNodes Pandapower	This scenario will start of from the Planned Growth Scenario, which already includes wind energy and a central heat grid and will be expanded with the following elements. • Energy storage (100 MWh) • Curtailment on 62 MVA • Smart charging of 90% of the electric vehicles, lowering and extending the charge cycle to avoid peak demand • Wind Focus with 140 MW • Peak Power Unit (PPU) 26 MVA running on biogas or green gas • Biogas production and upgrading to green gas to fill demand of heat grid and peak power production.
FLEX++ scenario Planned growth + flex + peaking assets on high level + curtailment **Model used** PowerNodes, Pandapower	The FLEX++ scenario adds additional options for flexibility and energy savings to the FLEX scenario. These include a 40% heat demand reduction based on a comprehensive insulation plan for the housing stock in the selected region. This plan assumes that all homes with insulation label D (or higher) will upgrade to label A+, and all homes with label E (or lower) will upgrade to label B. Additionally, electric cars in the region will use bi-directional charging for 40% of their battery capacity, combined with smart charging for 60%. The use of

bi-directional charging reduces the required capacity of the battery systems to 50 MWh as.

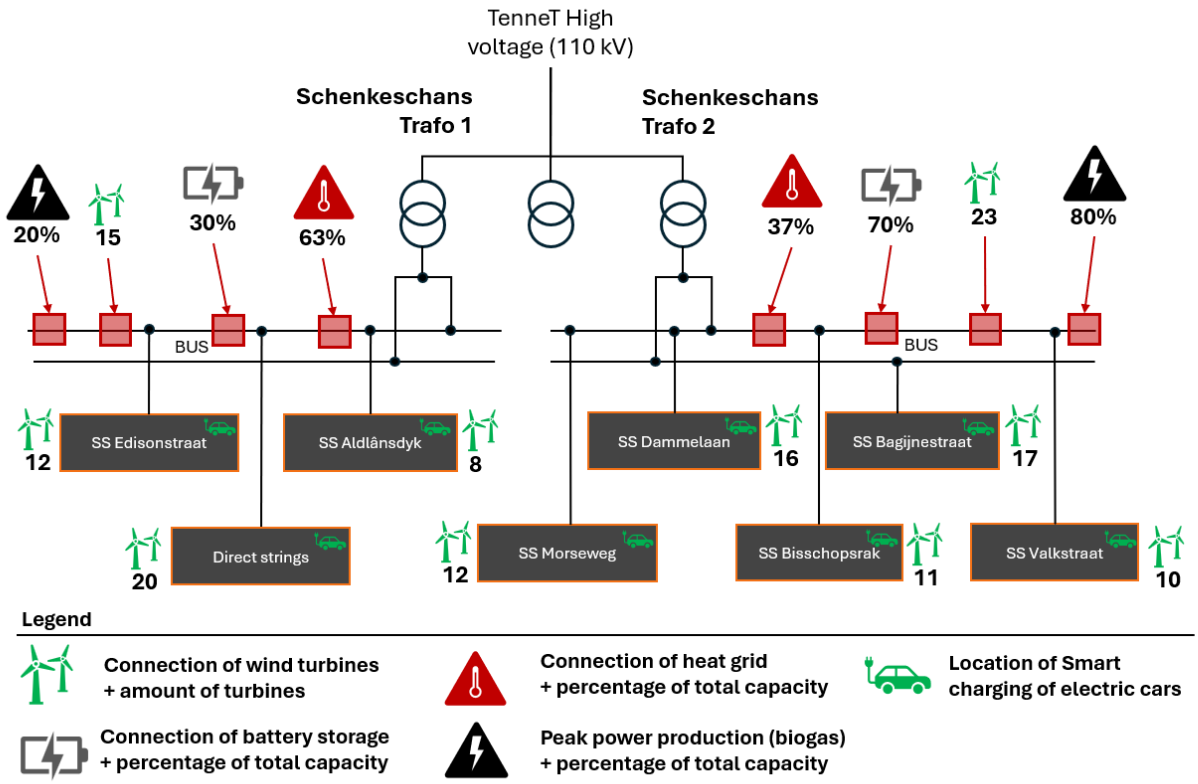

Figure 6.1: Overview of the electricity grid and the elements added in the energy flexibility scenarios.

Table 6.5 provides the flexibility scenarios and their descriptions and figure 6.1 gives an overvieuw of the used flexibility options in the electricity system.

6.4 Flexibility assesment scenarios

Based on the results from the flexibility scenarios an analysis is performed on the impact and cost of creating space on the electricity grid using flexibility options. Within the assessment, **the current total electricity profile of the Zwette for the HV-MV transformers is simulated in PowerNodes**, considering the influence of batteries/peaking generators and curtailment. The assesment will focus on freeing up capacity at the high voltage connection with TenneT. Within this analysis multiple combinations of batteries/peaking generators and curtailment will be simulated, to determine how much capacity can be freed on the demand or production side and the associated costs per asset/operation.

A total of 16 sub-scenarios have been simulated. These sub-scenarios were designed to shave the peaks on the production and demand sides by a certain value, initially using a specific amount of battery storage. Subsequent sub-scenarios employ other technologies such as gas peaker generators and curtailment. The goal is to free up the same amount of capacity using a combination of technologies rather than relying solely on batteries. This approach demonstrates the costs of a battery-only system compared to systems utilizing multiple technologies. The financial results of the scenarios assume that the project's primary aim is to free up capacity, not to simulate a profit-driven business case. Therefore, the financial results likely underestimate the revenues such a project could generate with profit-driven operation. To indicate the costs of the simulated projects, it is assumed that the projects break even on the energy costs part of their operation. For example, battery revenues from discharging are equal to the costs of charging, and for the peaking generator, fuel costs are equal to the revenue generated by selling electricity. Table 6.6 provides the general financial parameters used in the NPV calculations for the different scenarios.

Table 6.6: Parameters assumed in the NPV calculation. Source: conservative expert estimates

Parameter	Value	Unit
Project Lifetime	15	years
Tax Rate	25,8	%
Inflation Rate	3	%
Debt Ratio	60	%
Loan Interest Rate	4	%
Loan Term	12	years
Equity Return Rate	12	%
Cost of Equity	12	%
Cost of Debt	4	%
WACC Tax Adjustment	7	%
Working Capital Ratio	3	%
Contingency Percentage	7,5	%
Depreciation Life	15	years
Default WACC	8	%
Battery CapEx	400000	EU/MWh
Battery OpEx as % CapEx	2	%
Peaker gas generator CapEx	900000	EU/MW
Peaker gas generator OpEx as % CapEx	3	%
Energy curtailed price	300	EU/MWh

Table 6.7 gives the configuration and system characteristics per scenario for the flexibility assesment of the reference case.

Table 6.7: Sizing and other system characteristics determined by simulation for the different technologies per scenario.

Scenario	Battery Size (MWh)	Peaker size (MW)	Peaker annual operating hours (hours/year)	Peaker average operating power	Energy curtailed (MWh/year)
1	3	0	0	0,00	0
2	12	0	0	0,00	0
3	6	1,21	8	0,62	4,925
4	3	1,62	19	0,73	9,625
5	24	0	0	0,00	0
6	12	2,62	10	1,43	5,36
7	6	2,62	30	1,25	10,225
8	3	3,19	60	1,12	12,353
9	36	0	0	0,00	0
10	18	3,62	16	1,76	21,629
11	9	3,73	52	1,88	51,625
12	5	4,37	105	1,53	78,308
13	49	0	0	0,00	0
14	25	4,62	30	2,26	31,102
15	12	4,73	106	2,05	96,795
16	6	4,33	259	1,73	76,16

7 Results

In this section the assessment of energy demand, generation profiles, and local energy balance is discussed, followed by future PED scenarios, task T4.1. Next the Planed Growth Scenario scenario will be further developed by adding flexibility to lower the impact on the electricity grid and increase balance in the FLEX and FLEX++ scenarios, followed by the flexibility analysis of the reference scenario, task T4.4. Additionally, the PowerNodes model will be made available for stakeholders and used in stakeholders sessions, as part of task T4.6. Finally, results and conclusions from the scenarios will be discussed and a general tool will be proposed for performing high level analysis of grid congested area's.

WP 4: Demo Site Zwette VI, Leeuwarden
T4.1: Assessment of energy demand, generation profiles, and local energy balance
T4.2: Identifying regulatory, structural and technical barriers
T4.3: Identifying existing partnerships and networks at Zwette VI
T4.4: Assessment of the quality of flexibility
T4.5: Developing business models
T4.6: Developing a strategy for implementing PED

7.1 Deliverable D4.1: Local energy balance assessment

This section discusses the assessment of energy demand, generation profiles, and local energy balance, including future PED scenarios (task T4.1). Three main scenarios will be examined:

1. **Reference Scenario**: The current state of De Zwette (section 6.1).
2. **Autonomous Growth Scenario**: The region's development based on current trends and regulations (section 6.2).
3. **Planned Scenario**: A more actively planned development approach to reduce grid strain and enhance balance (section 6.2).

7.1.1 Energy demand (PowerNodes)

Reference Scenario (Figure 7.1a): The distribution of demand in the reference scenario for the total research area (section 3.1) is mainly from domestic consumption, followed by companies (Figure 7.1a). Current domestic consumption is defined as electricity use for lighting and appliances, excluding demand from electric heating options (e.g., heat pumps) and electric cars. Electricity demand for companies is not easily defined and can include lighting, appliances, industrial machines, or electric transport. Grid congestion in the Zwette area is heavily influenced by domestic electricity consumption. At the switching station level, both companies and residential areas are combined, meaning that grid congestion in one area can originate from another. Due to the design of the electricity grid, congestion can occur at multiple levels.

Autonomous Growth Scenario (Figure 7.1b): In the Autonomous Growth Scenario, focusing on future developments towards a PED, domestic electricity use can further increase its influence on the electricity grid. As electric heating and electric driving in residential areas develop, the current energy use (Figure 7.1a) will represent only one-third of future energy use (Figure 7.1b). The indicated 32% share of electricity use "demand Zwette" in Figure 7.1b represents the total current energy use shown in Figure 7.1a. Another third will be electricity demand for electric transportation, assuming half of the households actively use electric vehicles. The remaining third is for residential heat demand, primarily using air source heat pumps. Additionally, the gas requirements of hybrid heat pumps are met by upgraded biogas produced through manure digestion, requiring additional electricity demand. Essentially, the total electricity demand in the research area will triple in the business as usual PED scenario, excluding industrial demand expansion.

Planned Growth Scenario (Figure 7.1c): In the Planned Growth Scenario, a more strategic approach is used towards a PED, but the impact on energy demand distribution is not substantial. The overall system is slightly more efficient, but the main distribution remains one-third current demand, one-third transport, and one-third heating by heat (Figure 7.1c). The heat grid solution in this scenario is based on a hybrid system where a heat pump produces the bulk of the heat, resulting in electricity use.

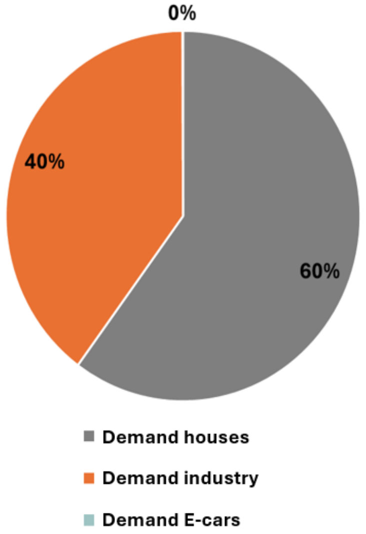

Figure 7.1a: Energy demand reference scenario

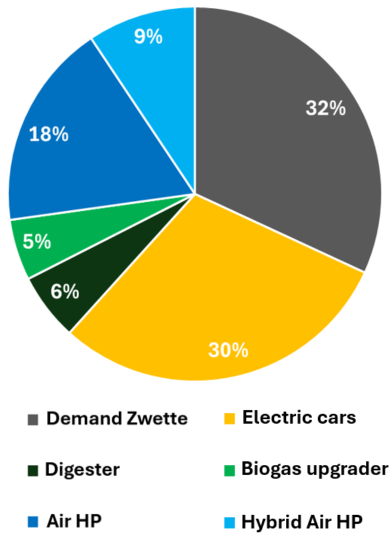

Figure 7.1b: Energy demand business as usual PED scenario

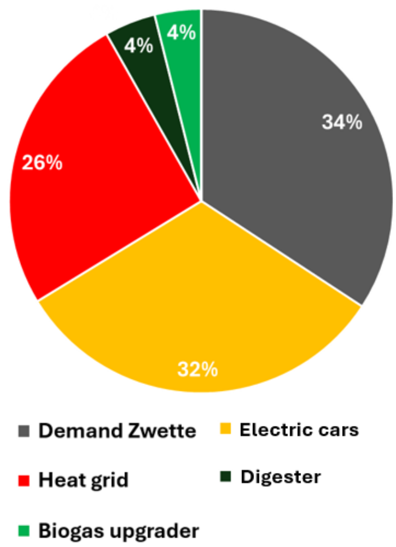

Figure 7.1c: Energy demand planned PED scenario

7.1.2 Energy production (PowerNodes)

Reference Scenario: The distribution of production in the reference scenario is mainly from roof-mounted solar PV, a large PV park, and medium wind turbines (Figure 7.2a). Overall, the largest share of production comes from solar PV.

Autonomous Growth Scenario: In the Autonomous Growth Scenario, focusing on future developments towards a PED, domestic electricity production from roof-mounted solar PV panels will grow substantially. Current regulations allow homeowners to produce electricity in the summer and store it for free in the electricity grid for use in the winter, which is ideal for combining with electric and hybrid heat pumps. To achieve a PED where yearly production and demand are equal, local renewable production needs to expand over tenfold.

Planned Growth Scenario: In the Planned Growth Scenario, a more strategic approach is used towards a PED, resulting in a substantial impact on energy production. All additional renewable energy production is achieved through wind power (Figure 7.2c). However, the overall yearly production is similar to the Autonomous Growth Scenario.

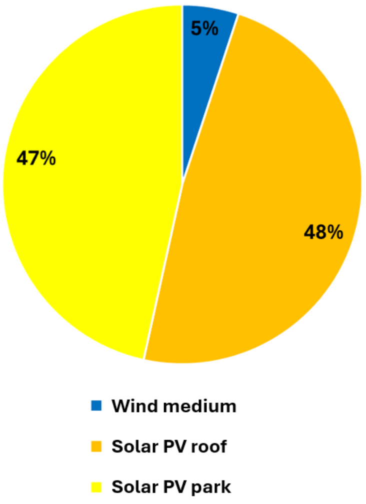

Figure 7.2a: Energy production reference scenario

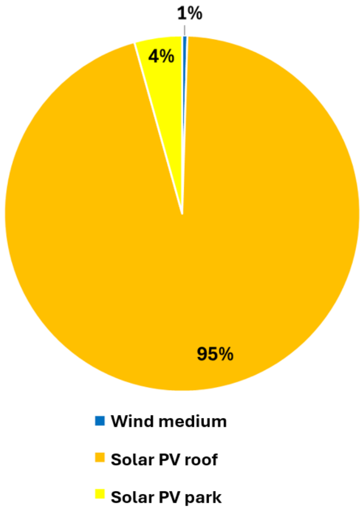

Figure 7.2b: Energy production business as usual PED scenario

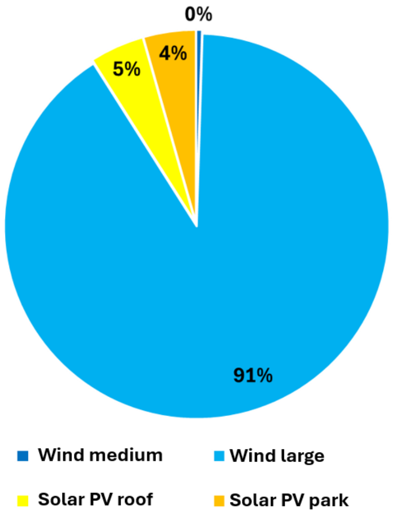

Figure 7.2c: Energy production planned PED scenario

7.1.3 Self-sufficiency (PowerNodes)

Reference Scenario: The large share of rooftop solar PV and the presence of a large solar park already cover a significant portion of the total yearly electricity demand (Figure 7.3). Additionally, most of the produced electricity is consumed within the same region, resulting in high self-consumption. Only around 4% of the local production is transported over the high voltage network to other demand locations. However, the region is not self-sufficient, as the current electricity demand does not include heat demand and electric transport.

Autonomous Growth Scenario: When heat and transport are added to the electricity demand in the region, more renewable energy is required to achieve a PED scenario. Using solar PV as the primary energy source results in a low self-consumption rate of 25%, as energy production mainly occurs in the summer while energy demand is higher in the winter. Consequently, there is a high export of electricity out of the region.

Planned Growth Scenario: Using wind as the primary energy source results in a higher self-consumption rate of 54%, as wind turbines also produce energy during winter periods. This reduces the amount of exported energy, although it remains substantial.

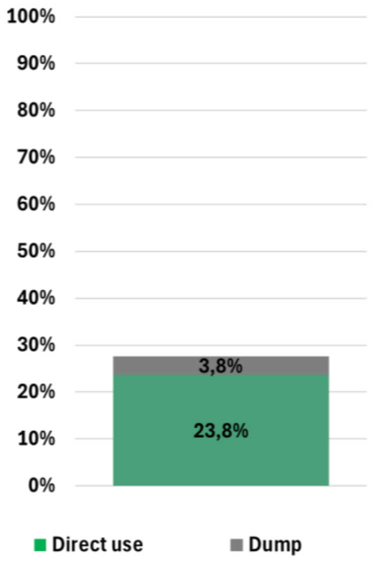

Figure 7.3a: Sufficiency reference scenario

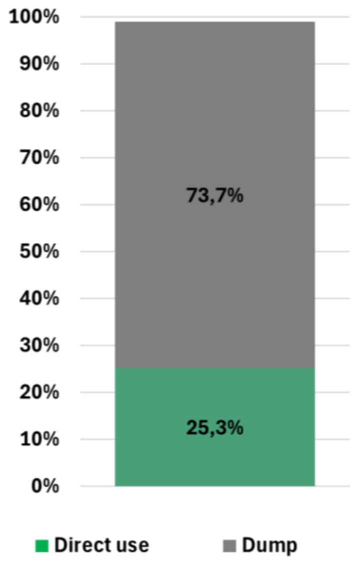

Figure 7.3b: Sufficiency business as usual PED scenario

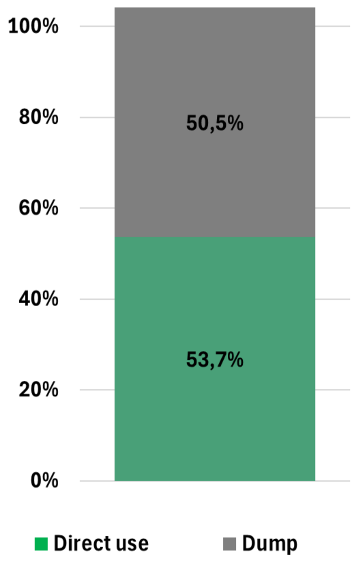

Figure 7.3c: Sufficiency planned PED scenario

7.1.4 Net Load Signal (PowerNodes)

Reference Scenario: The current electricity demand pattern of the region sits well within the physical limits of the two transformers (total capacity of 62 MVA), as shown in Figure 7.4a. This indicates that there is no capacity problem specifically for the two transformers located at the high voltage connection. Therefore, the core problem of grid congestion has another origin.

Figure 7.4a also shows the impact of solar PV production, indicated by number 1, where PV is mainly active during the spring and summer months, creating a distinctive curve in the middle of the NLS. As more PV is integrated into the region, this curve will become more pronounced. The NLS also contains an average residential demand pattern, indicated by number 2, with higher demand in winter than in summer due to lighting and increased indoor activities.

In addition to the yearly pattern, there is also a daily fluctuation that can vary per week and part of the year. Figure 7.4b provides an example of a winter week, indicated by number 3 in Figure 7.4a, at the end of January, where there is almost no renewable production and high demand. The results, also, indicate that the resulting NLS, and more specifically the fluctuations within it, are mainly caused by the connected residential area's to the Schenkenschans area. Therefore, households play a significant role in both the creating of grid congestion as well as the solution.

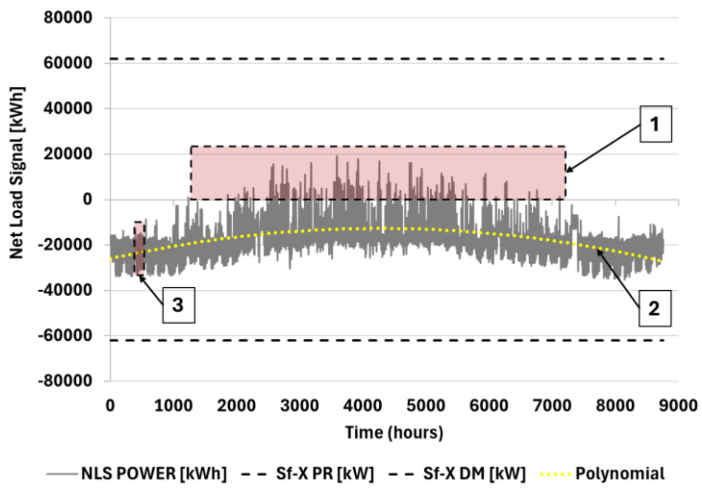

Figure 7.4a: NLS of reference scenario, connection to high voltage grid Leeuwarden

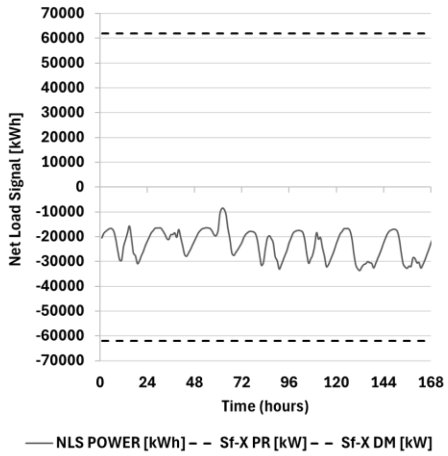

Figure 7.4b: NLS of winter week reference scenario

Autonomous Growth Scenario: In a future PED scenario based primarily on solar PV production, the capacity of the main transformers (totaling 62 MVA) is insufficient to handle the high overproduction during the summer months (see Figure 7.5a). Additionally, during the winter months, when houses are heated with air heat pumps, there is insufficient capacity available during cold periods. This results in periods of grid congestion due to both overproduction and high demand, which can impact the stability of the electricity grid.

The increased capacity of solar PV in the region is clearly observable in Figure 7.5a, indicated by number 1, where the maximum production of the combined PV installations easily surpasses the capacity of the main station's transformers, leading to grid congestion. The summer and winter patterns are also more pronounced in this scenario, as shown in Figure 7.5a with number 2. Solar PV production pushes the summer average up, while the higher electricity demand from electric heat pumps pulls the winter average down, resulting in a larger difference over the year.

Additionally, energy demand throughout the year increases due to the introduction of electric cars and green gas production, leading to grid congestion on the demand side even in summer. This creates situations where, over the course of a single day, there can be congestion on both the production and demand sides. Figure 7.5b, representing a spring week indicated by number 3 in Figure 7.5a, illustrates this scenario.

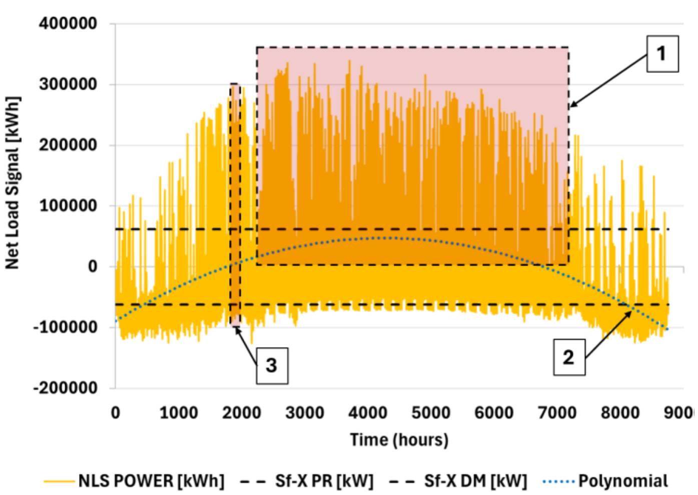

Figure 7.5a: NLS of autonomic growth scenario, connection to high voltage grid Leeuwarden

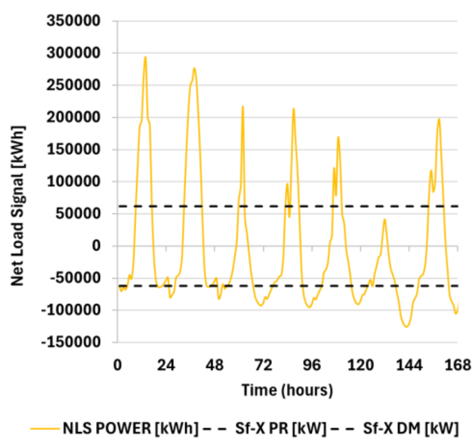

Figure 7.5b: NLS of spring week autonomic growth scenario

Planned Growth Scenario: In a future PED scenario based primarily on wind production, similar results to the solar PV PED scenario can be observed, where periods of overproduction and high demand impact the stability of the electricity grid, resulting in grid congestion. The increased capacity of wind in the region is clearly observable in Figure 7.6a, indicated by number 1, where the maximum production of the combined wind installations easily surpasses the capacity of the main station's transformers, leading to grid congestion. However, the maximum peak power of wind is half that of solar PV in the Autonomous Growth Scenario.

The summer and winter patterns are more balanced in this scenario, as shown in Figure 7.6a with number 2, because wind production is more evenly distributed throughout the year. Additionally, energy demand increases throughout the year due to the introduction of electric cars and green gas production, leading to grid congestion on the demand side even in summer. This creates situations where, over the course of a single day, there can be congestion on both the production and demand sides. Figure 7.6b, representing a winter week indicated by number 3 in Figure 7.6a, illustrates this scenario.

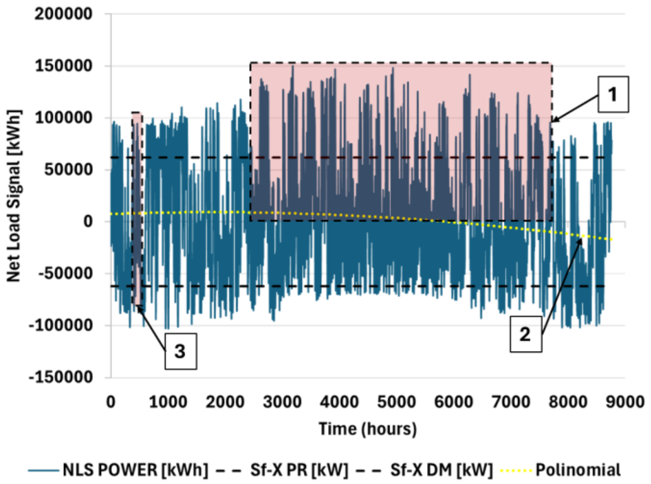

Figure 7.6a: NLS of Planned Growth Scenario, connection to high voltage grid Leeuwarden

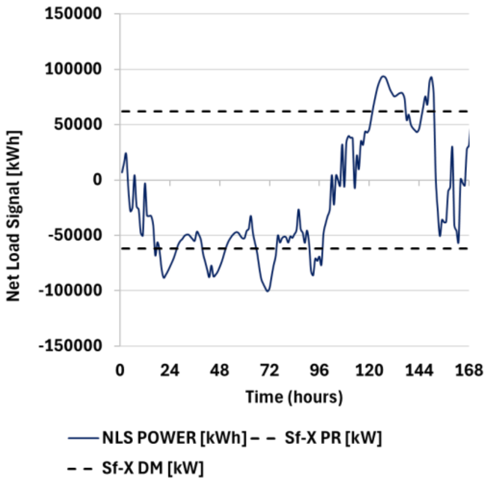

Figure 7.6b: NLS of winter week Planned Growth Scenario

7.1.5 Load Duration Curve (PowerNodes)

Within the net Load Duration Curve (NLDC), all three scenarios can be clearly indicated and compared in one overview (see Figure 7.7). The high peak production of solar PV and its low self consumption (or amount of produced electricity used directly in the area) are immediately apparent (Figure 7.7, number 1). Self consumption can also be observed in figure 7.3b Number 2 in Figure 7.7 highlights the higher self consumption of wind compared to solar PV, combined with a lower peak production (Figure 7.3c). Finally, number 3 indicates the impact of electric heating solutions (e.g., heat pumps and heat grids based on heat pumps) on the overall demand peak.Here wind has a lower demand peak as it produces more energy during the winter months.

Additionally, the increased demand from electric cars places the NLDC of the autonomous and Planned Growth Scenarios below the Reference scenario NLDC. Overall, the overproduction surpassing the maximum grid capacity is more significant for solar than for wind. For demand, the individual heat pump solution with solar is more significant than with a heat grid and wind.

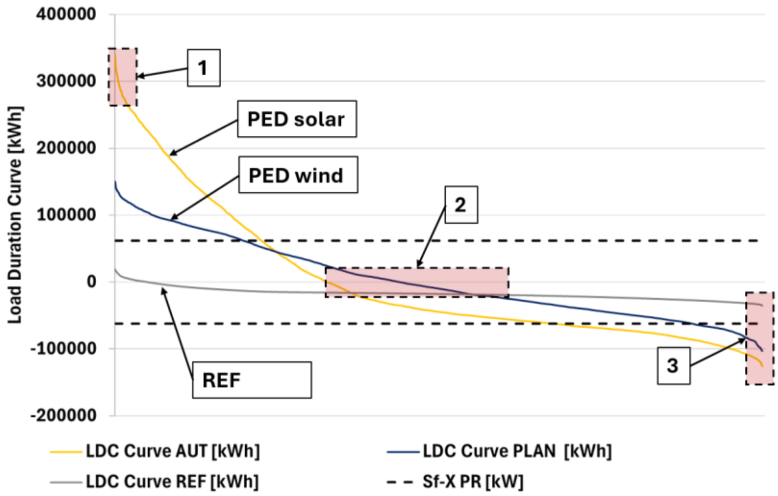

Figure 7.7: NLDC of reference, autonomic and Planned Growth Scenarios, looking at connection to high voltage grid Leeuwarden (Schenkenschans)

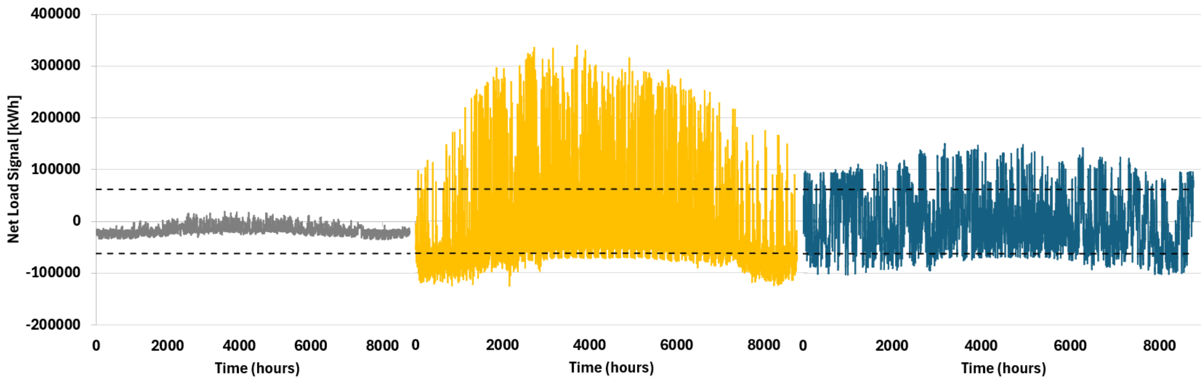

Figure 7.8: NLS of Reference scenario (Grey), Autonomic scenario (Orange), and Planned Growth Scenario (Blue), looking at connection to high voltage grid Leeuwarden (Schenkenschans)

7.1.6 Heat map grid congestion (PandaPower)

This subsection presents the heat map of grid congestion events over the simulations for each scenario. We primarily focus on the current loading of components, specifically line loading. Transformer loading is also considered but to a lesser extent. The transformer loading graphs can be found in the Appendix. A general indication of the overvoltage and undervoltage effects is also provided in the Appendix. For the results, not all time intervals of each scenario are solvable by the PandaPower model. On an hourly basis for the reference year 2021, there are 8,431 hours in the dataset after filtering the data for errors. The reference and Planned Growth Scenarios are solved for each time interval. However, for the Autonomous Growth Scenario, not all time intervals are solved. The Autonomous Growth Scenario is solved with at least one congestion event for 5,684 hours. There are 282 hours that are solved with no congestion events. For the remaining 2,465 hours, the power flow simulation does not converge. Generally a non-convergence in PandaPower implies either numerical instability in the model or a physically infeasible situation. For numerical instability the solver settings and other parameters can be tweaked to possible reach convergence. This was done in these simulations to no avail. So it is assumed the non-convergence is due to the other possibility, unfeasible physical circumstances, which are believeable due to the extreme loading the network undergoes.

Reference Scenario: Figures 7.9 and 7.10 present the line loading congestion results for the reference scenario. It can be observed that there are very few line loading congestion events, and the severity of the congestion is not extreme. Due to the uncertainty in the simulated profiles over this large network, it is probable that there is currently no physical line loading congestion occurring.

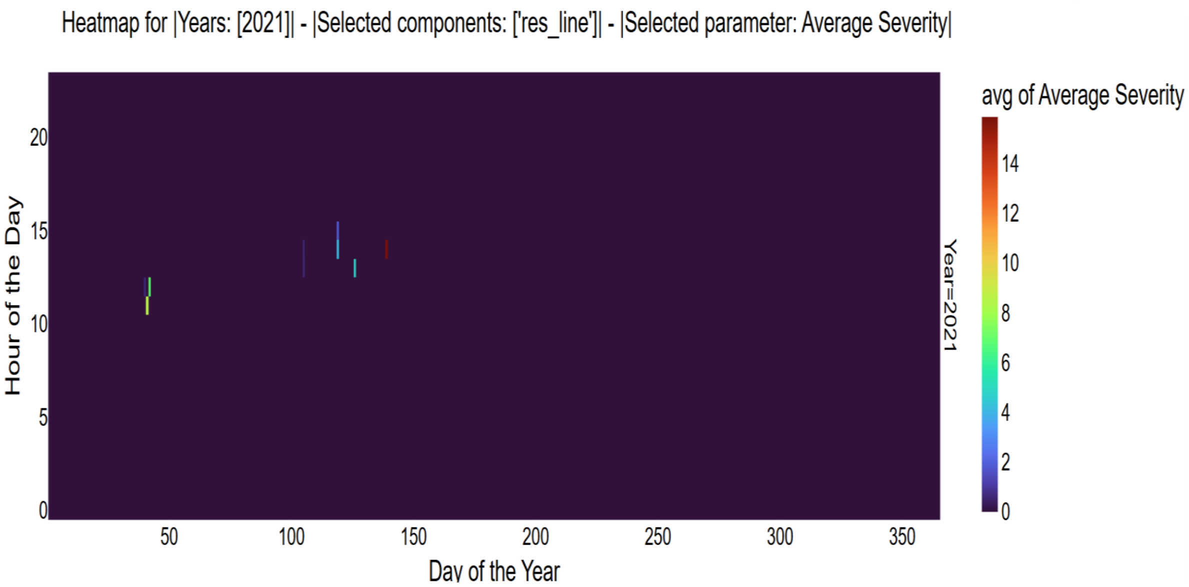

Figure 7.9: Current loading severity of lines during the powerflow simulation for the reference scenario.

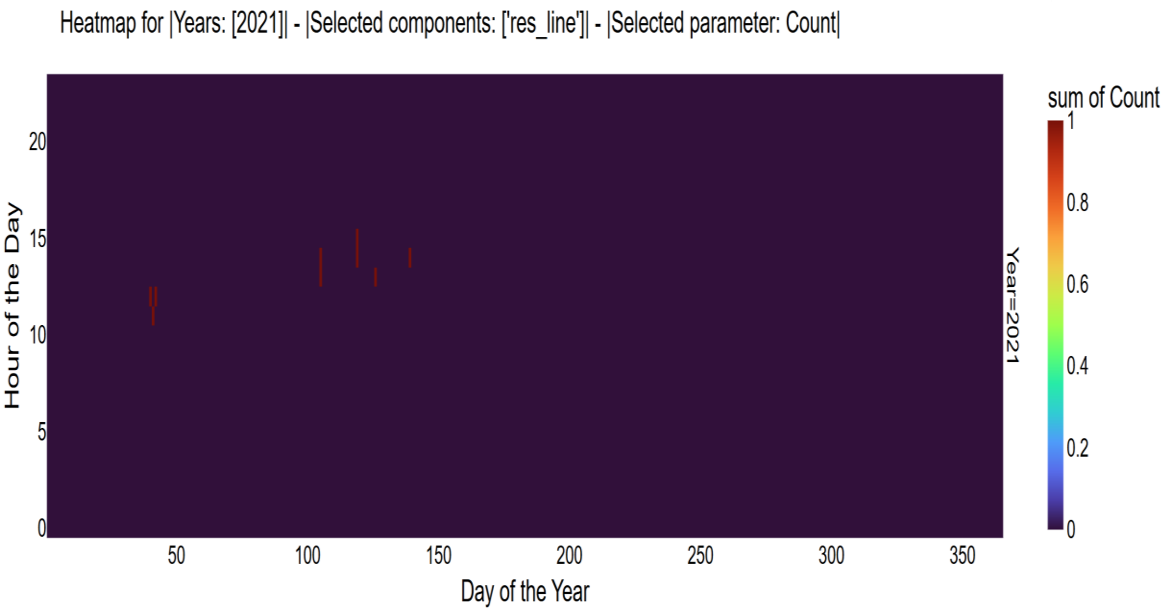

Figure 7.10: Count of current loading congestion events of lines during the powerflow simulation for the reference scenario.

Autonomous Growth Scenario: Figures 7.11 and 7.12 present the line loading results for the Autonomous Growth Scenario. It should be noted that the solver did not converge on a solution for all timesteps in this scenario. Approximately 29% of the timesteps did not converge, which can be seen in the plots as areas where the severity or count is 0. There are some timesteps with no congestion, accounting for around 3% of the timesteps, and these are also included in the areas where severity or count is 0.

The non-converged steps mostly occur during hours of high demand or high solar production. It can be observed that the line loading bar increased significantly compared to the reference scenario. The maximum line loading observed is on average around 90% above our physical limit for the solved timesteps. The non-converged timesteps are likely worse. Therefore, the lines in our network with the worst observed congestion would need to have at least twice the current capacity on average. The component specific plots will show that the worse components will require much more than average. This is shown in section 7.1.7.

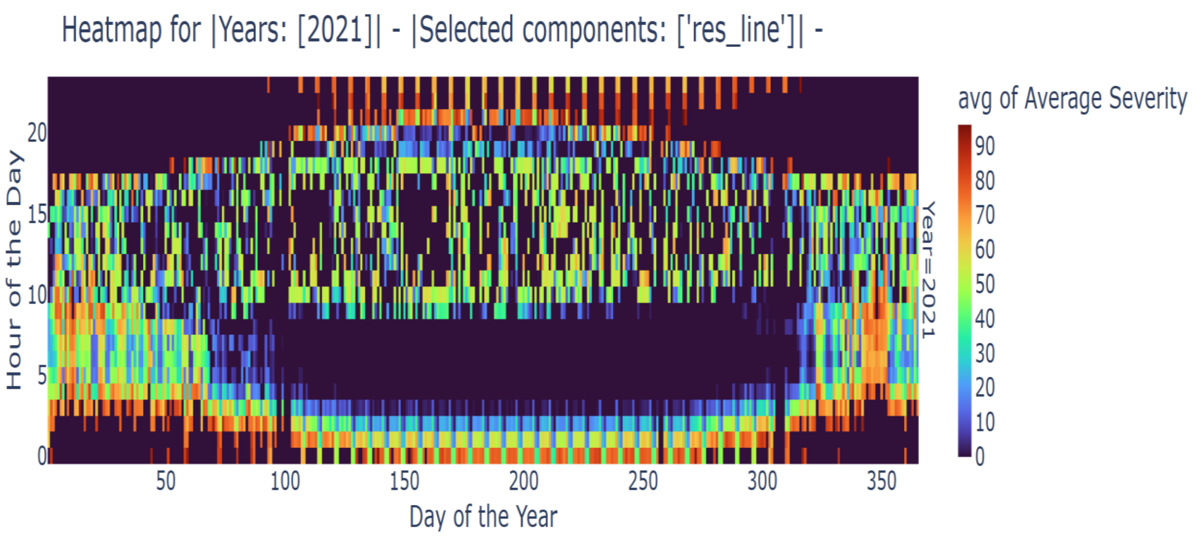

Figure 7.11: Current loading severity of lines during the powerflow simulation for the Autonomous Growth Scenario.

Figure 7.12 shows that the timesteps with maximum solar production coincide with the timesteps during which the most lines experience congestion (hours with high irradiance have all red spots). This is likely because this scenario distributes the PV capacity throughout the entire network. Consequently, all this capacity feeds in simultaneously from all levels of the grid, causing widespread congestion. During timesteps with no PV production, congestion occurs due to high demand. In these cases, power flows from the higher levels to the lower levels of the grid. Congestion likely occurs in a few lines at the higher level of the MV grid or in some lower-level lines with lower capacity (Hours with no irradiance have mostly only blue spots).

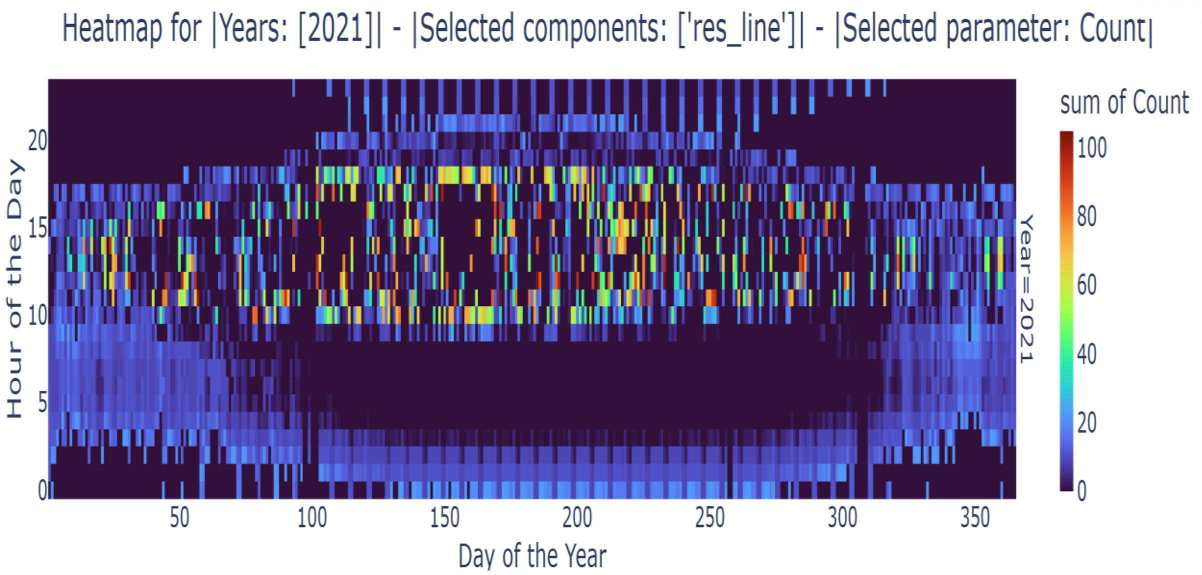

Figure 7.12: Count of current loading congestion events of lines during the powerflow simulation for the Autonomous Growth Scenario.

Planned Growth Scenario: Figures 7.13 and 7.14 present the line loading results for the planned growth and planned growth + flex scenarios. Unlike the Autonomous Growth Scenario, these scenarios converge for every timestep, indicating that the extreme conditions in this system are less severe than in the Autonomous Growth

Scenario. The highest severity conditions occur precisely during some of the timesteps that did not converge for the Autonomous Growth Scenario, supporting the idea that the unconverged timesteps in the Autonomous Growth Scenario would indicate even more extreme conditions.

There is also a contrast between the high solar production hours of the autonomous scenario and the planned scenarios. During these timesteps, the planned scenario performs relatively well in terms of congestion, whereas the autonomous scenario experiences high congestion. The highest observed line loading congestion is on average about 90% above the physical limit, comparable to the Autonomous Growth Scenario. For the Planned Growth Scenario, this is the confirmed worst condition, indicating that the capacity of these specific lines should be increased by a factor of 2. Component specific plots will show that there are some lines which require more reinforcement than by a factor 2. This is shown in section 7.1.7.

Figure 7.14 also shows that the highest number of lines undergoing congestion in one timestep in the Planned Growth Scenario is 14, in contrast to 100 lines in the Autonomous Growth Scenario. One reason for this difference is the way wind is integrated into the network, dispersed through the network in the middle of each string, allowing power to flow in both directions. Congestion likely occurs during timesteps with relatively lower demand and high wind production or relatively high demand and low wind production. In both cases, congestion mainly occurs in the higher-level lines.

For overproduction cases, due to the feed-in being in the middle of the line, there is no possibility for congestion on the lower levels. The lower-level lines also have relatively higher capacity to handle it due to higher simultaneity assumed at lower levels of the grid. As power flows upward into the network, the higher-level lines, designed with a lower level of simultaneity in mind, experience congestion. For the underproduction scenario, the effect of the heat grid and smart EV charging limits the increase in peak electricity demand. The lower-level lines, designed with higher simultaneity in mind, are relatively stronger than the higher-level lines. However, the overall demand has increased, leading to higher loading on the higher-level lines due to the lower simultaneity assumed. This is also apparent in the component-specific plots, aside from a few strings where the wind park feed-in was probably not optimal.

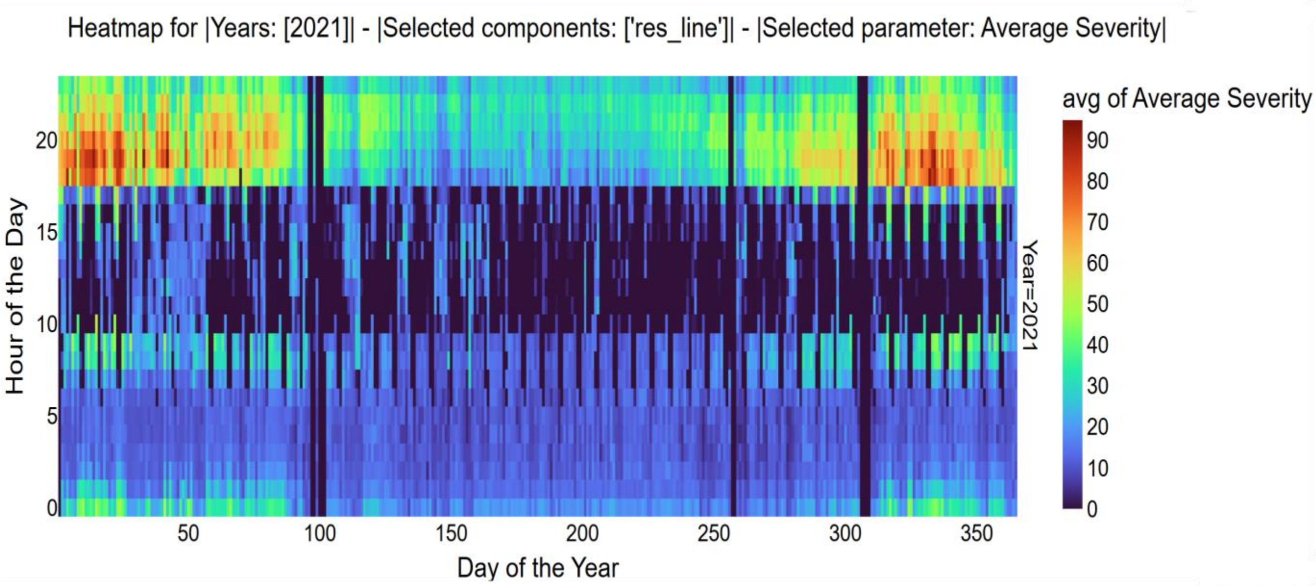

Figure 7.13: Current loading severity of lines during the powerflow simulation for the Planned Growth Scenario.

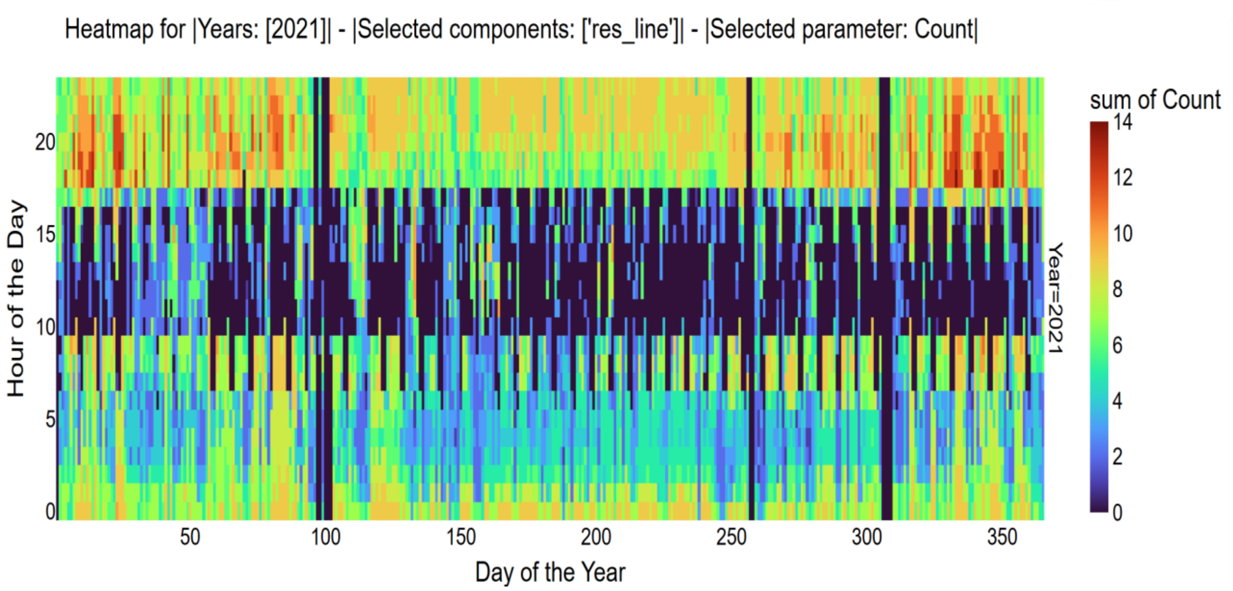

Figure 7.14: Count of current loading congestion events of lines during the powerflow simulation for the Planned Growth Scenario.

7.1.7 Severity and locational grid congestion plots (PandaPower)

This section presents the locational component of congestion events for our different scenarios. First, a few contrasting network plots are provided for each scenario to illustrate the various conditions possible. Then, the summarized severity and count for line loading are given. The transformer loading graphs can be found in the Appendix.

Figure 7.15 shows the network plot for the reference scenario during one time interval in the winter. Generally, there is no congestion occurring in this plot, as indicated by the few red elements. The few red dots are voltage-related, which we do not consider.

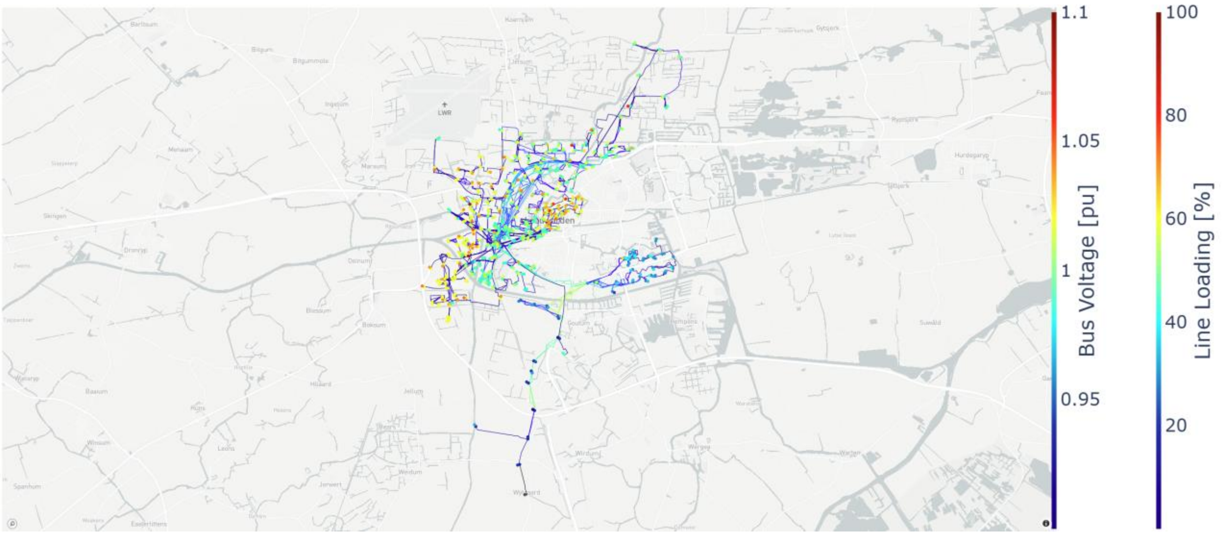

Figure 7.15: Network plot for the reference scenario, 01-01-2021 16:00. Winter relatively high demand hour.

Figure 7.16 shows the same time interval but for the Autonomous Growth Scenario. This is a relatively favorable time interval for this scenario, indicated by low line loading, minimal transformer loading, and few dots indicating extreme under and overvoltage.

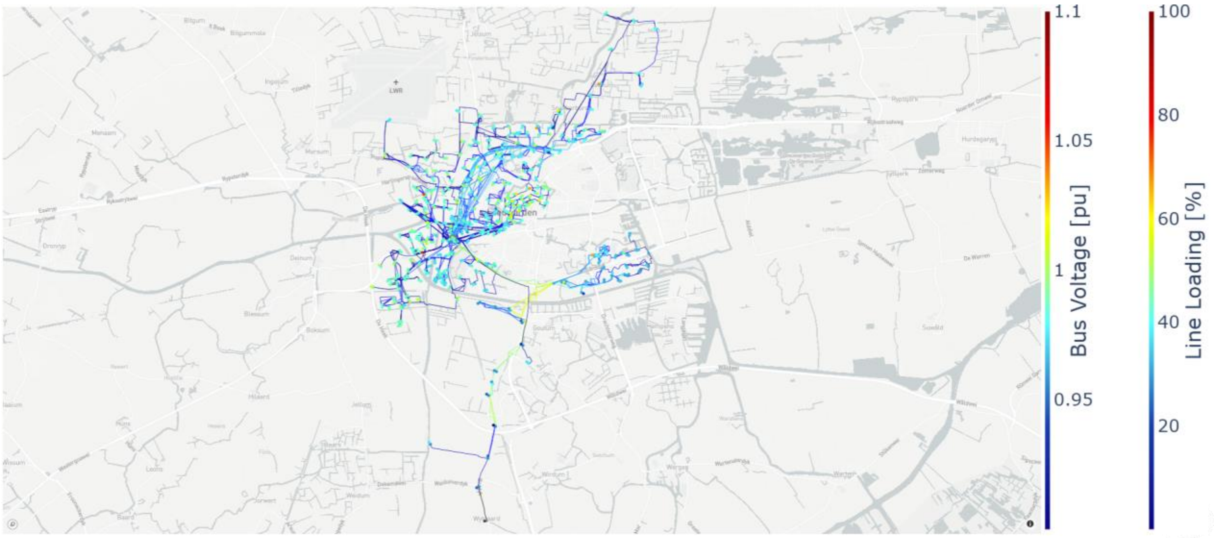

Figure 7.16: Network plot for the Autonomous Growth Scenario, 01-01-2021 16:00. Winter relatively high demand hour.

Figure 7.17 shows the same time interval but for the planned growth and planned growth + flex scenarios (they have the same plot). In most time intervals, the conditions in the planned scenario are better than in the Autonomous Growth Scenario. However, this is one time interval where that is not the case. This is particularly apparent in the lower right side of the grid, where the dark blue dots indicate undervoltage and the red lines indicate strong line loading.

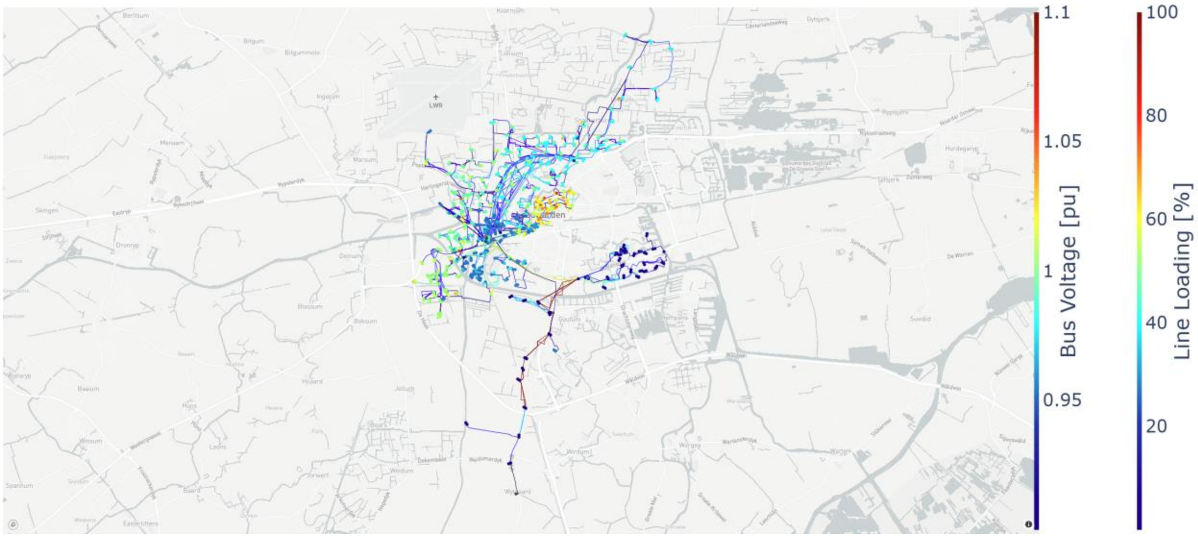

Figure 7.17: Network plot for the Planned Growth Scenario, 01-01-2021 16:00. Winter relatively high demand hour.

Figure 7.18 presents the network plot for the reference scenario during the same hour as the previous plots, but in the summer. Overall, the reference scenario does not exhibit any extreme conditions.

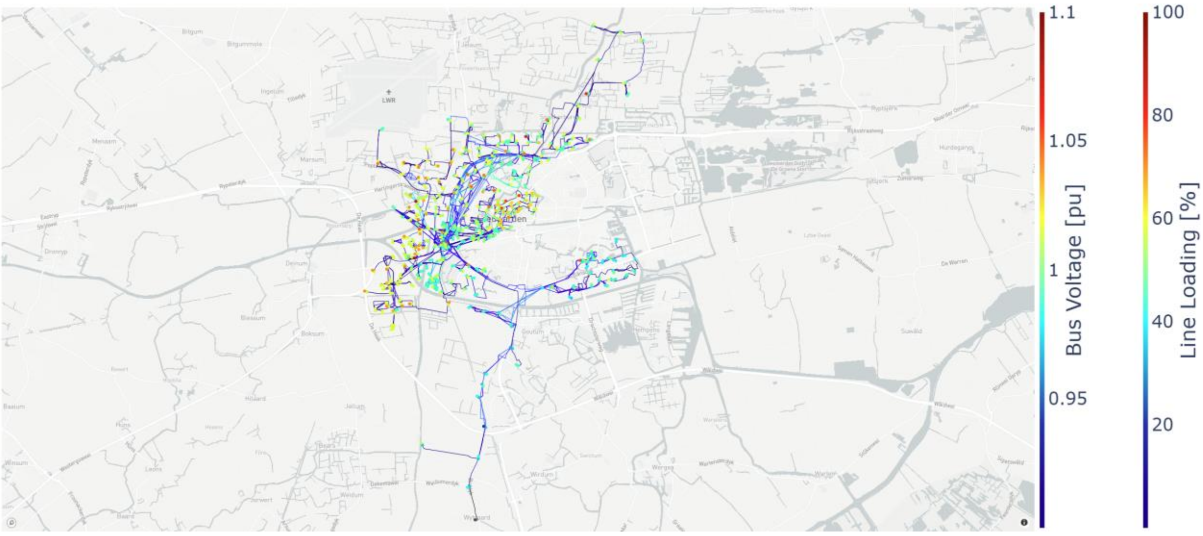

Figure 7.18: Network plot for the reference scenario, 01-07-2021 16:00. Summer relatively high demand hour.

Figure 7.19 illustrates the same summer hour for the Autonomous Growth Scenario. The impact of PV feed-in is clearly visible, with numerous red dots indicating overvoltage, likely caused by PV. Additionally, some lines are colored in higher line loading shades, especially those in the southern part of the grid.

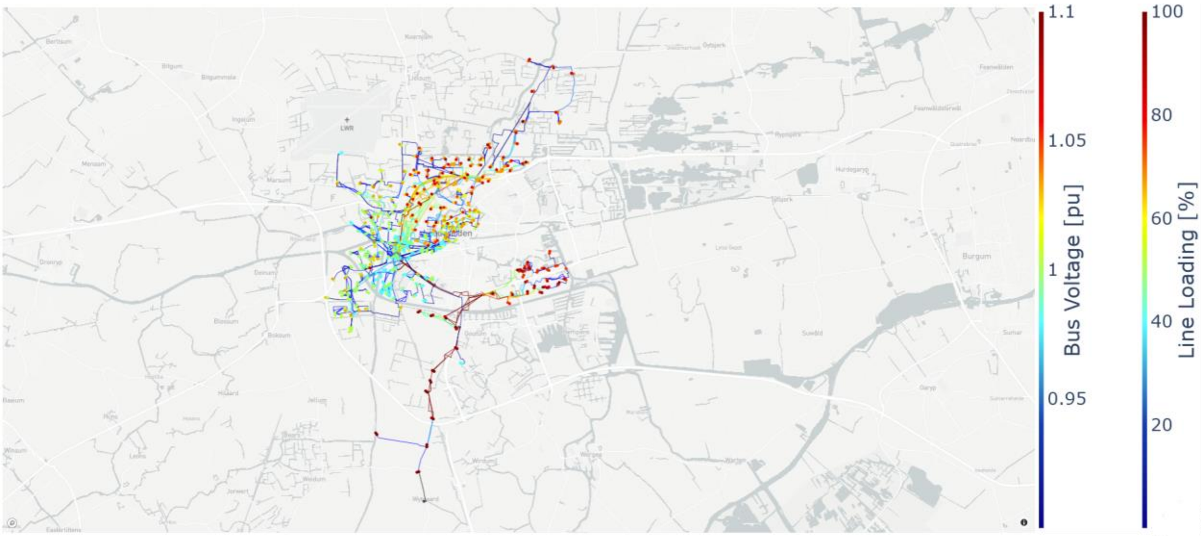

Figure 7.19: Network plot for the Autonomous Growth Scenario, 01-07-2021 16:00. Summer relatively high demand hour.

Figure 7.20 depicts the same summer hour for the planned (+ flex) growth scenarios (they have the same plot). Compared to the Autonomous Growth Scenario, the network conditions are significantly better. While there are still some red dots indicating overvoltage, the overall situation is improved. This snapshot represents one timestamp in the entire year, but the general conclusion applies to most other timesteps. As expected, the planned scenario typically results in better electric grid conditions than the autonomous scenario.

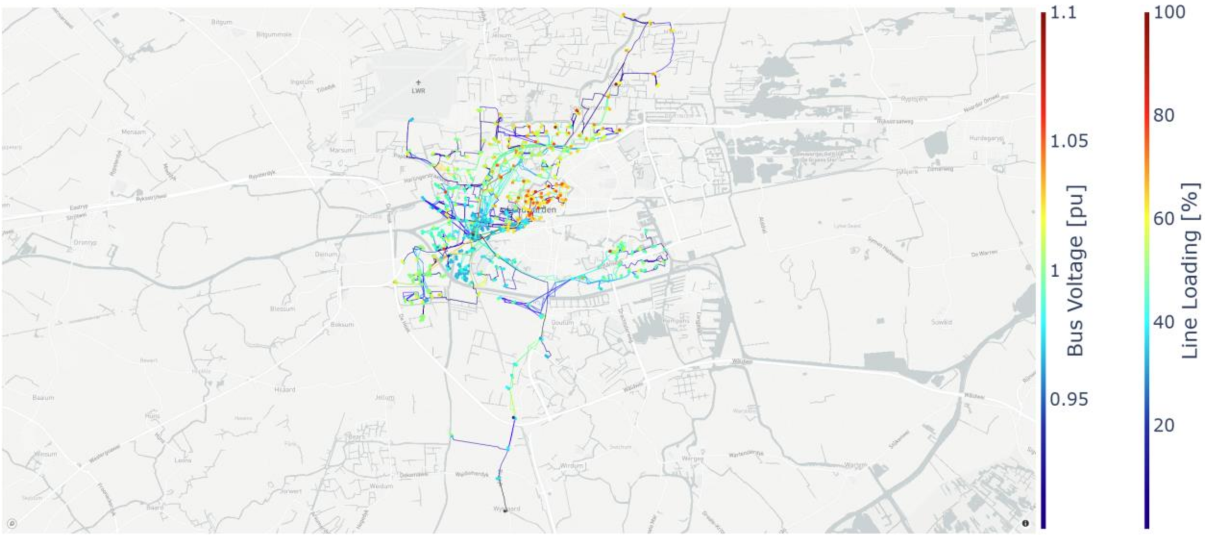

Figure 7.20: Network plot for the Planned Growth Scenario, 01-07-2021 16:00. Summer relatively high demand hour.

Figures 7.21a and 7.21b present the component-specific line loading congestion severity and count for the reference scenario. These figures can be compared to Figures 7.7 and 7.8, which provide the temporal component of line loading severity and count. The box and bar plots indicate that only one line in the network (L000278) under the Valkstraat switching station experienced overloading throughout the entire simulation. This is out of 381 lines considered. The line loading is not extreme, with an average overloading of 4%. This overloading occurs for approximately 10 hours per year. Given the limited number of hours and the non-extreme nature of the overloading, this falls within the uncertainty range of all the profiles simulated for this power flow analysis. The specific string under the SS Valkstraat consists of simulated profiles that are both residential and industrial, which strengthens the uncertainty argument. Additionally, the switching station for this line is not one of those where transformer overloading occurs. Therefore, it is likely that the reference scenario does not exhibit any physical grid congestion.

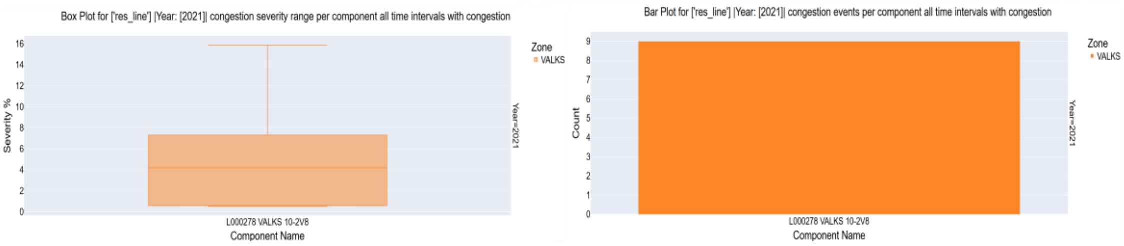

Figure 7.21a&b: Line loading congestion severity box plot and congestion count bar plot for the reference scenario.

Figures 7.22 and 7.23 present the component-specific line loading congestion severity and count for the Autonomous Growth Scenario. These figures can be compared to Figures 7.9 and 7.10, which provide the temporal component of line loading severity and count. The box and bar plots indicate that 111 out of 381 lines experienced overloading throughout the entire simulation. The congestion is distributed across all zones in the network, with some zones experiencing more congestion than others. The line overloading shows wide distributions, with the highest values for most lines exceeding 50% and the most extreme lines exceeding 150% of their physical limits. Most congested lines require a capacity upgrade of around 50%, while the most extreme lines need 2-4 times more capacity. To enable a solar-based PED with heat pump and EV integration, 29% of the lines need a capacity upgrade.

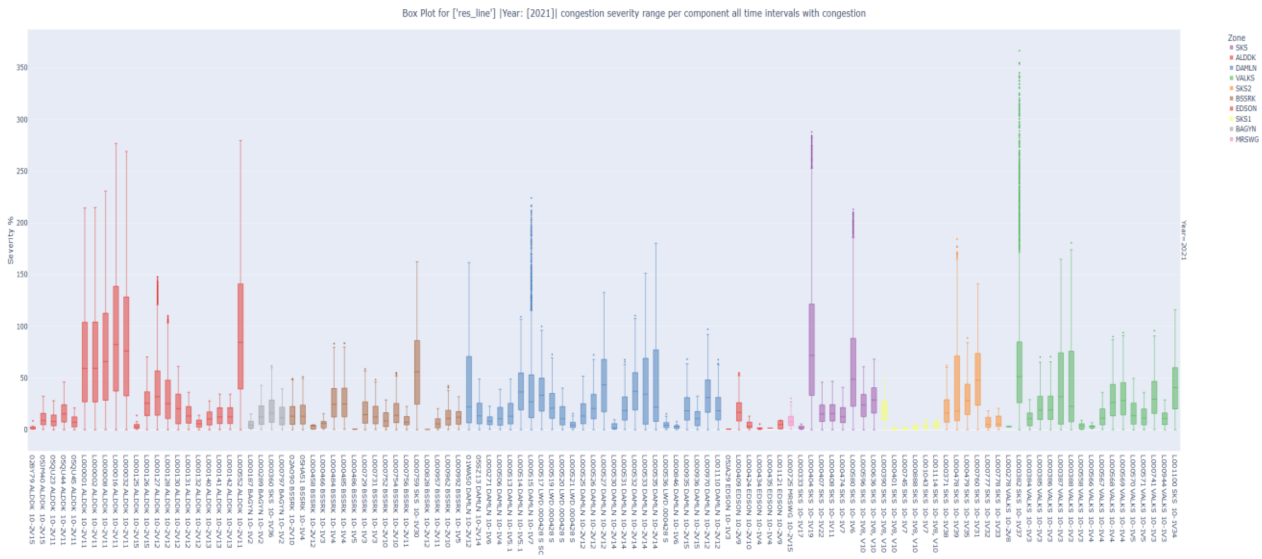

Figure 7.22: Line loading congestion severity box plot for the Autonomous Growth Scenario.

For the event count, it appears that the lines with the heaviest overloading also have the highest number of events. These extreme lines include a mix of low-capacity lines at lower levels, average lines, and some higher-capacity lines. It is important to note that the count and severity are based on converged time intervals, and 29% of the time intervals did not converge, which would likely result in worse outcomes than those shown here.

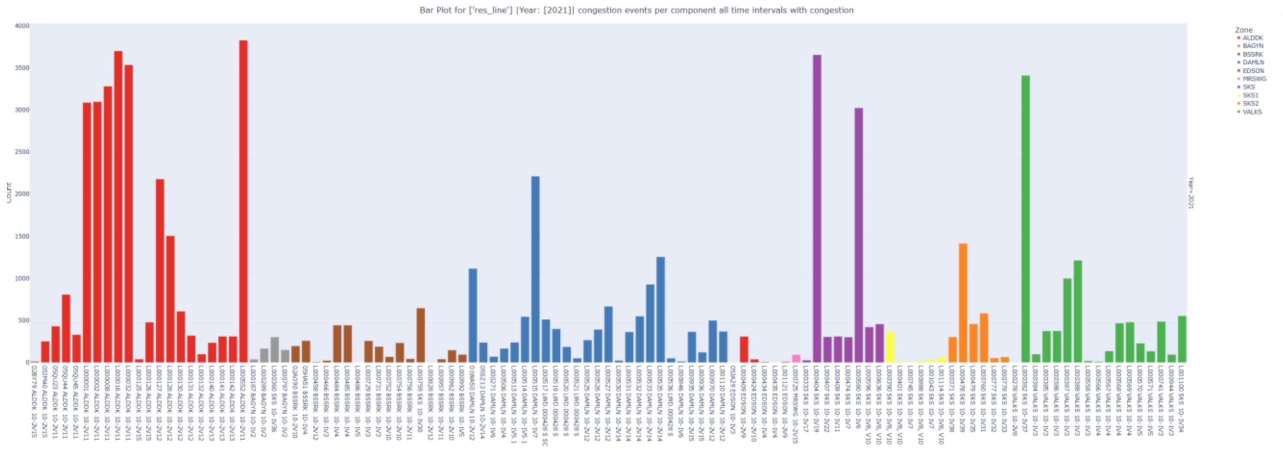

Figure 7.23: Line loading congestion events count for the Autonomous Growth Scenario.

Figures 7.24 and 7.25 present the component-specific line loading congestion severity and count for the planned (+ flex) growth scenarios. These figures can be compared to Figures 7.13 and 7.14, which provide the temporal component of line loading severity and count. The box and bar plots indicate that 25 out of 381 lines experienced overloading throughout the entire simulation. The congestion is distributed across different zones in the network, with some zones experiencing more congestion than others. The line overloading shows wide distributions, with the average maximum value for most lines around 60% and the most extreme lines exceeding 100% of their physical limits. Most congested lines require a capacity upgrade of around 60%, while the most extreme lines need 2-3 times more capacity. To implement the Planned Growth Scenario on the MV grid, 7% of the lines need a capacity upgrade. This is approximately four times fewer lines needing upgrades compared to the Autonomous Growth Scenario.

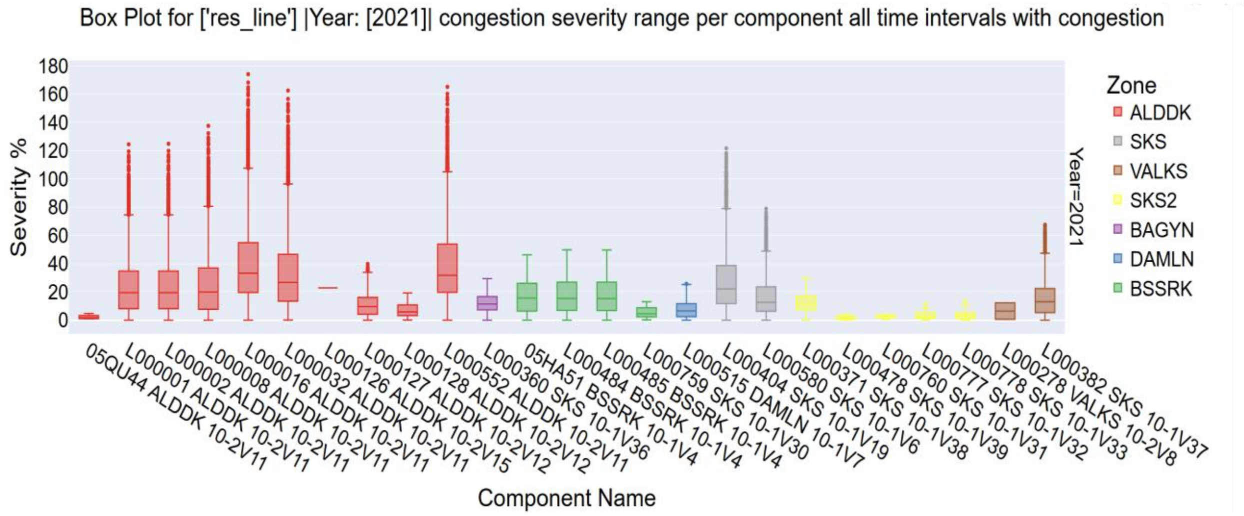

Figure 7.24: Line loading congestion severity box plot for the Planned Growth Scenario.

Examining the locations of the specific lines experiencing congestion in this scenario reveals some interesting observations. Ten out of the 25 lines are directly connected to the MV-HV station, indicating that much of the congestion occurs at a higher level in the network. Another six lines are directly connected to a switching station, representing the second highest level in this network. Only nine lines are at a deeper level in the network. All of these nine lines are part of three strings, and they are all connected to one of the six lines linked to a switching station. Notably, six of these lines are on the same string, meaning almost a third of these lines come from one string. This string includes the first six elements in the box and bar plots. The capacity of the lines in these strings is also the lowest in the network (0.08 kA vs. 0.185 kA average). By reinforcing this one string and a few other strings, the lines in the network would be able to handle this scenario. It is also evident that the count of congestion events for this string is by far the highest, while the count for other lines is relatively low. Although the distribution of wind parks was done evenly, it is likely not the most optimized distribution. A more optimized distribution could further reduce the amount of line congestion.

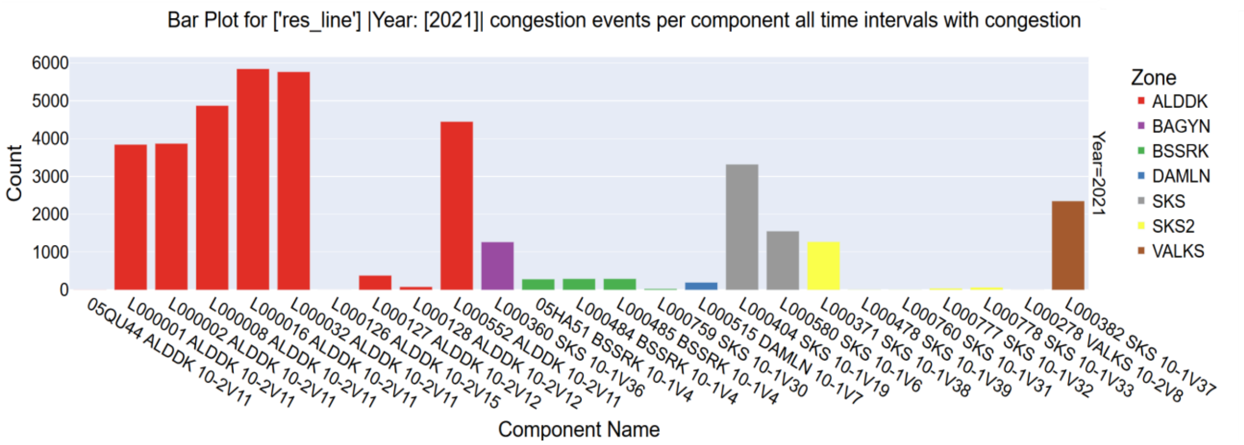

Figure 7.25: Line loading congestion events count for the Planned Growth Scenario.

These scenarios indicate that our current network is unlikely to experience congestion. However, for future scenarios involving PEDs, careful consideration is needed to determine the necessary upgrades.

In the Autonomous Growth Scenario, congestion is expected at every level of the network due to simultaneous PV production. On the demand side, there will be hours at night with no PV, requiring all demand to be transported from the highest to the lowest levels in the grid. Consequently, congestion will also occur throughout the network. Even with better control of demand through smart EV charging or the implementation of a heat network, production issues will still cause congestion. The only way to support a PED using solely solar power would be through widespread grid reinforcement or sufficient storage distributed across the network to store the bulk PV production.

In the Planned Growth Scenario, dispersed wind production leads to significantly less congestion. The congestion is concentrated in specific strings that could be reinforced, requiring much less network-wide reinforcement. Without smart charging and a heat network, demand will increase, and there will be times with no wind and high demand, leading to congestion. However, wind generally aligns better with demand than solar, so congestion will likely be less severe than in the Autonomous Growth Scenario. In this case, grid reinforcement or sufficient storage to store wind production and discharge it later to meet demand will be necessary. Ultimately, the chosen system must be based on multiple criteria, considering stakeholder preferences and tolerances.

7.2 Deliverable D4.2: Barriers for implementing PED's in the Netherlands

Within this section the technical barriers for implementing a PED are explored. Other influencing factors including spatial, economic, legal, and social are discussed in other deliverables of the FlexPost project.

Technical grid capacity: The most obvious barrier for PEDs in the Zwette case is the technical capacity of the electricity grid. The grid was designed based on projected electricity use without considering electric heating and transport options. Many of the electricity grids in the Zwette area were built in the previous century when heat pumps, electric cars, or even electric cooking were not anticipated. Additionally, industries are also turning to more efficient electric processes. Hence, the current electricity grid in the Zwette area was not designed with the new direction towards significant electrification in mind.

Reinforcing the entire electricity grid might seem like a viable solution; however, this will require a lot of manpower, time, equipment, and material. Moreover, it will create bigger problems with imbalance, merely shifting the problem elsewhere. Since grid congestion originates at the houses and businesses, the entire grid from low, middle, to high voltage must be strengthened. This results in the following barriers:

- The energy transition indicates electrification as a potential solution, increasing demand.
- Grid capacity at all levels needs reinforcement.
- Grid reinforcements are unlikely to keep pace with the timeline of the energy transition.

Simultaneity factor: Both on the demand and production side, renewable options have a high simultaneity factor, meaning they often operate or are active at the same time. Grid operators used the simultaneity factor to design electricity grids. By understanding how large groups of households behave in terms of electricity use, grid operators concluded that, on average, a household uses around 1.5 kW of power continuously. Therefore, the grid was designed with that factor in mind.

However, the simultaneity factor has increased significantly as we all produce electricity simultaneously with our solar PV panels when the sun shines. Additionally, we all want to heat our houses when it is cold, and with electric heat pumps, this means we all use electricity at the same time. Finally, when returning from work in the evening, we tend to charge our electric cars simultaneously, plugging them in after reaching the driveway. Combined, these factors can result in a simultaneity factor of almost 5 to 8 kw per household, which is around six times higher than the factor used for designing most electricity grids for households. This effect is instrumental in creating grid congestion and indicates that it is very temporary, like traffic jams. Grid congestion tends to occur at specific moments during sunny or cold days, and between these moments, there is often enough capacity. Hence, the grid must be designed to handle the highest peaks, regardless of how short they might last. This results in the following barriers:

- Electrification and renewable production often come with a high simultaneity factor.

- The simultaneity factor only occurs at specific times, leading to overdesigning the system for the highest peaks in load.
- High loads originate at the lowest level of the electricity grid.

Dunkelflaute: This term requires some explanation, which essentially refers to periods throughout the year when there is almost no solar irradiation or wind available for renewable energy production, combined with potential moments of high demand (e.g., low temperatures). During these moments, the grid is maximally strained, and the options for managing this are often either not available (e.g., wind and solar PV production) or already depleted (e.g., batteries, storage). A Dunkelflaute might occur only once per year; however, the electricity system must be able to cope.

The aforementioned often results in the need for very high capacity of, for instance, emergency power or tripling the installed capacity of battery storage just to cover this specific moment in time. Dunkelflautes are often very difficult to predict and avoid, and the options for managing them are limited to seasonal storage and currently fossil power plants. Furthermore, the impact of Dunkelflautes in the future with higher rates of electrification will most likely be more substantial, affecting both grid congestion and the balance of demand and supply. This results in the following barriers:

- Dunkelflautes are difficult to manage as technical options are often already exhausted.
- To manage Dunkelflautes, high capacities of backup power are required.
- With high rates of electrification, the impact of Dunkelflautes will be more substantial.
- Grid congestion will most likely occur during Dunkelflautes.

7.3 Deliverable D4.4: Flexibility assessment scenarios

Within the flexibility assessment two scenarios are explored, where additional storage, smart charging, and peak power production is added to the Planned Growth Scenario. In the **FLEX scenario** energy storage, smart charging, curtailment, and peak power (PPU) using locally produced biogas will be integrated in the Planed Growth scenario. Additionally in the **FLEX++ Scenario,** Energy savings (e.g. insulation of housing stock) will be included combined with bi-directional charging, thereby using electric transport in the region as local batteries.

7.3.1 Energy demand (PowerNodes)

Adding flexibility to the mix does not directly influence regional demand. The main elements of current demand and electric transport remain similar to the planned PED scenario. However, there is a substantial difference between the demand of the heat grids in the Flex and Flex++ scenarios (figures 7.26b and 7.26c). This difference results from the insulation of all houses, reducing the electricity demand of the heat grid from 22% to only 14%. Additionally, total demand will increase as batteries and bi-directional charging create additional demand. Smart charging and storage collectively generate an additional demand of around 15%. This additional demand helps absorb overproduction from intermittent renewable sources or shifts demand peaks to more suitable times for the electricity grid.

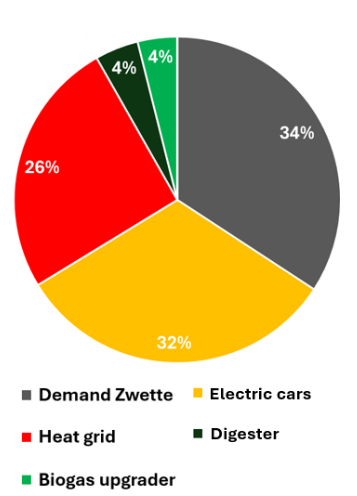

Figure 7.26a: Energy demand planned PED scenario

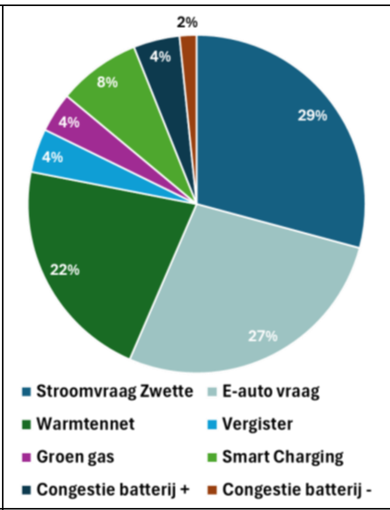

Figure 7.26b: Energy demand Flex scenario

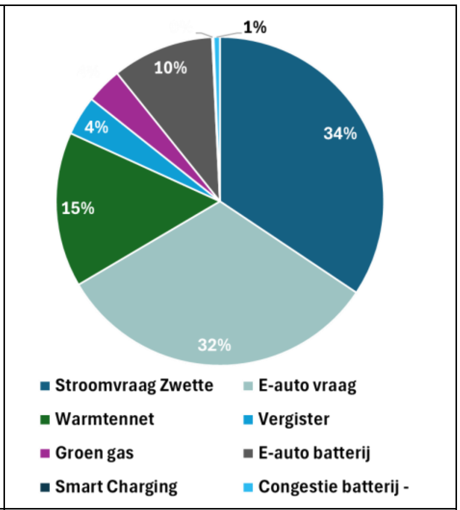

Figure 7.26c: Energy demand Flex ++ scenario

7.3.2 Energy production (PowerNodes)

In the Flex scenarios, energy production is almost entirely shifted towards wind energy, which more closely matches the demand NLS due to its consistent production throughout the year. This makes wind energy more available not only for meeting demand but also for recharging batteries. The amount of energy generated on a yearly basis is almost similar between all three scenarios. Additional production is generated by storage systems, such as bi-directional charging and batteries. As shown in Figure 7.27, these systems initially have an energy demand before they are filled and capable of producing energy. Like in reality, batteries have both an energy demand and energy production capacity.

Figure 7.27b and c show negative production, representing curtailment, or the shutting down of renewable production during peak production moments. In this context, the added production by storage in the Flex scenarios is essentially stored wind energy. Finally, there is a very small percentage of peak power production that is only active during high demand peaks that cannot be met by storage options or flexible demand. This energy is produced by engines running on biogas.

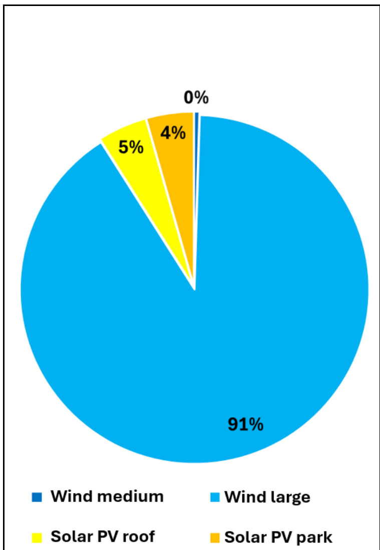

Figure 7.27a: Energy production planned PED scenario

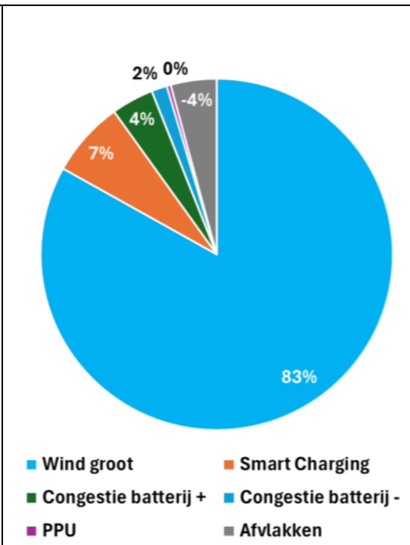

Figure 7.27b: Energy production Flex scenario

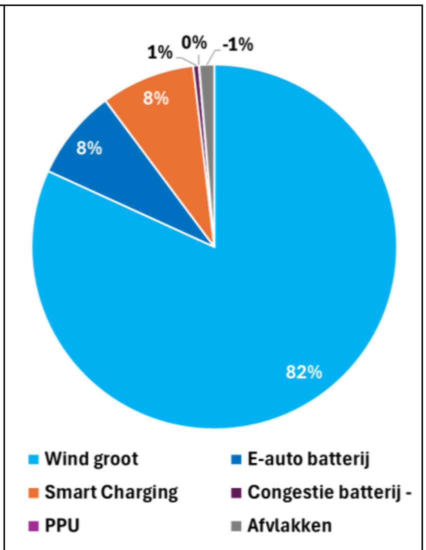

Figure 7.27c: Energy production Flex ++ scenario

7.3.3 Self-sufficiency (PowerNodes)

The planned PED scenario, used as the starting point for the Flex scenarios, is a PED from an energy perspective where the total yearly renewable production of the region exceeds the total yearly energy demand. However, when using storage and bi-directional charging systems, energy is lost in the process, reducing the total yearly production. On the other hand, self-consumption in the region improves by up to an additional 23% in the Flex++ scenario (figure 7.28).

In the Flex scenario, more energy is lost due to curtailment. However, adding storage options to manage the grid and mitigate grid congestion requires more energy production to compensate for system losses. This places additional strain on the already burdened electricity grid and the densely populated urban area.

Overall, using wind production, heat grids, and storage options can ensure almost 80% self-consumption of locally produced electricity, significantly reducing the strain on the central high voltage transportation grid of the Netherlands. While local grid congestion is greatly reduced, it cannot be entirely prevented in some bottlenecks, necessitating grid reinforcement in parts of the electricity grid.

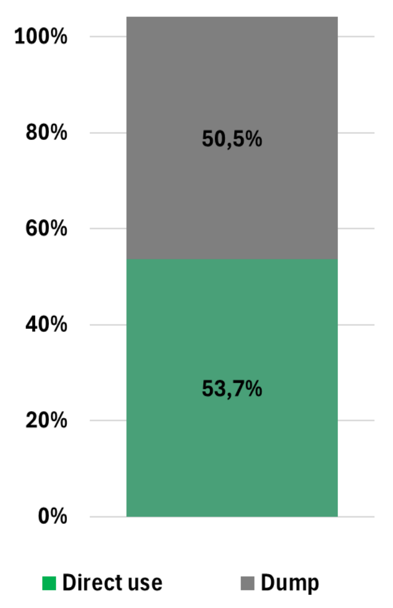

Figure 7.28a: Self Sufficiency planned PED scenario

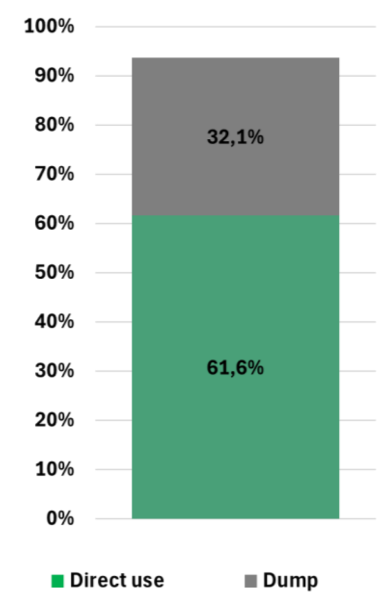

Figure 7.28b: Self Sufficiency Flex scenario

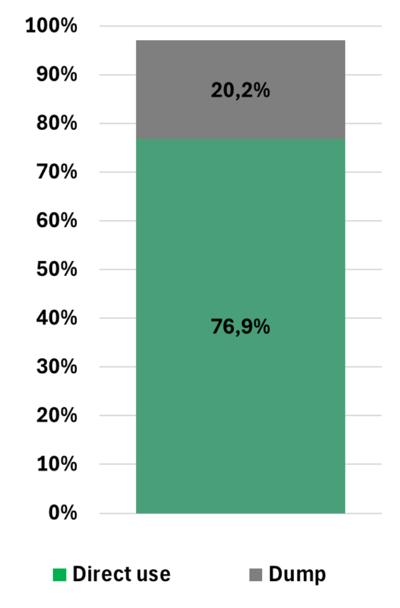

Figure 7.28c: Self Sufficiency Flex ++ scenario

7.3.4 Net Load Signal (PowerNodes)

Within the Net Load Signals in figure 7.29 the impact on the measurement point of the electricity grid is indicated. The colors represent the three incorporated scenario's with blue the Planned growth PED scenario based on wind and a heat grid, green the Flex scenario and with red the Flex++ scenario.

Flex scenario: By incorporating flexible power solutions such as batteries, peak power, and smart charging, a viable solution for the high voltage connections location can be achieved. However, this approach requires a central heat grid solution combined with a significant increase in wind energy. Within the NLS (see figure 7.29 below, green line), grid congestion is minimized by adhering to the limits of the main switching station and transformers. Despite this, there remains a considerable imbalance between the set limits, where grid congestion at lower levels in the electricity system below the main switching station can still occur. This indicates that further research is needed to identify local grid congestion points and plan grid reinforcements or the placement of flexible power sources nearby to mitigate the issue.

Both this scenario and the Flex++ scenario will require an emergency power system to absorb peak demand, which will be necessary for approximately 66 full load hours per year. Additionally, these scenarios anticipate that car owners will charge their vehicles over an extended period, thereby mostly avoiding fast charging. Finally, the battery will be effectively utilized throughout the year for both overproduction and demand management.

Flex ++: In the Flex++ scenario, additional storage in electric cars is achieved through bi-directional charging, and heat usage is reduced by an extensive insulation program, saving up to 40% of the original heat demand. In the NLS (see figure 7.29, red line), fluctuations are substantially decreased, resulting in longer periods where demand and production are balanced. The effect on grid congestion is comparable to the Flex scenario, with fewer instances where loads approach maximum capacity. However, large amplitudes of demand or production peaks still occur in the NLS, placing more strain on the central balancing system.

Currently, these variations are primarily balanced using fossil gas-fired power plants, which will need to be replaced by renewable alternatives. Imbalances outside the reach of batteries will be particularly challenging to address. The results indicate that grid congestion can be managed, but further research is needed to optimize the use of combinations such as smart and bi-directional charging, battery storage, and peak power production for more effective de-central grid balancing.

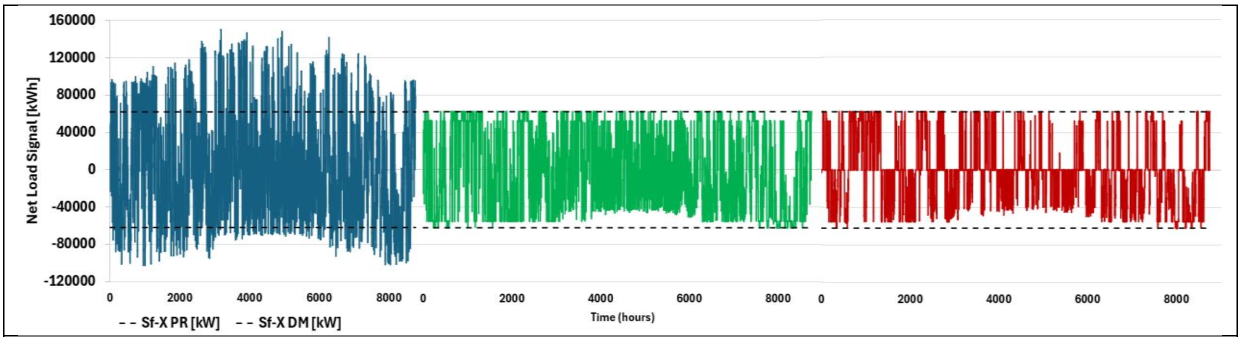

Figure 7.29: NLS of autonomic growth scenario, connection to high voltage grid Leeuwarden

7.3.5 Load Duration Curve (PowerNodes)

Within the net Load Duration Curves in figure 7.30 the specific functions of the used balancing technologies become more apparent. The colors represent the three incorporated scenario's with blue the Planed growth PED scenario based on wind and a heat grid, green the Flex scenario and with red the Flex++ scenario.

Flex scenario: Within the Flex scenario, the limits set by the grid operator are not exceeded (see Figure 7.30, green line). On the far left of the figure, the NLDC initiates curtailment to prevent production from surpassing the grid's capacity. This is followed by smart storage, which activates by charging when the load on the electricity grid exceeds a set threshold. When the load falls below this setpoint, the battery immediately discharges to be ready for the next cycle.

The sloping line in the middle of Figure 7.30 represents the combination of normal demand and wind production, similar to the Planned Growth PED scenario. Within this area, the NLS fluctuates between overproduction and demand (see Figure 7.29, green line), which does not exceed the grid's maximum capacity. However, it significantly impacts the balance of the electricity grid. This imbalance must be corrected elsewhere in the grid through flexible generation or storage. Near the far right of the NLDC, the batteries are also active during demand peaks.

Similar to overproduction, batteries can discharge during peak demand loads and recharge immediately afterward for the next peak demand. In theory, both functions of managing overproduction and peak demand can be handled by a single battery system. However, during transitions from peak demand to peak production, the state of charge may be insufficient. For instance, if the battery discharges after an overproduction peak, it may not be ready for a subsequent peak demand load.

The final peak demand load, beyond the range of batteries, is managed using emergency power generation, such as (bio)diesel generators or hydrogen fuel cells. The generator activates when the peak demand load exceeds a setpoint in the grid. The results indicate that the installed capacity of peak power required to manage the peak demand load for the Schenkenschans area is around 25 MW, comparable to a small power station.

Flex ++: In the Flex++ scenario, the additional storage provided by electric cars significantly impacts the NLDC (see Figure 7.30, red line). The grid congestion management strategies remain mostly the same, using curtailment and smart batteries for overproduction, and smart batteries and emergency power for peak demand. However, the need for emergency power is reduced to around 20 MW, and the need for smart battery storage capacity decreases from 100 to 50 MWh.

Results indicate the biggest impact occurs in the middle of the NLDC (see Figure 7.30, red line), where bi-directional electric cars are active. Using smart bi-directional charging and discharging, demand and production are balanced within the Schenkenschans area for almost half of the year, demonstrating the substantial potential of using electric cars as batteries.

Overall, the total storage capacity available if all transport in the Schenkenschans area is electric is estimated to be around 1300 MWh, which is ten times higher than the required smart battery capacity in the Flex scenario. Finally, the Flex++ scenario indicates a manageable load within the current limits of the electricity grid while achieving a Positive Energy District, suggesting potential technical feasibility.

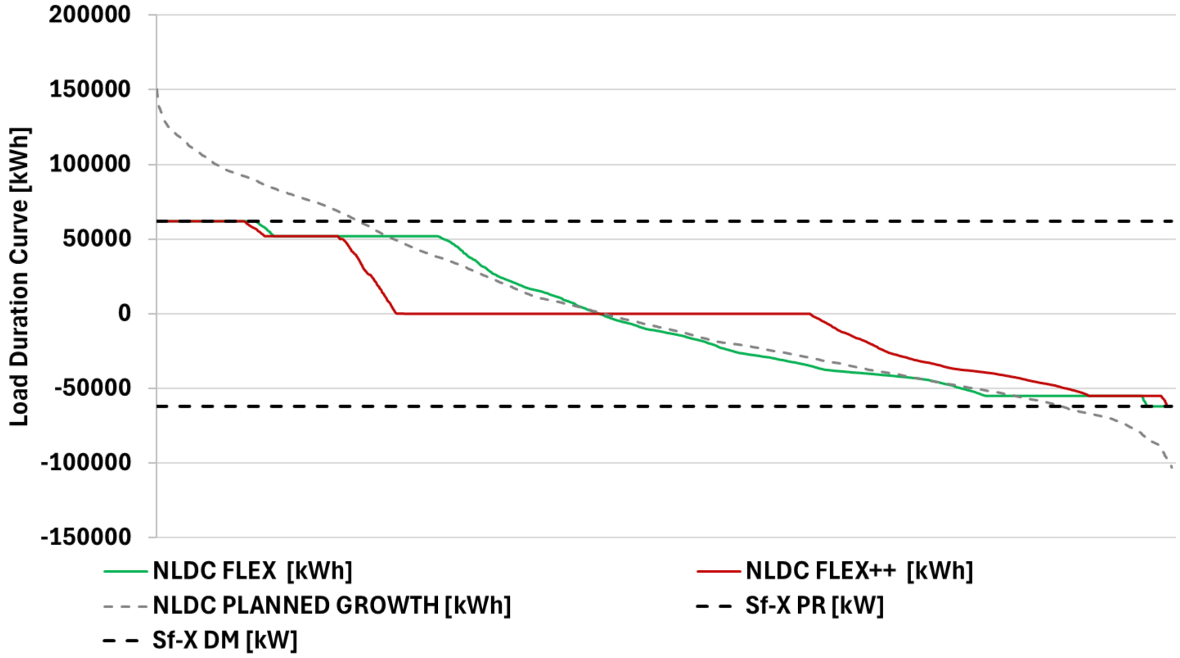

Figure 7.30 NLDC of reference, autonomic and Planned Growth Scenarios, looking at connection to high voltage grid Leeuwarden (Schenkenschans)

7.3.6 Heat map grid congestion (PandaPower)

The output for PandaPower in this scenario is comparable to the normal Planned Growth Scenario, with the key difference being that the HV-MV transformer does not experience physical overloading due to the added assets (batteries, peaker, and curtailment). Refer to Sections 7.1.4 and 7.1.5, Figures 7.11 and 7.12 for line loading, and the appendix Figures A.5, A.6, A.10, and A.11 for transformer loading.

7.3.7 Severity and locational grid congestion plots (PandaPower)

The output for PandaPower in this scenario is comparable to the normal Planned Growth Scenario, with the key difference being that the HV-MV transformer does not experience physical overloading due to the added assets (batteries, peaker, and curtailment). Refer to Sections 7.1.4 and 7.1.5, Figures 7.15 and 7.18 for the network plots, Figures 7.25 and 7.27 for line loading, and the appendix Figures A.18, A.19, A.22, and A.23 for transformer loading.

7.4 Deliverable D4.4: Flexibility assessment analysis reference scenario

In this section the current total electricity profile of the Zwette for the HV-MV transformers is simulated in PowerNodes, considering the influence of batteries/peaking generators and curtailment. This represents the reference scenario. The Pandapower simulation for the reference case indicated no congestion at the MV level. As a result, we can use the high-level profiles to determine how much capacity can be freed up, as there are no transmission constraints in the MV level grid. Therefore, there is no need to free up capacity at the MV level. It is assumed that the congestion status has been called at the HV voltage level by Tennet. Using batteries/peaking generators and curtailment at this level can free up certain capacities that could be utilized by other entities in the MV level of the grid. Multiple combinations of batteries/peaking generators and curtailment have been simulated, allowing us to determine how much capacity can be freed on the demand or production side and the associated costs per asset/operation. The results of these simulations are presented in Figure 7.31.

The x-axis of Figure 7.31 represents the amount of capacity freed in MW when operating the energy project. There are two y-axes. The left-hand y-axis shows the NPV of the cost breakdown of CAPEX and OPEX for a particular technology, indicated by the vertically stacked bars. The positive side of the left-hand y-axis represents the production side, while the negative side represents the demand side. These are both negative financial flows, but in the convention of our plot, they are indicated this way to mirror the production and demand sides. The scenario number is indicated on top of the bars. The right-hand y-axis shows the cost to free up 1 MW of capacity on either the production or demand side by operating the energy project. This is indicated by the marker symbols, which share the x-coordinates with the bars. Green squares represent the production side, and red circles represent the demand side. Since we simulate multiple projects that free up the same amount of capacity, these scenarios are grouped and centered around the freed-up capacity x-axis coordinate. This shared x-axis coordinate is indicated by the vertical dashed red line around which the grouped bars are centered. The horizontal dashed red line indicates the NPV value of the project using an unlevered cash flow calculation. The goal of this section is not to detail an entire business case; we show only the cost components. The dashed horizontal red line is lower than the stacked bars due to some positive cash flow components in the calculation that we do not show here.

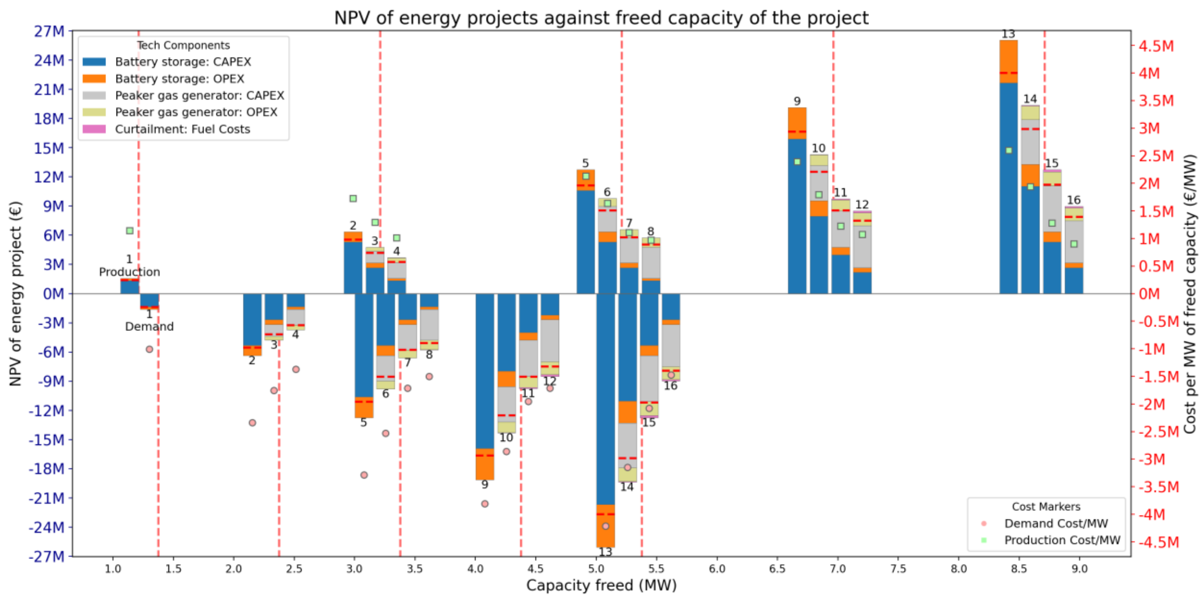

Figure 7.31: The amount of capacity freed (x-axis) on the production (positive y-axis) and demand (negative y-axis) side using different energy technology combinations and the total NPV (left y-axis) and the cost per MW of freed capacity (right y-axis).

Figure 7.31 provides the following insights into using these technologies to free up capacity:

- It is easier to free up production-side capacity than demand-side capacity. For the same energy project, more capacity is unlocked on the production side than on the demand side, and the cost per MW is lower for the production side.

- Generally, combining technologies leads to lower costs than using only storage. The cost per MW is higher for storage-only projects. This is likely because the usage rate of the additional installed storage capacity to meet the last peak demands is much less cost-effective compared to the initial units of installed storage capacity. Using a different technology to handle the last few peaks of demand makes the first few units of the other technology more cost-effective than the last few units of the storage technology. The system can be incrementally sized to achieve the optimal mix of technologies to free up the most capacity at the lowest cost.

The largest simulated project freed up approximately 5.4 MW on the demand side and 8.7 MW on the production side. The cost per MW was around 900K/MW for the production side and 1.46M/MW for the demand side. Given the inherent uncertainty in such cost estimates, a sensitivity analysis was performed to show the impact of various cost parameters on the estimates. This is illustrated in Figure 7.32. Since no economies of scale effects were assumed in the cost figures used, all these relationships are linear. The effects also align with the distribution of the bar chart in Figure 7.31.

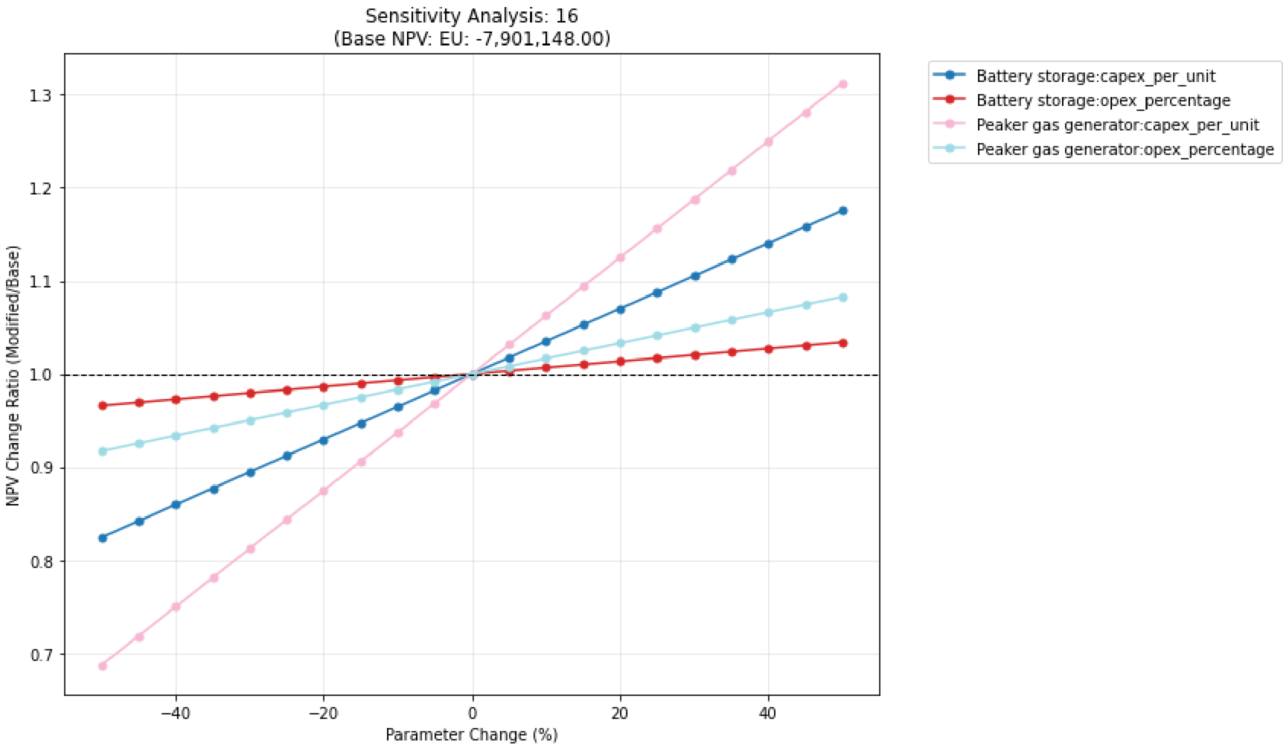

Figure 7.32: Sensitivity analysis on the CAPEX and OPEX assumptions of scenario 16 technologies.

The y-axis of Figure 7.32 represents a normalized value compared to the base case value. Using this chart, the NPV under different cost assumptions can be calculated by applying the normalized value. These cost estimates assume that the project assets break even on their fuel costs and energy sold. Since the assets will likely operate under conditions that generate revenue, these estimates are conservative. For example, the battery will typically peak shave on the production side when there is overproduction from decentralized renewable sources (solar), which usually correlates with lower prices. Conversely, the battery will discharge to meet demand when there is a lack of production, which usually correlates with higher prices. Therefore, the battery's operation is expected to generate more revenue from discharging than costs from charging, making the cost estimate less negative than our figure with the breakeven assumption.

The same logic applies to the peaker generator, which will only be dispatched during high demand, high price intervals, likely leading to more revenue than fuel costs. Note that in the modeling of the peaker generators, it was assumed they are 100% dispatchable with no ramping constraints at startup. If there are ramping constraints for the most extreme scenarios, the peaker generator is probably undersized, and the cost estimates should be higher. Since the relationship is linear, the cost estimate can be scaled with the peaker capacity to obtain the new cost estimate.

7.5 Deliverable D4.6: Stakeholder engagement

Within the Zwette case analysis (energy balance) focus was placed on two specific stakeholders namely the Distribution System Operator (Liander) and the Municipality of Leeuwarden. With Liander representing the electricity transportation and distribution system mainly from a technical perspective and the municipality of Leeuwarden representing the Zwette industrial area and the energy transition goals set both nationally and locally. For both stakeholders we attempted to optimize the collaboration and information sharing through workshops and also train the trainer sessions.

7.4.1 Grid operator Liander

The grid operator responsible for the Zwette area is Liander and their support, data, and technical knowledge was instrumental for the technical analysis of the Zwette case itself. To minimize the time requirement from their specialists and to optimize the time eventually planned, the planned sessions where organized in model walkthrough workshops. During this workshops the experts from Liander, the municipality of Leeuwarden and the Hanze would sit together and go through the model question by question, thereby, validating both the PowerNodes and Pandapower model. This approach requires good preparation by the modeling party (Hanze) to specify, prioritize, and organize the walkthrough session such that it can be performed efficiently and effectively within one or two afternoons. Next to this, finding common language was also very important, which also requires good preparation and clear presentation of both question and results. When there is no common language miscommunication will arise. Within the meeting we focused on the expertise of Liander and asked questions and show results from a grid operator perspective, using their own models and graphs as a starting point (figure 7.34 and 7.35).

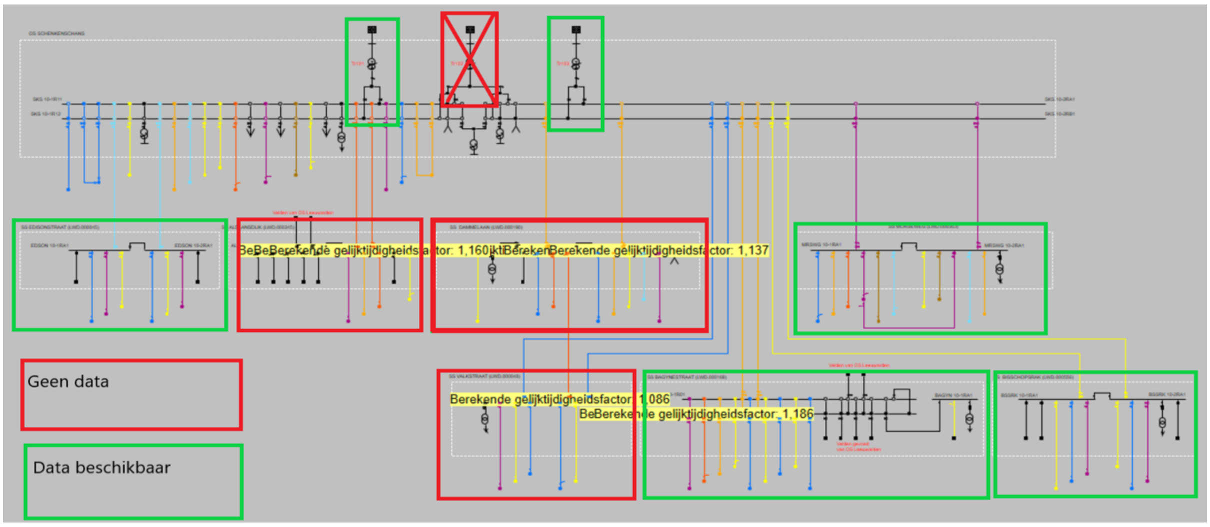

Figure 7.34: Grid structure of mid voltage grid Leeuwarden (Schenkenschans)

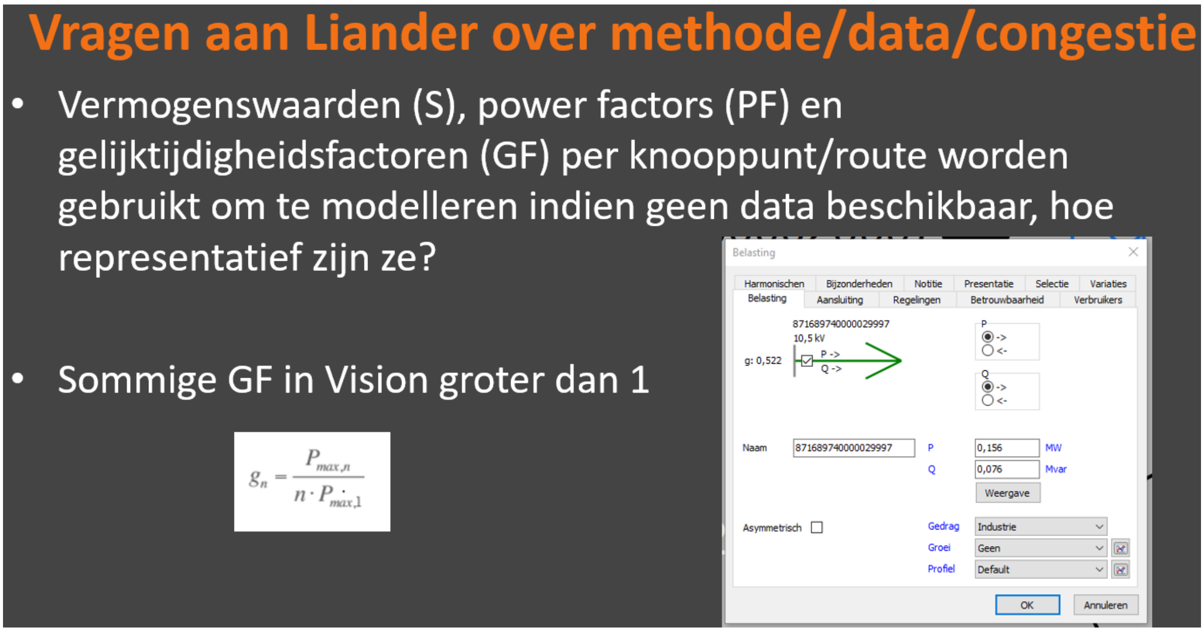

Figure 7.35: Example question posed during workshop regarding settings in the Vision model used by Liander)

7.4.2 Municipality of Leeuwarden

When performing scenario studies there are essentially infinite possibilities and possible tweaks that can be made. Next to this to understand these infinite options and tweaks the receiver of the information will need some idea of the model used and or the system modelled. Therefore, an additional goal was formulated to transform the PowerNodes model, so that it can be used on a high level for running scenarios for Positive Energy Districts (figure 7.36). Additionally, a course will be developed including a manual for the model to educate potential users.

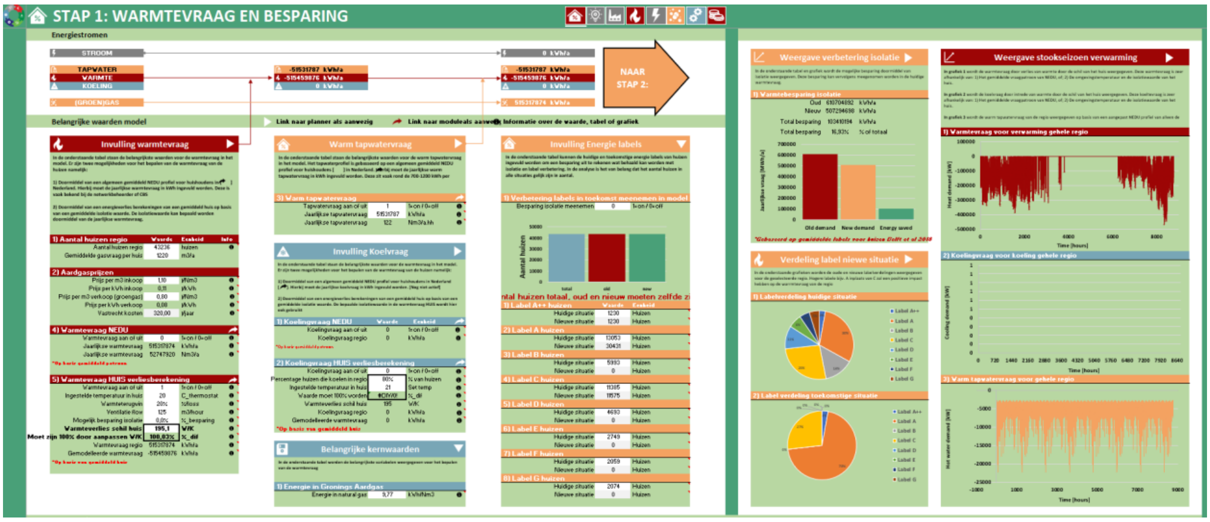

Figure 7.36: Example of scenario planner in the PowerNodes model that can be used by external parties like the municipality of Leeuwarden

In figure 7.37 below the first trial version of this course was given to the municipality of Leeuwarden wherein they actively engaged with the model, programming and analyzing scenarios of the Zwette area. The model used in this session specifically contains data of companies and the local electricity grid that can be analyzed by the municipality on high voltage to low voltage level. Meaning that with the PowerNodes model, solutions can be analyzed for individual companies or small residential (one low voltage substation) areas to switching stations and up to the connection with the high voltage grid. For example, the PowerNodes model can enable users to fill in data of specific neighborhoods e.g. low voltage transformer and or gas station and model a potential PED including the strain on that specific area on the grid. The aforementioned approach can give a high level overview in a limited amount of time looking at potential problems and solutions for planning towards a PED. Most importantly, when actively working on these scenarios participants gain vital knowledge of the energy system required to make informed decisions within future PED solutions.

Figure 7.37: Example of train the trainer session [1] for the municipality of Leeuwarden

Figure 7.38: Example of train the trainer session [2] for the municipality of Leeuwarden

8 Discussion

When modelling, simplifications and assumptions are made, therefore, the results must also be reviewed with this in mind. The PandaPower part of the modelling the approach could be more robust if there is more real data employed in the simulation. Due to the network being relatively large and many profiles not standard, assumptions need to be taken that could be unrealistic. If the simulation is done with incorrect profiles, the powerflow could be wrong. For the reference case there were no result that indicate extreme scenarios. Thus if the assumptions do not introduce large errors it should still give results within an acceptable margin of error and should be relatively accurate.

For the grid simulations in Pandapower, the current grid architecture was used. However, this might change as the grid can be actively managed, creating different switching solutions and, with them, different grid flow pathways. For company electricity data, Kenter was approached to supply hourly profiles of the last full year. However, the dataset does not contain all companies or households, and every dataset has errors. To model household demand patterns, historical average patterns were used in combination with general yearly energy demand, which do not always reflect actual conditions taking into account weather, or local events. This introduces uncertainty into these demand profiles. Weather data from the weather station in Leeuwarden (station number 270) of the Royal Dutch Meteorological Institute (KNMI) was used. The data includes Global Horizontal Irradiance (GHI) (W/m²), ambient temperature (°C), and wind speed (m/s). However, the data works with wind speeds in steps of 1 meter, and cloud movement is not included as it differs per location, which will make wind production predictions in the PowerNodes model less accurate. Overall, multiple assumptions and generalizations were required to program both Pandapower and PowerNodes, increasing sensitivity and lowering accuracy.

Grid congestion is a combination of technical aspects, modeled in this report, and administrative aspects, which include contracted power of companies, projected growth of demand, indicated and planned growth of demand, safety aspects for guaranteeing the supply of energy, and others not included in the analysis of this report. The aforementioned makes grid congestion complex from multiple perspectives, also adding to the complexity of the solutions. Furthermore, grid congestion is very local and can occur in a specific street up to a connection point to the high voltage grid. Therefore, solutions provided at the main station level might not solve all grid congestion problems below the balanced point. Some areas or weak links in the electricity grid will need to be reinforced. The reference scenario indicated some localized grid congestion based on simulated power-flows. However, most profiles were simulated, and the congestion results fell within the margin of error for these synthetic profiles. Discussions with the DSO suggested that actual congestion was unlikely. Additionally, the model does not account for dynamic operations such as switching, leading to certain uncertainties. Therefore, Pandapower is not employed for these scenarios, as aggregated/individual profiles are sufficient to indicate flexibility potential. Conducting a power-flow simulation for a scenario with likely no physical grid congestion offers no added benefit when focusing on line and transformer loading.

Within this report, results indicate there is no current grid congestion in the Zwette from a technical perspective, which is logical as that would mean blackouts would occur. However, this does not mean that grid congestion is not present, as the administrative factors also need to be taken into account. Still, Grid congestion is already a problem in the Zwette case. One key lesson learned is that a grid congestion status does not necessarily indicate physical grid congestion in the local grid. The procedure used by the DSO to declare a grid congestion status includes long-term growth forecasts, incorporating a safety margin due to reliability standards before actual physical grid congestion occurs. Therefore, a power-flow simulation might indicate no physical grid congestion, resulting in a 'paper congestion.'

Additionally, the actual grid operation could be more dynamic than our electricity grid model, which is based on a static network configuration. Dynamic operations, such as switching during non-optimal performance, are not accounted for in our static network model. These operations could influence power-flow results, introducing inherent uncertainty in the power-flow outcomes. Also, Both the FLEX and the Flex++ scenario anticipate that car owners will charge their vehicles over an extended period, thereby mostly avoiding fast charging.

Also, the planned technical solutions will have a substantial footprint on the available space in the Zwette as well as a significant price tag, which also needs to be considered. Regulations and laws are also part of the aforementioned.

9 Conclusion

Within this report and the FLEXPOSTS project, the focus is placed on analyzing the Zwette case to better understand grid congestion now and in future growth scenarios, and to analyze the impact of potential solutions. First, the focus will be on potential methodologies and tools that can be used for analyzing current and future grid congestion, as well as the impact of potential solutions, task T3.1.

WP 3: Process innovation, business models and circularity
T3.1: Developing methodologies for implementing PEDs
T3.2: Developing business models and PED implementation strategies
T3.3: Replication Toolkit

Next, these tools will be used to model the De Zwette area in Leeuwarden to perform a current state analysis, followed by future PED scenarios as part of task T4.1. One of the future PED scenarios will be further developed by adding flexibility to lower the impact on the electricity grid and increase balance, as part of task T4.4. Additionally, the PowerNodes model will be made available for stakeholders and used in stakeholder sessions, as part of task T4.6. Finally, results and conclusions from the scenarios will be discussed, and a general tool will be proposed for performing high-level analysis of grid-congested areas.

WP 4: Demo Site Zwette VI, Leeuwarden
T4.1: Assessment of energy demand, generation profiles, and local energy balance
T4.2: Identifying regulatory, structural and technical barriers
T4.3: Identifying existing partnerships and networks at Zwette VI
T4.4: Assessment of the quality of flexibility
T4.5: Developing business models
T4.6: Developing a strategy for implementing PED

Traditionally, the intervention by the electricity grid system operator has been to reinforce or expand the grid. However, other options such as flexible production, demand and production side management, and storage have not been studied in depth. This raises the question:

What are the optimal interventions or combinations of interventions to manage grid congestion, considering different technological options?

This main challenge is being analyzed at the De Zwette demo site, where we aim to quantify the techno-economic impact of various solutions to alleviate grid congestion, while considering regulatory, structural, and technical barriers.

D4.1 Local energy balance assessment

Within the energy balance assessment three main scenarios are worked out namely; the reference scenario, describing the current situation; the autonomic growth scenario, projecting current developments towards a future PED; and the planned scenario, where the municipality actively steers the development of the PED.

In the **Reference scenario,** the resulting NLS, and more specifically the fluctuations within it, are not only caused by industry but also in equal measures by the residential areas connected to the Schenkenschans area. Therefore, results indicate that, households play a significant role in both creating grid congestion and providing solutions. However, currently there are very few line loading congestion events, and the severity of the congestion is not extreme. Due to the uncertainty in the simulated profiles over this large network, it is probable that there is currently no physical line loading congestion occurring. Which seems logical as line overloading would mean loss of electricity or local blackouts, which would not escape the attention of both Liander and the municipality of Leeuwarden.

However, in the **Autonomous Growth Scenario,** where there is an expected growth in solar PV on rooftops of 400 MW combined with heat pumps, the maximum production of the combined PV installations easily surpasses the capacity of the main station's transformers, leading to grid congestion. Additionally, energy demand throughout the year increases due to the introduction of electric cars and green gas production, leading to grid congestion on the demand side even in summer. This creates situations where, over the course of a single day, there can be congestion on both the production and demand sides. The range of maximum line loading observed is around 0-350% above our physical limit for the solved timesteps. The non-converged or unsolvable timesteps by the Pandapower model are likely worse. Timesteps with maximum solar production coincide with the timesteps during which the most lines experience congestion. This is likely because within this scenario PV capacity is distributed throughout the entire network. Consequently, all this capacity feeds in simultaneously from all levels of the grid, causing widespread congestion. Therefore, the lines in the network with the worst observed congestion would need to have at least 4,5 times the current capacity.

Within the **Planned Growth Scenario,** there is an expected growth in wind energy and heat production will be filled in using a heat grid. Results indicate that the impact on the electricity grid is less substantial than for the Autonomous Growth Scenario. Still, the increased demand from electric cars substantially increases the demand peaks compared to the Reference Scenario. However, unlike the Autonomous Growth Scenario, for this scenarios Pandapower found a solution for every timestep, indicating that the extreme conditions in this system are less severe than in the Autonomous Growth Scenario. During these timesteps, the planned scenario performs relatively well in terms of congestion, whereas the autonomous growth scenario experiences high congestion. The range of maximum line loading observed is around 0-180% above our physical limit and thus less severe than the Autonomous Growth Scenario. For the Planned Growth Scenario, this is the confirmed worst condition, indicating that the capacity of some specific lines should be increased by a factor of approximately 3. Congestion likely occurs during timesteps with relatively lower demand and high wind production or relatively high demand and low wind production. In both cases, congestion mainly occurs in the higher-level lines. The lower-level lines also have relatively higher capacity to handle it due to higher simultaneity assumed at lower levels of the grid. As power flows upward into the network, the higher-level lines, designed with a lower level of simultaneity in mind, experience congestion. The effect of the heat grid and smart EV charging limits the increase in peak electricity demand. Furthermore, in the Planned Growth Scenario, dispersed wind production leads to significantly less congestion. The congestion is concentrated in specific strings that could be reinforced, requiring much less network-wide reinforcement. Without smart charging and a heat network, demand will increase, and there will be times with no wind and high demand, leading to congestion. Results show that the highest number of lines undergoing congestion in one timestep in the Planned Growth Scenario is 14, in contrast to 100 lines in the Autonomous Growth Scenario. One reason for this difference is the way wind is integrated into the network, dispersed through the network in the middle of each string, allowing power to flow in both directions. However, wind generally aligns better with demand than solar, so congestion will likely be less severe than in the Autonomous Growth Scenario. In this case, grid reinforcement or sufficient storage to store wind production and discharge it later to meet demand will be necessary. Ultimately, the chosen system must be based on multiple criteria, considering stakeholder preferences and tolerances.

D4.2 Barriers for implementing PED's in the Netherlands

Within this report only the technical barriers for implementing a PED are explored. Other influencing factors including spatial, economic, legal, and social are discussed in other deliverables of the FlexPost project. Below the main barriers encountered during the Zwette case.

Technical grid capacity: The most obvious barrier for PEDs in the Zwette case is the technical capacity of the electricity grid. The grid was designed based on projected electricity use without considering electric heating and transport options, resulting in the following main barriers:

- The energy transition indicates electrification as a potential solution, increasing demand.
- When increasing local demand and renewable production (e.g. Solar PV, Electric transport, heat pump, electrification of processes) grid capacity at all levels needs reinforcement, from high voltage, middle voltage, to low voltage.
- Grid reinforcements are unlikely to keep pace with the timeline of the energy transition.

Simultaneity factor: Both on the demand and production side, renewable options have a high simultaneity factor, meaning they often operate or are active at the same time. Grid operators used the simultaneity factor to design electricity grids, resulting in the following main barriers:

- Electrification and renewable production often come with a high simultaneity factor.
- The simultaneity factor only occurs at specific times, leading to overdesigning the system for the highest peaks in load.
- High loads can originate at the lowest level of the electricity grid at the connection with individual users.

Dunkelflaute: This term requires some explanation, which essentially refers to periods throughout the year when there is almost no solar irradiation or wind available for renewable energy production, combined with potential moments of high demand (e.g., low temperatures) , resulting in the following main barriers:

- Dunkelflautes are difficult to manage as technical options are often already exhausted.
- To manage Dunkelflautes, high capacities of backup power are required.
- With high rates of electrification, the impact of Dunkelflautes will be more substantial.
- Grid congestion will most likely occur during Dunkelflautes as all the demand will need to be transported in from central production or storage facilities (currently often central fossil power plants).

D4.4. Flexibility assessment analysis

Flexibility scenarios: Within the flexibility assessment two scenarios are explored, where additional storage, smart charging, and peak power production is added to the Planned Growth Scenario. In the **FLEX scenario** energy storage, smart charging, curtailment, and peak power using locally produced biogas will be integrated in the Planed Growth scenario. Additionally in the **FLEX++ Scenario,** Energy savings (e.g. insulation of housing stock) will be included combined with bi-directional charging, thereby using electric transport in the region as local batteries.

Within the Flex scenarios results indicate that using wind production, heat grids, and storage options can ensure almost 80% self-consumption of locally produced electricity, significantly reducing the strain on the central high voltage transportation grid of the Netherlands. While local grid congestion is greatly reduced, it cannot be entirely prevented in some bottlenecks, necessitating grid reinforcement in parts of the electricity grid. However, despite this, there remains a considerable imbalance between the set limits, where grid congestion at lower levels in the electricity system below the main switching station can still occur. This indicates that further research is needed to identify local grid congestion points and plan grid reinforcements or the placement of flexible power sources nearby to mitigate the issue.

Both this scenario and the Flex++ scenario will require an emergency power system to absorb peak demand, which will be necessary for approximately 66 full load hours per year. Additionally, these scenarios anticipate that car owners will charge their vehicles over an extended period, thereby mostly avoiding fast charging.

Flexibility assessment analysis reference scenario: This analysis focusses on freeing up capacity at the high voltage connection with TenneT. Within this analysis multiple combinations of batteries/peaking generators and curtailment will be simulated, to determine how much capacity can be freed on the demand or production side and the associated costs per asset/operation.

Results indicate that, battery systems can be effectively utilized throughout the year for both overproduction and demand management. The cost of freeing up capacity at the high voltage connection with TenneT per MW of was around €900K/MW for the production side and €1.46M/MW for the demand side.

The following main lessons learned could be extracted from the reference scenario analysis:

- It is easier to free up production-side capacity than demand-side capacity. For the same energy project, more capacity is unlocked on the production side than on the demand side, and the cost per MW is lower for the production side.
- Generally, combining technologies leads to lower costs than using only storage. The cost per MW is higher for storage-only projects. This is likely because the usage rate of the additional installed storage capacity to meet the last peak demands is much less cost-effective compared to the initial units of installed storage capacity. Using a different technology to handle the last few peaks of demand makes the first few units of the other technology more cost-effective than the last few units of the storage technology. The system can be incrementally sized to achieve the optimal mix of technologies to free up the most capacity at the lowest cost.

From the future flexibility scenario’s:

- Heat grids can help solve grid congestion in the mid to lower voltage grid.
- Using the potential of electric cars as batteries holds great promise; however, there are no guarantees of availability at every moment of the day.

D4.6: Stakeholder engagement

Engaging and including stakeholders in the technical phase of PED design and analysis is not often integrated and utilized, however, it is becoming more and more important, as solutions are often not manageable by one stakeholder. For strong solutions interdisciplinary collaboration is required over multiple disciplines. Also, collaboration and mutual understanding in the beginning of the process will help the continuation of the process. From the process of stakeholder engagement within this technical analysis, vital information was gathered from both the grid operator and the municipality, required for more accurately modelling the Zwette case. Furthermore, stakeholder engagement can broaden as well as deepen the discussion on the topic as new viewpoints are integrated in the analysis itself.

Within the technical scenarios two main process where utilised:

1) For the validation of both the PowerNodes and Pandapower models interactive workshops where organized between the Hanze, Municipality of Leeuwarden and Liander. During this workshops we did a walkthrough the modelling approaches and data used in the analysis.
2) For further understanding of the results from the analysis in the Zwette case and for using the knowledge gained in other potential cases a general model was produced that can be used by third parties. This model was handed over to the municipality of Leeuwarden together with train the trainer sessions. The PowerNodes tool can provide customized flexibility assessments for different subsections of the grid if profile data for those subsections is available. During stakeholder sessions, the municipality received

training on using the tool. This tool is generally appliline to any industrial area, enhances the municipality's knowledge, and empowers them to conduct such analyses independently in the long term.

Project experience indicates that, stakeholder engagement should (also) be part of the technical analysis right from the very beginning, which is advised for all other PED projects or technical analysis in general.

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Appendix

Transformer current loading % heat maps

The following Figures give the transformer loading for the different scenario's for transformers consuming and producing. For the reference scenario although there are moments that certain transformers go over their physical limit, most of these are all under the same switching station. The rest are all limited to one transformer for two other switching stations. The profiles for these transformers are also all simulated. After a meeting with the DSO it was not deemed abnormal for a transformer to be overloaded physically as longs as this does not occur too often. The overloading was not extreme, less than 10% on average for consumption and production. As this value was not too high it was deemed likely that it falls into the uncertainty inherent in simulating the profiles. Also because there was (almost) no line current loading congestion it seems likely that these results do not represent actual congestion in the reference scenario. Based on this we conclude that it is likely that there is no physical congestion present in the reference scenario.

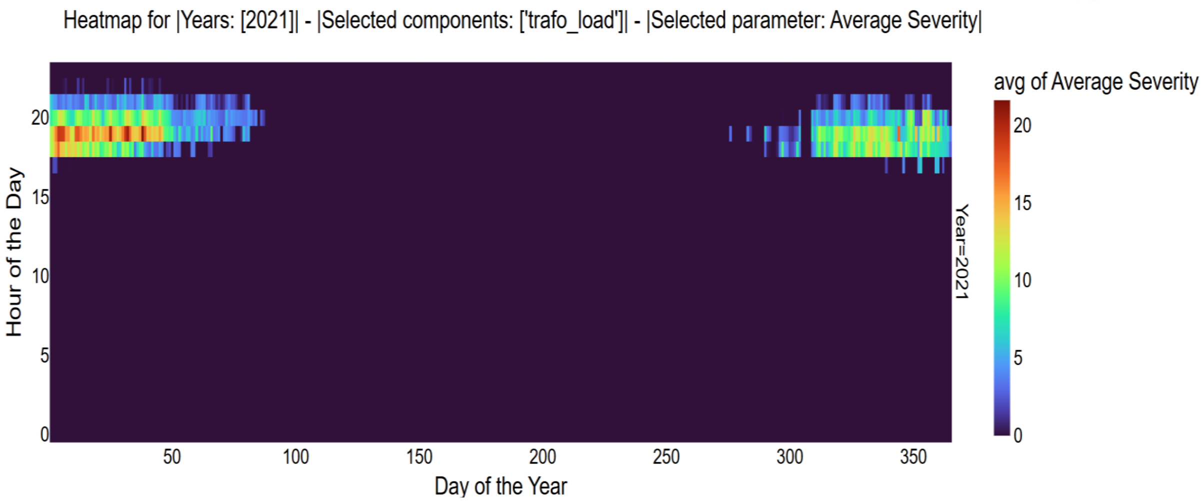

Figure A.1: Current loading severity of transformers consuming power during the powerflow simulation for the reference scenario

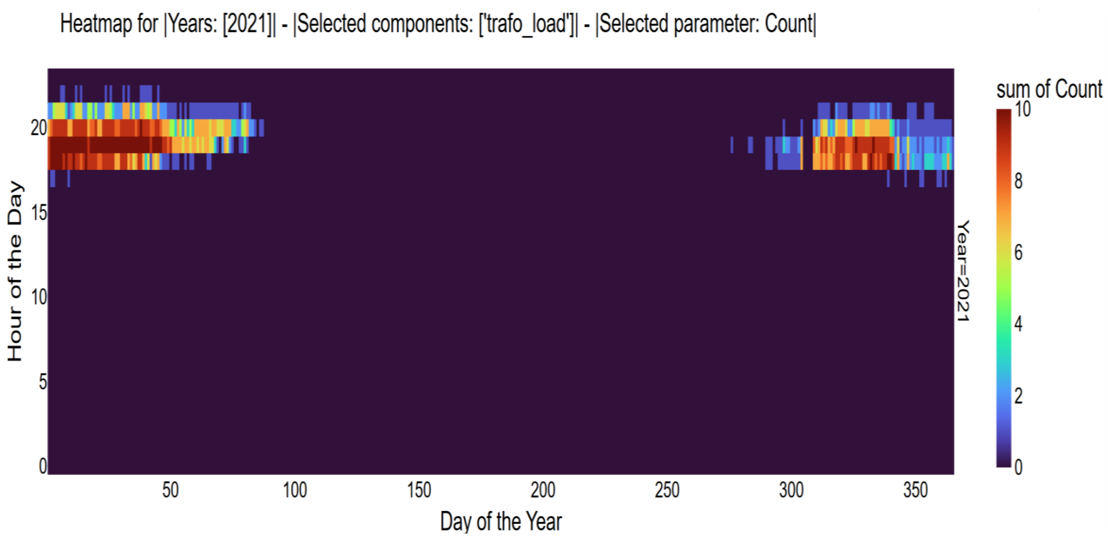

Figure A.2: Count of current loading congestion events of transformers consuming power during the powerflow simulation for the reference scenario.

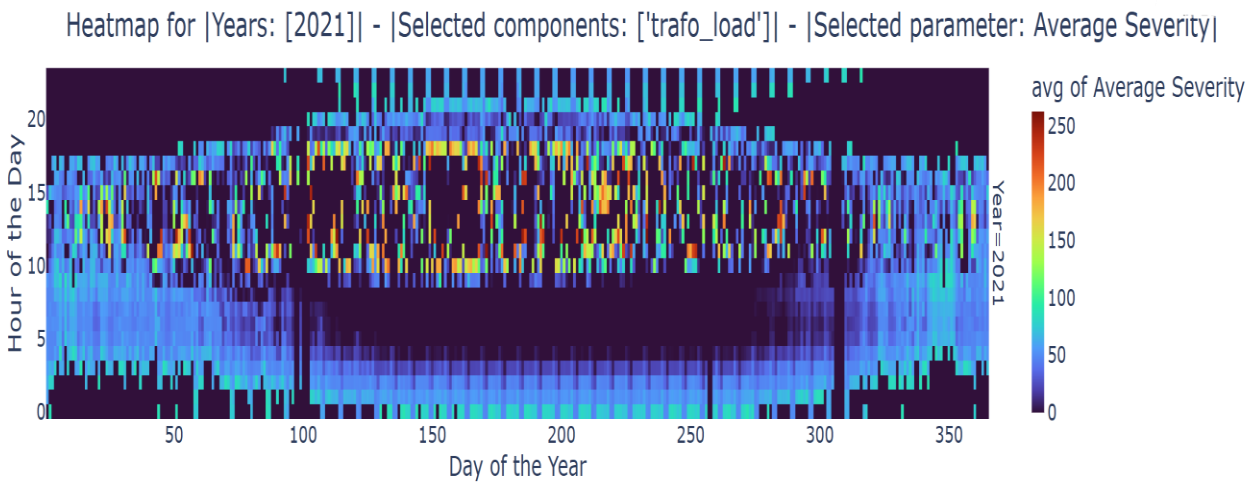

Figure A.3: Current loading severity of transformers consuming power during the powerflow simulation for the Autonomous Growth Scenario.

The only transformers which we have data for are the KVB transformers and the HV-MV transformers. The high amount of congestion here is mostly residential transformers which have not been installed with the capacity in mind to handle electrified heating and transport. Note: 29% of Autonomous Growth Scenarios did not converge.

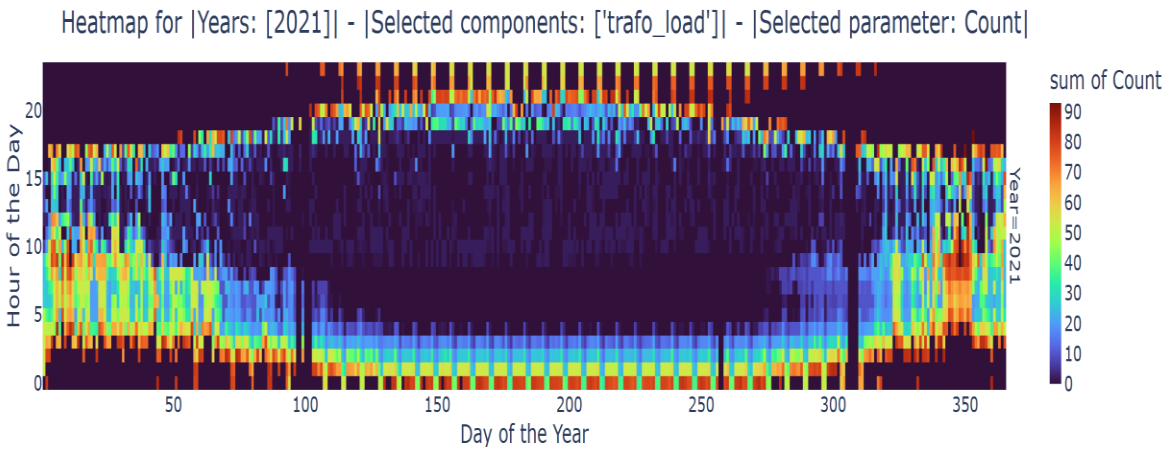

Figure A.4: Count of current loading congestion events of transformers consuming power during the powerflow simulation for the Autonomous Growth Scenario.

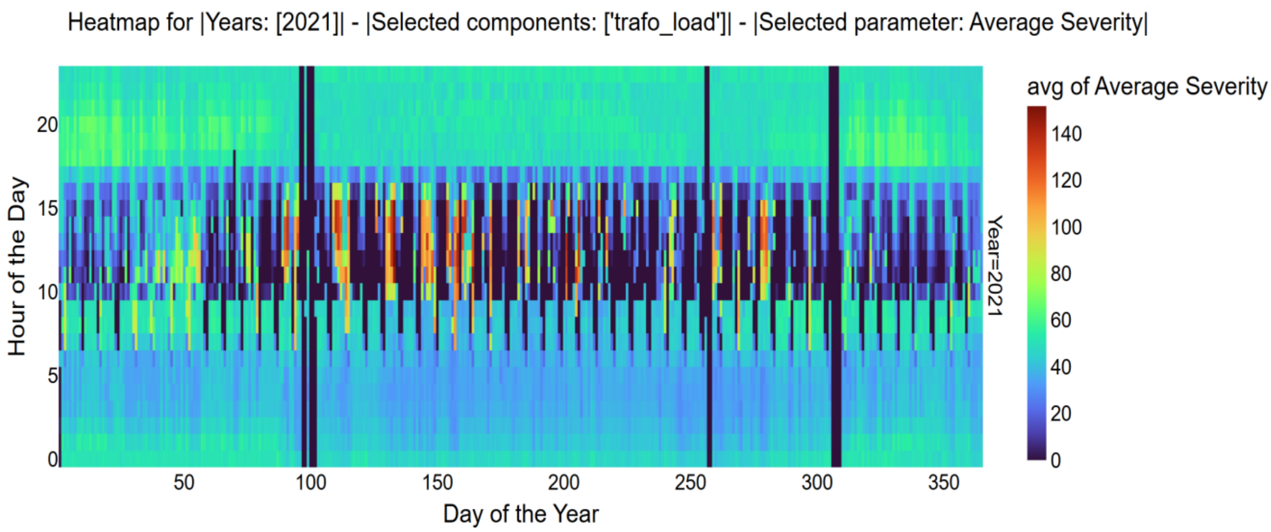

Figure A.5: Current loading severity of transformers consuming power during the powerflow simulation for the Planned Growth Scenario.

The same is the case for the Planned Growth Scenario where even with smart charging the KVB transformers cannot handle this demand. There is consistent loading of these transformers throughout the day, only between 10-17 there is a dip.

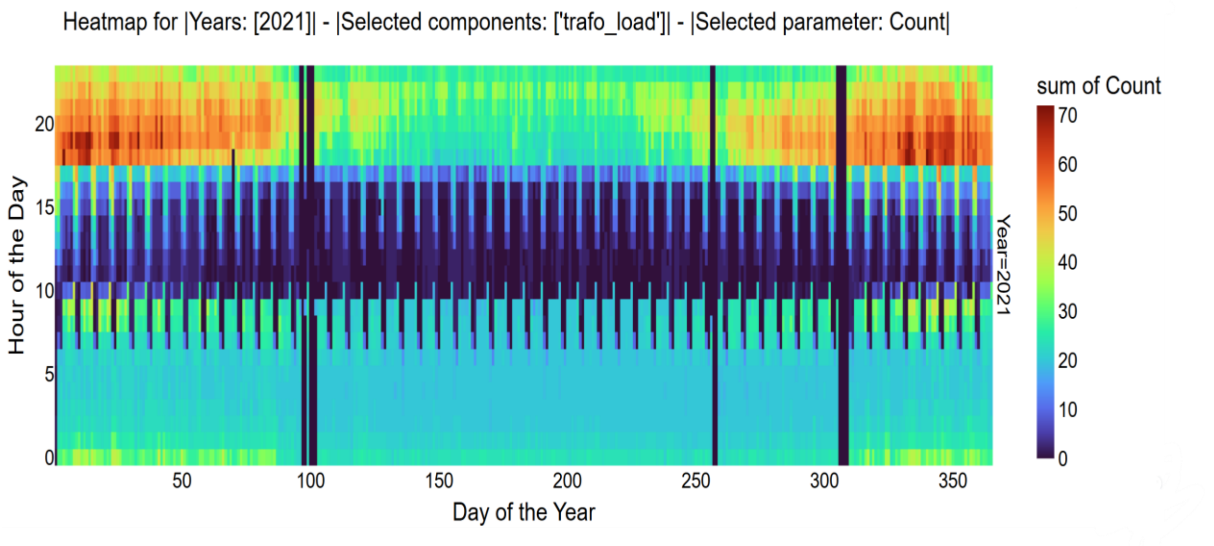

Figure A.6: Count of current loading congestion events of transformers consuming power during the powerflow simulation for the Planned Growth Scenario.

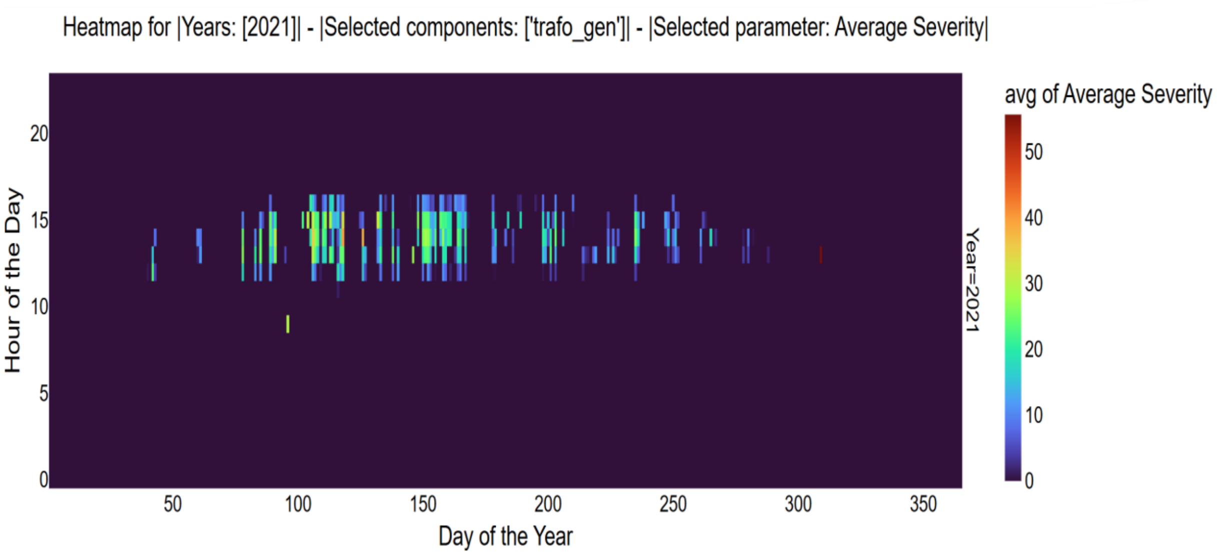

Figure A.6: Current loading severity of transformers injecting power during the powerflow simulation for the reference scenario.

There is not much loading of these transformers for injection of power in the reference scenario.

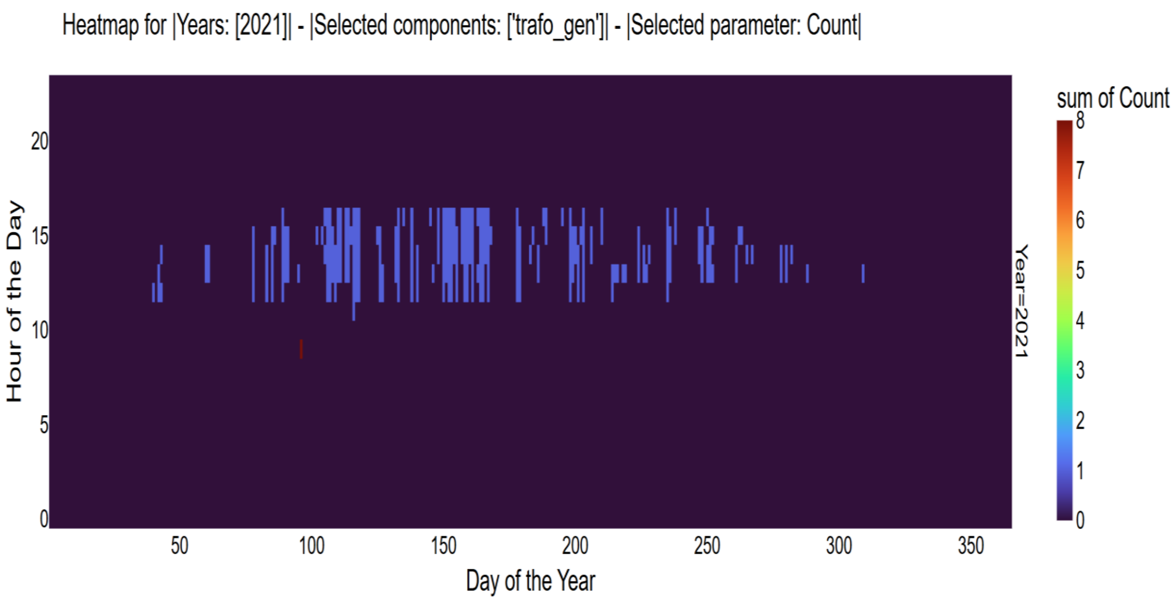

Figure A.7: Count of current loading congestion events of transformers injecting power during the powerflow simulation for the reference scenario.

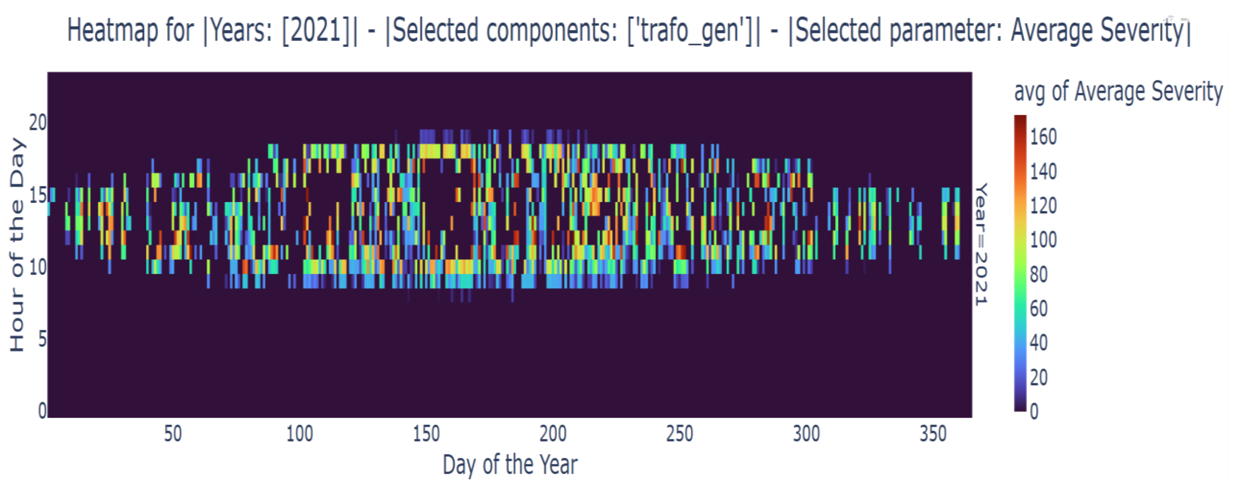

Figure A.8: Current loading severity of transformers injecting power during the powerflow simulation for the Autonomous Growth Scenario.

Autonomous growth shows high overloading of these transformers during solar hours which is what is expected.

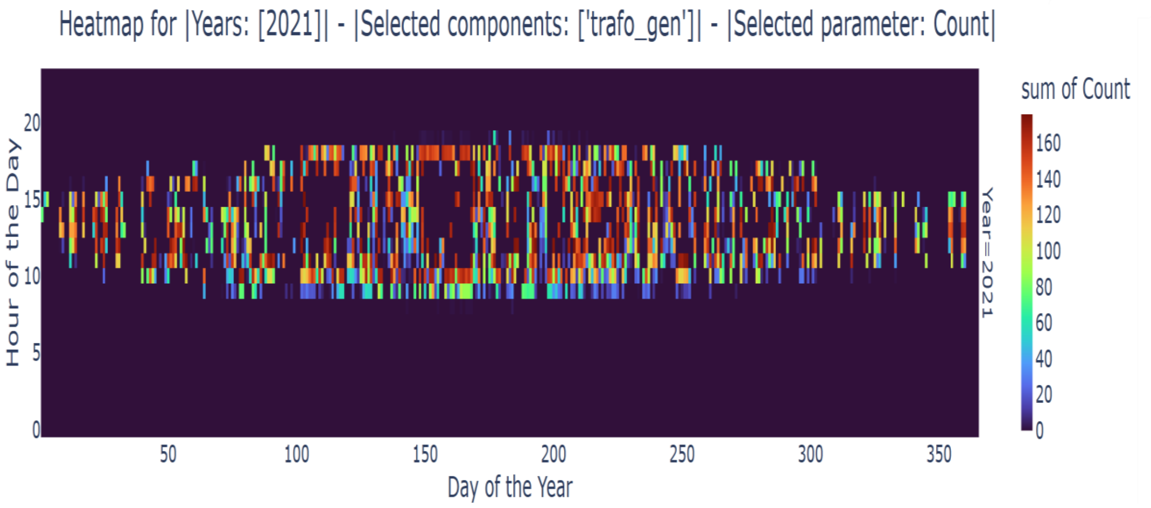

Figure A.9: Count of current loading congestion events of transformers injecting power during the powerflow simulation for the Autonomous Growth Scenario.

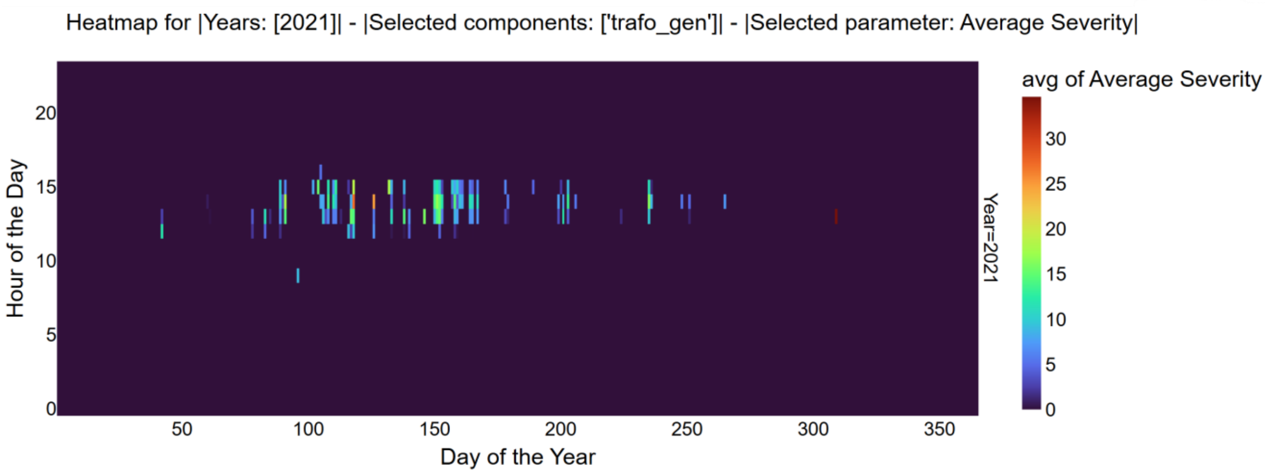

Figure A.10: Current loading severity of transformers injecting power during the powerflow simulation for the Planned Growth Scenario.

Planned growth is less as no more PV is added in this simulation and the feed-in of the wind turbines does not cause KVB transformer congestion.

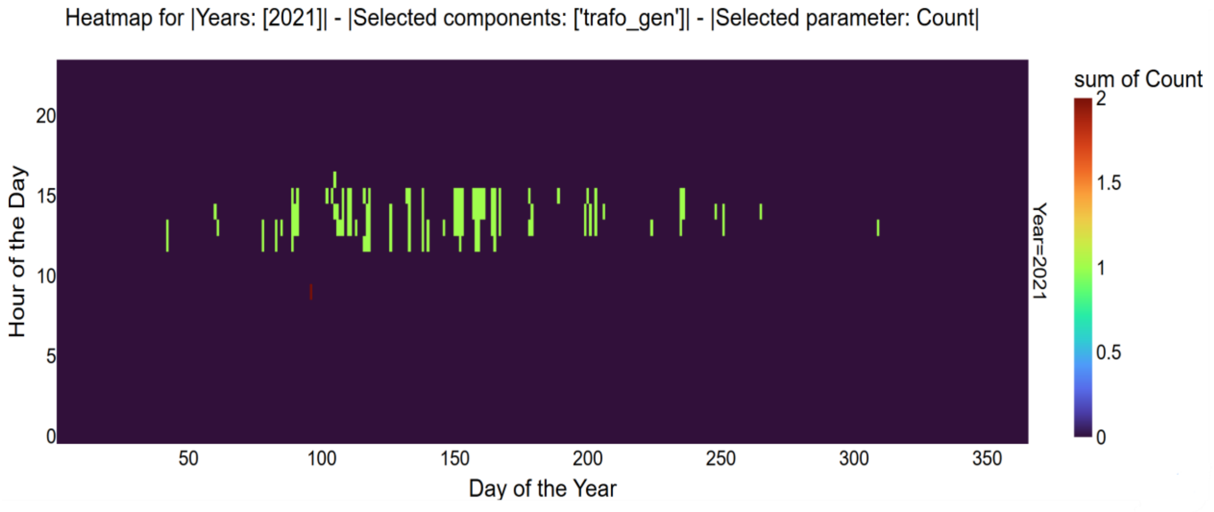

Figure A.11: Count of current loading congestion events of transformers injecting power during the powerflow simulation for the Planned Growth Scenario.

Transformer current loading % boxplot and barplots

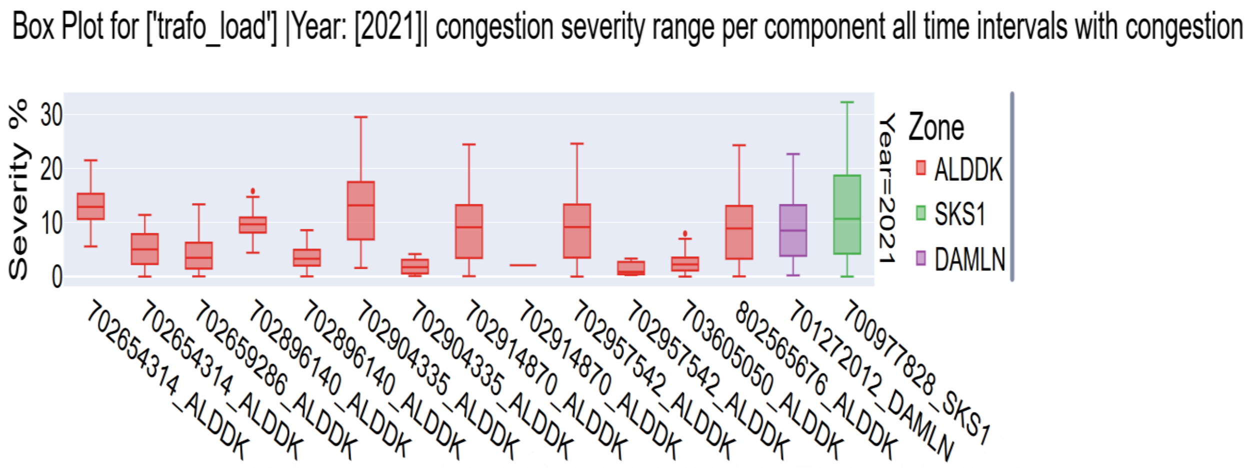

Figure A.12: Current loading % per component for transformers consuming power from the grid for the reference scenario.

For the reference case all the overloaded transformers are KVB transformers. The severity is also not very high and the results fall within a margin that is believeably attributable to modelling assumption uncertainty.

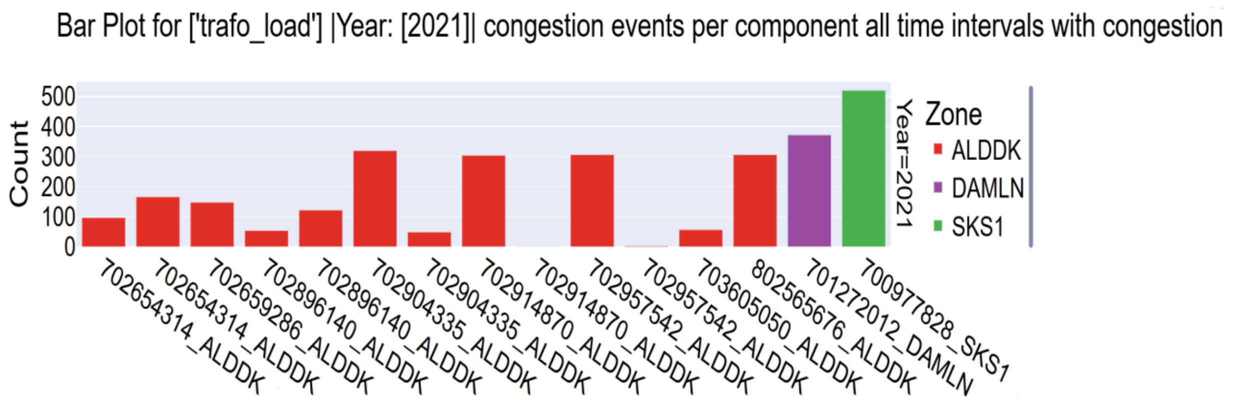

Figure A.13: Number of congestion events per component for transformers consuming power from the grid for the reference scenario.

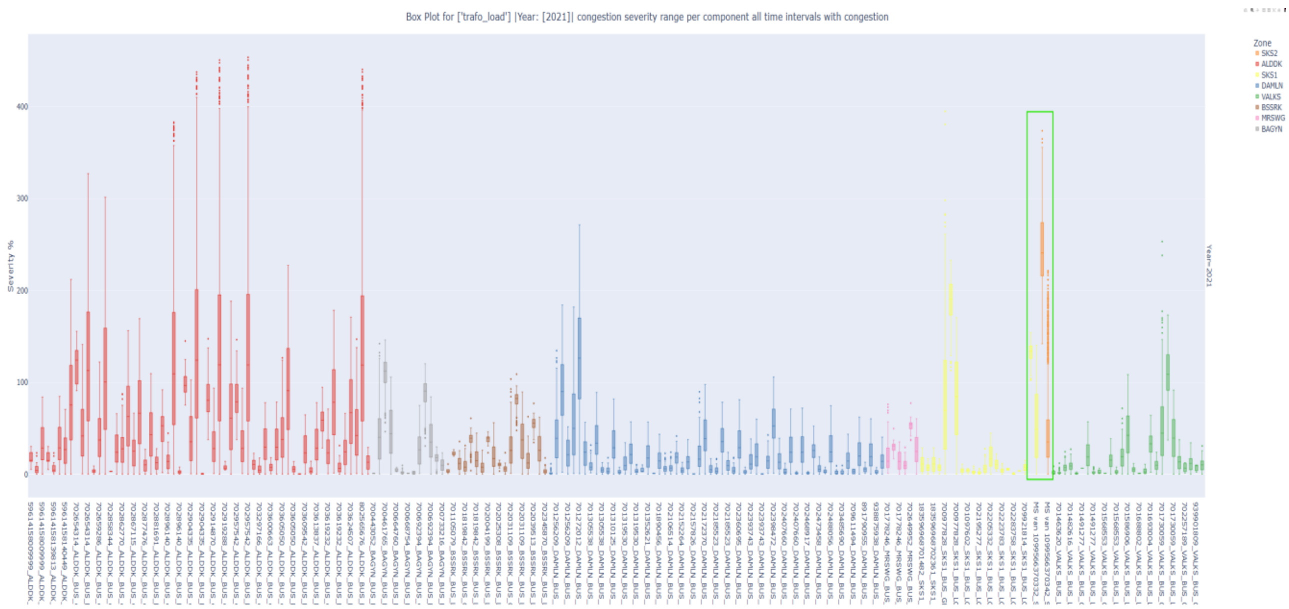

Figure A.14: Current loading % per component for transformers consuming power from the grid for the Autonomous Growth Scenario. Green box is the MV-HV transformer.

Demand congestion for transformers is apparent throughout the whole network. The MV-HV transformer's bars are indicated with the green box.

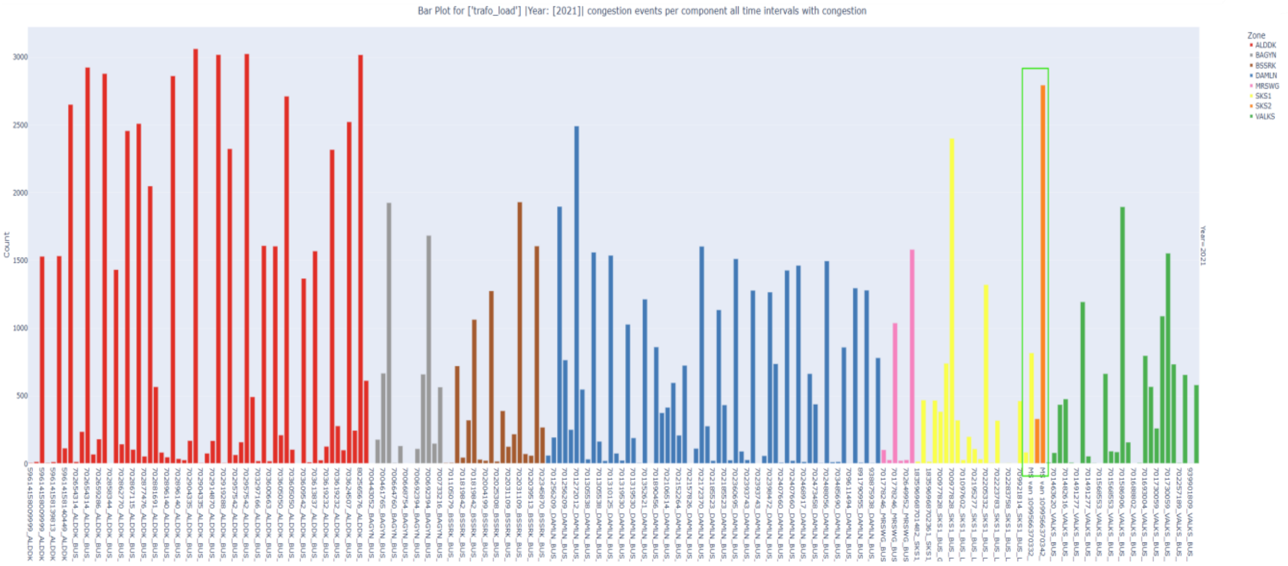

Figure A.15: Number of congestion events per component for transformers consuming power from the grid for the Autonomous Growth Scenario. The green box is the HV-MV transformer.

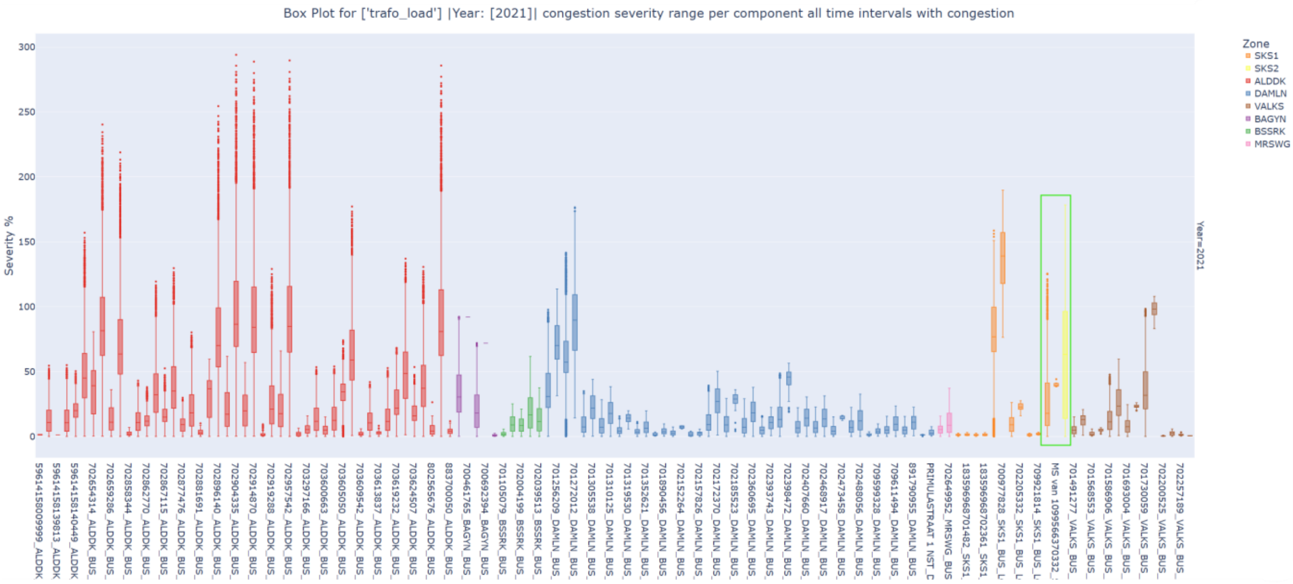

Figure A.16: Current loading % per component for transformers consuming power from the grid for the Planned Growth Scenario. The green box indicates the HV-MV transformers.

The Planned Growth Scenario transformers also cannot handle the demand side. Compared to line loading, to implement a PED for both future scenarios, KVB transformers have to be reinforced.

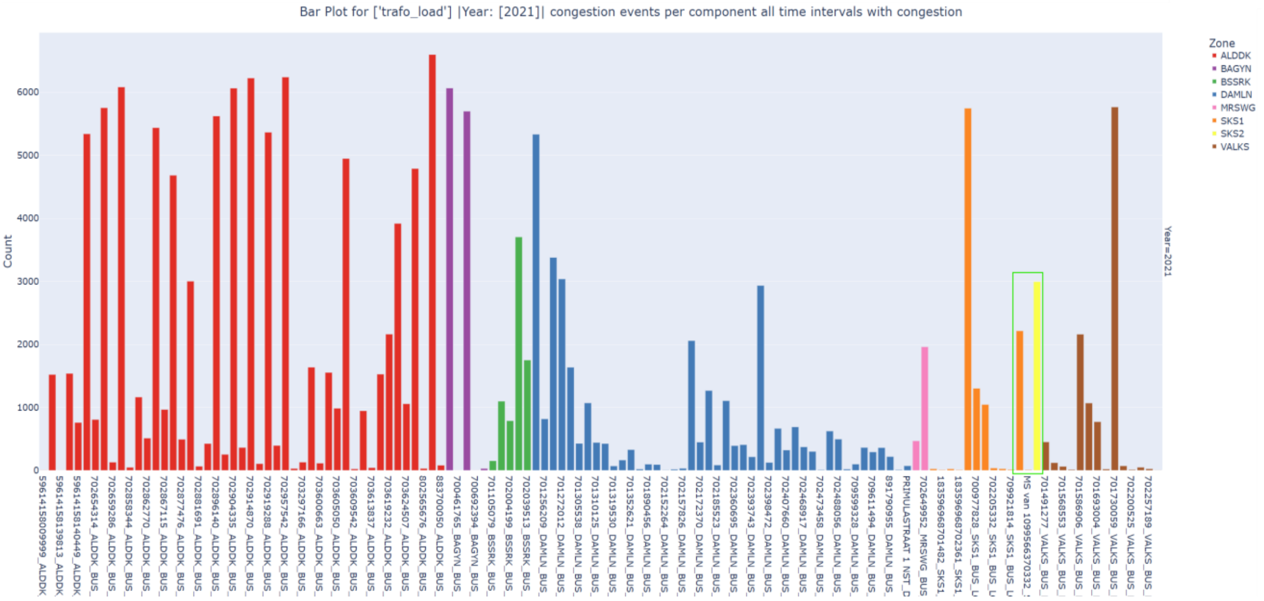

Figure A.17: Number of congestion events per component for transformers consuming power from the grid for the Planned Growth Scenario. The green box is the HV-MV transformer.

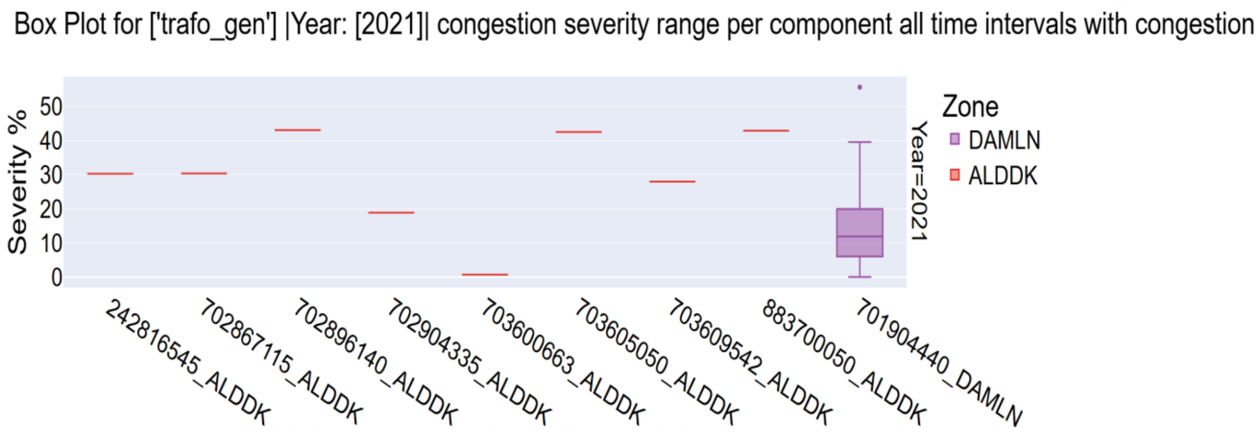

Figure A.18: Current loading % per component for transformers injecting power to the grid for the reference scenario.

For the reference scenario there is not much congestion when feeding into the grid.

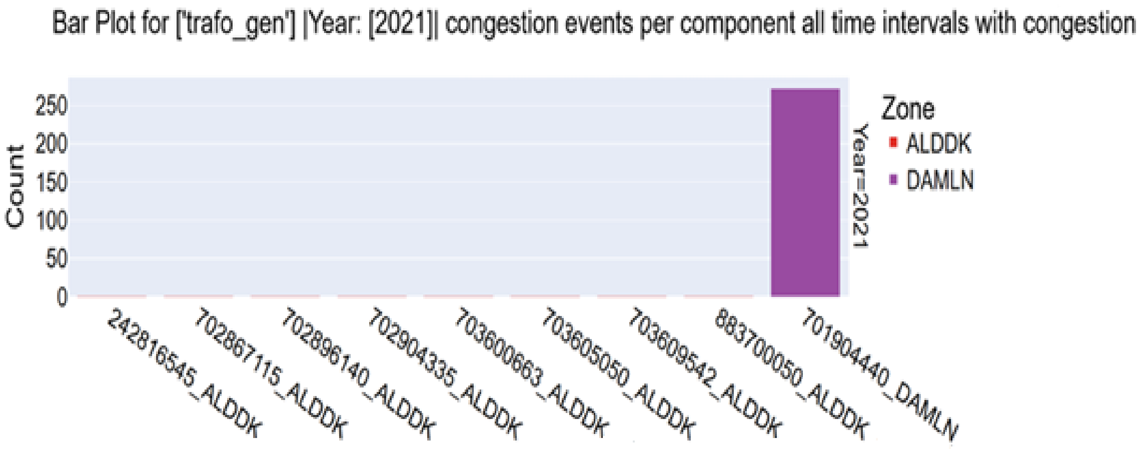

Figure A.19: Number of congestion events per component for transformers injecting power to the grid for the reference scenario.

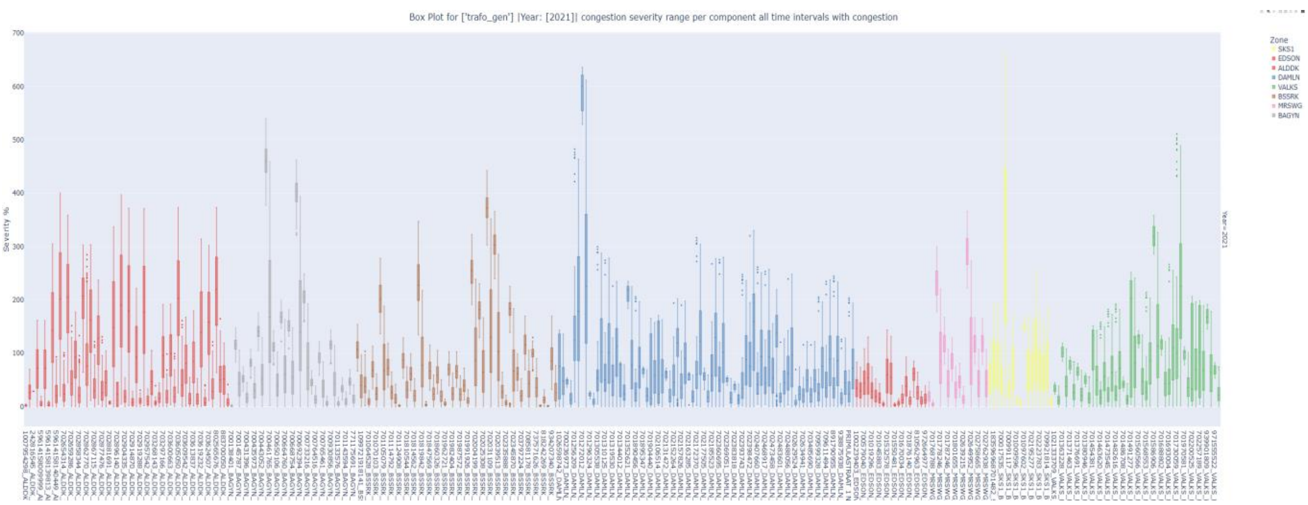

Figure A.20: Current loading % per component for transformers injecting power to the grid for the Autonomous Growth Scenario.

For the Autonomous Growth Scenario the overloading is over the whole network due to the distributed nature of the PV capacity. KVB transformers have to be reinforced to make this possible.

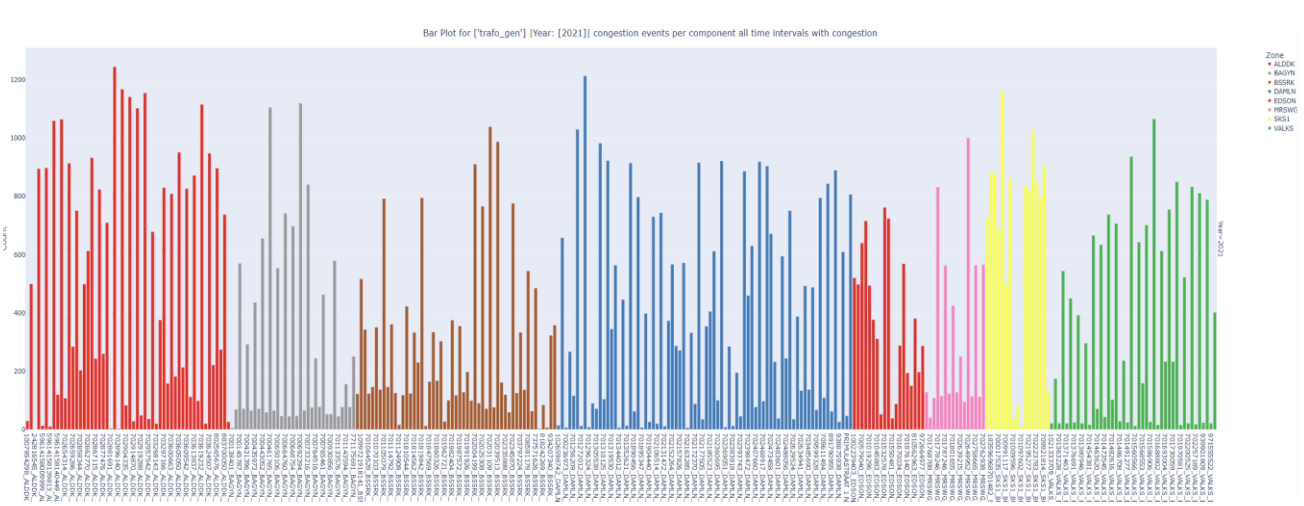

Figure A.21: Number of congestion events per component for transformers injecting power to the grid for the Autonomous Growth Scenario.

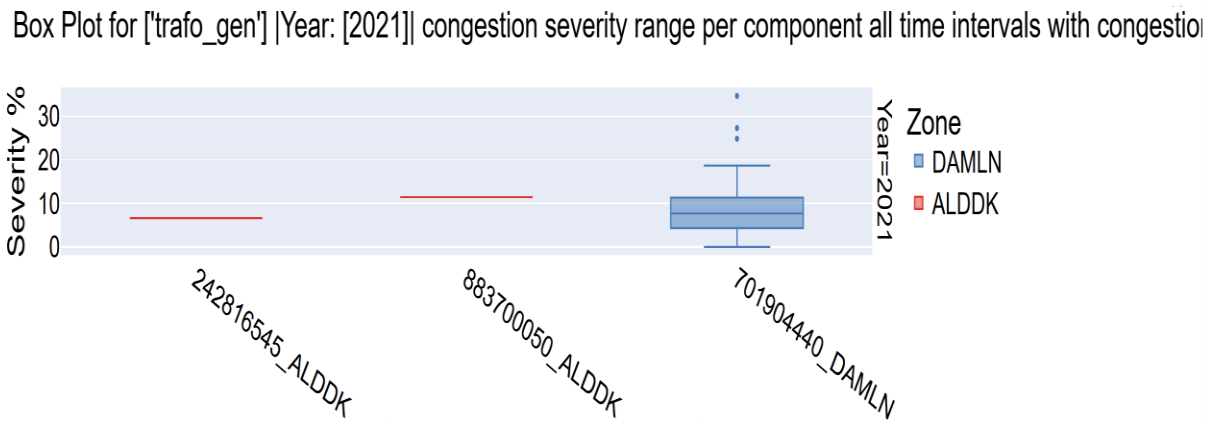

Figure A.22: Current loading % per component for transformers injecting power to the grid for the Planned Growth Scenario.

For the Planned Growth Scenario there is no production side congestion of KVB transformers because the wind generated electricity is fed directly into the MV grid.

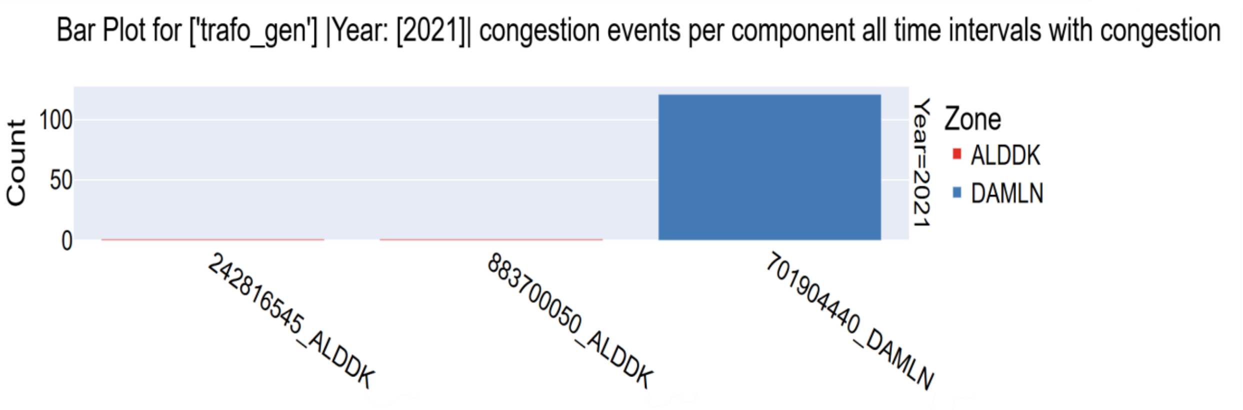

Figure A.23: Number of congestion events per component for transformers injecting power to the grid for the Planned Growth Scenario.

Voltage results summary

This research focused on the current overloading aspect of the components in the grid. However the simulations also gave the results of voltage levels through the grid. As the graphical results are comparable to the current loading, showing them would require many more figures. Instead the general conclusion from the voltage results are given per scenario in the following table. The graphical results are obtainable by request.

Table A.1: Summary of voltage results

Scenario	Voltage range	Observation
Reference	-3% - +2%	The range is not very extreme above/below our limits and the count not very high. Likely in the margin of error of the allocation of the data over the network. All time intervals converged.
Autonomous	-10% - +6%	This is the worst scenario in terms of voltage results. Also the simulation does not converge for all time steps. This occurs for around 29% of the timesteps. Specifically the timesteps with high demand or high solar production. So the limits indicated here are the worst of the timesteps that solved. For unsolved timesteps the results would be even worse.
Planned	-12% - +2%	Only the undervoltage is tending to be extreme but this is in very limited time steps. The overvoltage is limited to around 2% above our limit which is not that different from the reference. All time steps solve indicating the system does not get into exteme scenario like the autonomous one. Voltage is much less a problem compared to autonomous scenario. A simulation with voltage control elements would probably have better results. Most of the extreme voltage results are in the ALDKK zone, and specifically the KVB busses. This indicates the residential area needs more reinforcement?
Planned + flex	-12% - +2%	Same as the planned