

Effect of transition to sustainable heat sources in greenhouses on the grid stress in a horticultural MV electricity grid.



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Preface

This master's thesis project represents what I find most interesting about my master's: bridging two worlds that should interact with each other but are approached individually. JUVA gave me the chance to explore the interaction between the technical and socio-economic sides of grid interaction, whilst also experiencing the difference between the academic and corporate worlds.

It was not always easy to exist between these different worlds, each with its own approach. Therefore, I would like to thank my company supervisor, Silvana, for all the help she has given me. Your enthusiasm and attention for me, as an individual, really helped me to believe in myself and to continue forward. I really enjoyed all the brainstorming and structuring we did together. I was really lucky with you as a supervisor, and I couldn't have wished for a better fit.

I also want to thank Laura, who allowed me to start this adventure. Even though you had your hands full with a lot of other students, you always ensured that I got the help I needed at the right moment. This also brings me to Joel, who really helped me simplify all the technical problems I had and was always available to help. Your patience in explaining helped me to quickly fathom the problems I was facing, something I really needed. With both, I noticed how much you value the students you are supervising, something I wish other students could experience more of. I just want to say, don't ever forget how much that brings to the people you are supervising. You inspire me to pursue a similar path.

Lastly, I want to thank all my colleagues at Capturam. You really welcomed me as one of the team and made working on the thesis a lot more enjoyable. You showed interest in the work I was doing, which made me feel valued and helped me continue my work. I hope more students can have the same experience of doing their thesis in your team.

Contents

Abstract	iv
1. Introduction	1
2. Greenhouse interaction with MV electricity grid and associated markets	4
2.1 Power system optimization of greenhouse in literature	4
2.2 Crop distinction	6
2.3 Environmental control in a greenhouse	6
2.3.1 Temperature regulation in the form of heat demand	6
2.3.2 Light	7
2.3.3 CO ₂	7
2.3.4 Humidity	8
2.4 Asset and commodity overview	8
2.4.1 Heat generation	8
2.4.2 CO ₂ generation	9
2.4.3 Storage	9
2.4.4 Lighting	9
2.4.5 Gridconnection	10
2.4.6 PV generation	10
2.5 Associated greenhouse markets	10
2.5.1 Crop market and distinction	10
2.5.2 Gas market	11
2.5.3 Day-ahead and intraday Epex market	11
2.5.4 Grid stability and Ancillary service markets	12
2.5.5 Greenhouse control strategy	12
3. Model design	14
3.1 General model design	14
3.2 Future scenario's	16
3.2.1 Scenario sketches	16
3.2.2 Current scenario	16
3.2.3 Full Geothermal	16
3.2.4 Mixed commodity	17
3.2.5 Full P2H	17
3.3 Greenhouse categories & asset profiles	18
3.3.1 Asset sizing, profile and distribution	18
3.3.2 Demand	20
3.4 Commodity pricing and generation	21
3.4.1 Gas pricing	21
3.4.2 Epex pricing and extra electricity costs	21

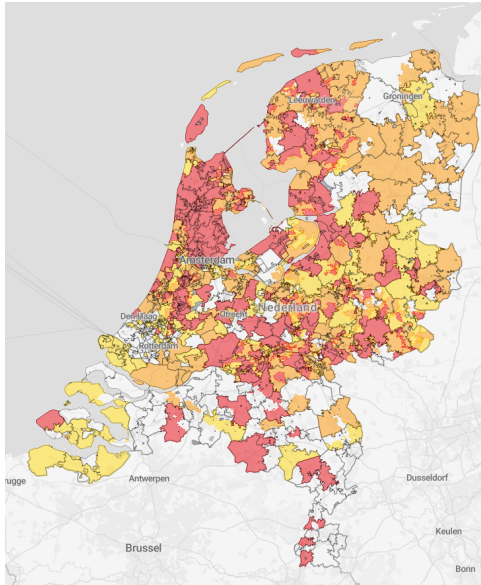
3.4.3	Governmental energy tax and distribution tariff	22
3.5	Assets representation of the greenhouse agent	23
3.6	Dispatch control of greenhouse agent	23
3.6.1	Policy: lighting dispatch	24
3.6.2	Policy: heatpump and eboiler dispatch	25
3.6.3	Policy: gasboiler dispatch	26
3.6.4	Policy: CHP dispatch	27
3.6.5	Calculating the dispatch price	28
3.7	PV generation greenhouse agent	29
3.8	Case scenario	30
3.8.1	Case Network	30
3.8.2	Profile distribution	32
3.9	Electrical grid simulation	34
4.	Model results and discussion	35
4.1	Greenhouse model	35
4.2	Network description	39
4.3	Grid voltage of the case network	40
4.4	Grid voltage of the case per network branch	42
4.5	Electrical current flow values at branch coupling	45
4.6	Conclusion of the discussion	48
5.	Conclusion	51
6.	Recommendations	52
6.1	Future scenarios	52
6.2	Including extra electricity markets	52
6.3	Including electricity capacity tariff	52
7.	Appendix	53
7.1	Asset sizing	53
7.2	Network parameters	55

Abstract

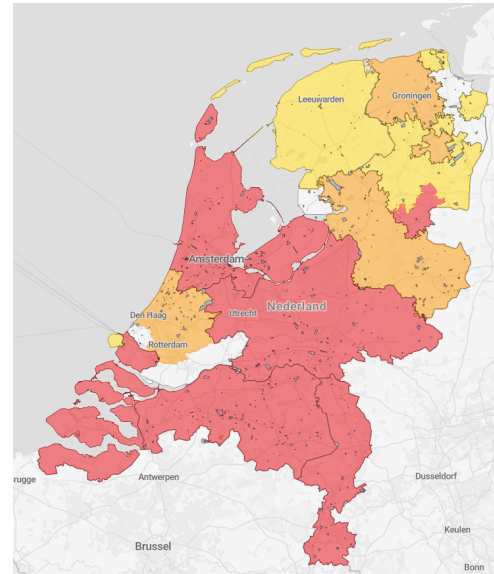
Greenhouses in horticultural MV grids face a transition to meet their heat demand with sustainable heat sources; however, the effect of the transition on the network stress is unknown. This research simulates the dispatch of greenhouses under 3 different transition scenarios: Full geothermal, Mixed commodity, and Full Power-to-heat. The dispatch control of the greenhouse is based on the day-ahead electricity prices, gas prices, and strategic position on other associated greenhouse markets. Network parameters of an MV grid case study with 29 greenhouses were calculated based on their power exchange. For the calculation, a numerical solver from another research was used. Network simulations show a transition from feed-in to consumption behaviour for all future scenarios. This behaviour change is associated with a decrease in CHP dispatch, which is strongest for the geothermal scenario. The P2H scenario mainly shows large single peak consumptions for the months with high heat demand caused by the dispatch of P2H assets at the same time instants. The mixed commodity scenario has the best voltage and current values of the three scenarios. This research highlights the importance of decentralized power generation by the CHP unit to compensate for the high electricity demand of the artificial lighting.

1. Introduction

The current technological and energy transition poses some big challenges for the electrical distribution grid. One of these challenges is the huge increase in electricity demand, causing congestion in assigning distribution capacity within the grid. Figure 1 displays a congestion map of the Netherlands. The orange and red colors indicate waiting lines to receive grid capacity and highlight the congestion problem.



(a) Regional grid



(b) HV grid

Figure 1: Available capacity in the Netherlands [1]. Red means no capacity available and waiting lines, and white means capacity available and no waiting lines.

Westland Infra is one of the 6 Distribution System Operators (DSO's) in the Netherlands. However, the distribution area of Westland Infra is relatively small compared to some of the other DSO's which is shown in Figure 2. The reason for the existence of this small DSO has to do with the large penetration of commercial greenhouses in the area. These commercial greenhouses are huge consumers of electricity and gas and have different needs than the standard residential and industrial areas. They are vital for the operation of the area and are characterized by decentralized generation units and a demand for both heat and light. The demands are met through various technologies present in the greenhouse, which are called assets.

Westland is not the only area that has such a greenhouse cluster. Aalsmeer and Waddinxveen are just two other examples in the Netherlands with similar greenhouse clusters. Greenhouse clusters also exist outside of the Netherlands, with greenhouses near Odense in Denmark and Malmö in Sweden as two other examples.

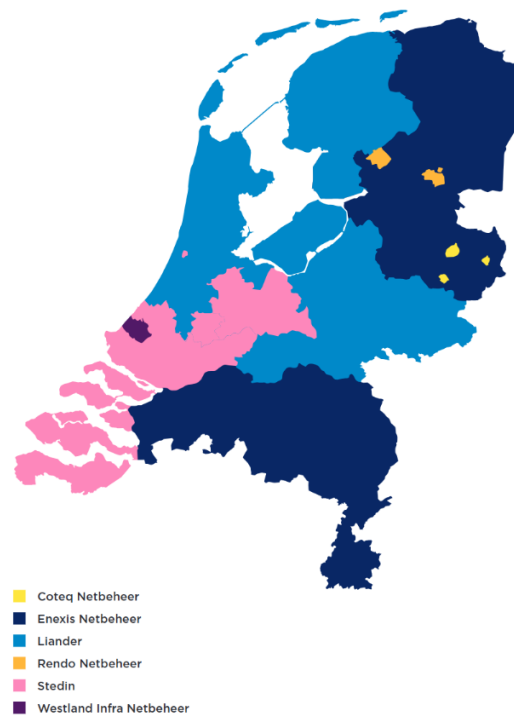


Figure 2: Map of the distribution areas of the six DSO's in the Netherlands with the area of Westland infra in purple [2].

Heat demand of these greenhouses is mainly met with fossil-fuel driven heat sources such as gas boilers and Combined Heat and Power units (CHP units). This last technology provides a lot of power injection in this area, giving a unique feature to the distribution area in which, before the penetration of Photovoltaic (PV) energy, often only consumption occurred. Moving to renewable heat sources, such as Power to Heat (P2H) or geothermal energy, could change the character of the interaction of greenhouses with the electricity grid completely, resulting in the main question of this research: "How does the sustainable transition of greenhouses influence the network stress of a horticultural medium Voltage grid?"

To answer this main question, the following sub-questions will be answered:

- Which markets are associated with the greenhouse electricity interaction, and how do they influence the dispatch of the assets present in the greenhouse?
- How do future greenhouse clusters meet their heat demand?
- How will greenhouses with renewable heat sources dispatch on day-ahead electricity markets?
- What is the effect of renewable heat assets on the network stress of a medium voltage case study?

These questions are answered in the report in the following way:

- Chapter 2 contains the theoretical background of this report. In this section, previous studies into the dispatch of greenhouse and their interaction with the MV grid are discussed. In the same section, working principles and main concepts of the greenhouses are presented.
- In Chapter 3, a design is presented of a greenhouse dispatch model together with future scenarios about renewable asset distribution. Furthermore, an MV grid case scenario is presented, which is used to simulate the grid parameters of the dispatch model. The combined results are presented and discussed in Chapter 4
- Conclusions of the findings and recommendations on further research can be found in Chapters 5 and 6 respectively.
- In Chapter 7, the appendix, additional information about the model can be found.

2. Greenhouse interaction with MV electricity grid and associated markets

This section is dedicated to explain the working principles of a greenhouse, its interactions with the electricity grid and associated markets, and to highlight earlier research in these fields.

A greenhouse is a completely enclosed structure made out of transparent material, most often glass, to regulate the climate of the plants that grow inside it. The first greenhouses were just static structures to enhance the local climate. Nowadays, greenhouses are so modern that climates in the greenhouses are actively regulated. This active climate regulation costs a lot of energy, making the horticultural sector an active participant in the energy markets.

In this section, first, earlier research is discussed about greenhouse and electricity grid interaction, after which fundamental concepts of the greenhouse are discussed. These concepts include a distinction between crop type, their demands for climate regulation, their technologies to achieve this climate regulation, and lastly, the interaction with the markets in which they participate. At the end of this section, the interaction of greenhouse clusters in medium voltage distribution systems is discussed.

Information from the Chapters 2.3 2.4 and 2.5 is obtained via interviews of several people active in the greenhouse sector. The people interviewed are shown in Table 1, together with their role in the sector. External sources outside these interviews are stated with citations.

Table 1: Interviewed people who shared their information about the operation of a greenhouse and associated markets.

Role	Crop	Date of interview
Energy advisor/ Project Manager	Several	28-02-2025
Energy Advisor	Tomatoes	19-03-2025
Energy advisor	Tomatoes	20-03-2025
Owner, Crop specialist	Chrysant	28-03-2025
Owner, Crop specialist	Chrysant	31-03-2025

2.1. Power system optimization of greenhouse in literature

Currently, there are mainly two ways in which greenhouses are researched with respect to their interaction with the electricity grid. The first is most often viewed from a greenhouse perspective, in which it tries to optimize either the inclusion of renewable electricity sources or to reduce grid interaction by researching operation as a Microgrid. The other approach is to see how the flexibility of the greenhouse can be used to provide ancillary services for the electricity grid. These ancillary services are mainly indirect via most often price-based demand

response programs. As the goal of this research is to examine how the energy transition affects the grid stress in horticultural medium voltage network, it is important to combine these two approaches. In such a way, the asset dispatch of a greenhouse can be modeled, which is then based on both the climate control as well as earnings of participating in the energy market. Table 2 summarizes research done into power consumption optimization and inclusion of renewable electricity sources, whereas Table 3 summarizes research done into the influence of new market mechanisms on the greenhouse's operation and their influence on the electricity system.

Table 2: Literature about greenhouse power systems

Source	Commodities	System type	Assets of considered system	Optimization or control objective
[3]	Electricity	Grid tied	PV+battery system	Energy cost + PV consumption
[4]	Electricity, gas, heat	Microgrid	CHP, Boiler and Heatpump	Energy cost optimization
[5]	Electricity	Grid tied	PV+BESS	Battery SOC and Grid use
[6]	Electricity and gas	Microgrid	WT, PV, BESS and CHP	Climate conditions (MPC)
[7]	Electricity	Microgrid cluster	WT,PV, BESS and Renewable generators	Climate conditions (MPC)

Table 3: Literature about demand response implementation in greenhouses.

Source	Commodity	DR target size	Assets or considered system	Focus
[8]	Lighting	Greenhouse	Lighting	Adoption DR in lighting dispatch control
[9]	Lighting	Network	Lighting	Adoption rate greenhouses
[10]	Temperature, light, humidity, water, CO ₂	Greenhouse	Greenhouse (including PV battery system)	Control with DR adoption of multiple crop types and asset configuration
[11]	Temperature, light, humidity, CO ₂	Greenhouse	Greenhouse (including PV battery system)	Deeplearning model for DR control
[12]	Heat, electricity	Greenhouse	Greenhouse, renewable production, crop quality	Influence of DR adoption on production quality and production costs

From a DSO point of view, two things are lacking in the stated research. None of the proposed researches show any inclusion of a physical grid between the greenhouses. Furthermore, in all research, greenhouses are approached solely for their cultivating nature, whereas in reality, they are often actively participating in the energy market, which is a secondary form of income. These associated markets are taking too little into account while modeling the greenhouses. This research tries to close that gap by contributing in the following way:

- Proposing a simple greenhouse model that relates more closely to the actual operation of a greenhouse, by integrating associated markets in their dispatch control.
- Insights into how the penetration of renewable heat sources affects the network stress of a horticultural medium voltage electricity grid.

2.2. Crop distinction

In the greenhouse sector a distinction is made between ornamental crops, most often flowers, and vegetable crops. This distinction is made because the product value of both crops is different. Vegetables are used to supply the food market and are often sold by their mass. Flowers are sold for their ornamental value; therefore, appearance is more important than their mass. These differences in product value give different climate constraints per crop and will be discussed more extensively throughout this chapter.

2.3. Environmental control in a greenhouse

There are 5 parameters important in the climate control of a greenhouse: temperature, light, CO₂, humidity, and water. Controlling these parameters ensures more control over the growing process of your plants. However, these parameters influence each other and can differ locally, creating a certain microclimate, making a greenhouse complex to model. In this subchapter, 4 of the 5 parameters are explained further to highlight their influence on the electricity system. The 5th parameter, water, is essential for the plants' survival and is always added manually to control the exact amount. However, water has almost no interaction with energy commodities and will, therefore, not be discussed further in this research.

2.3.1. Temperature regulation in the form of heat demand

Heat demand can be represented by the thermodynamic principles. The main component is the energy flow that occurs because of a difference between the temperature inside the greenhouse and the ambient temperature outside the greenhouse. The energy flow becomes larger if the temperature difference increases. Another way of increasing the energy flow is by introducing an air flow by opening up the windows. Warm air will now diffuse with the colder outside temperature, increasing the total heat flow. Other components of heat flow are radiating heat because of solar irradiance and heat convection because of the air flow (wind) and water flows (rain or snow) near the surface. Thermodynamic models differ for greenhouses in regard to other buildings, as plant evaporation is an important factor.

The monthly heat demand profile of a greenhouse is not flat throughout the year but varies

per month and is mainly dependent on outside temperature, solar irradiance, and wind. In general, heat demand follows a bathtub curve a flat, low heat demand in the summer and a high demand at the start and end of the year, during the winter months. Just above the flat demand in the summer is called the base load; the high edges of the bathtub are called the shoulder and peak loads. Base load is the demand that is present almost every moment of the year and can be met by a constant heat source. Peak loads occur fewer times a year but are essential in operation. Going below certain temperatures can result in heavy crop loss. Controlling the temperature also influences the humidity level inside the greenhouse.

Figure 3 displays the mentioned bathtub curve of a tomato crop. The first and last periods are higher in demand, whereas periods 4 to 10 are lower. The 13th period differs from this pattern because crops are exchanged in this period.

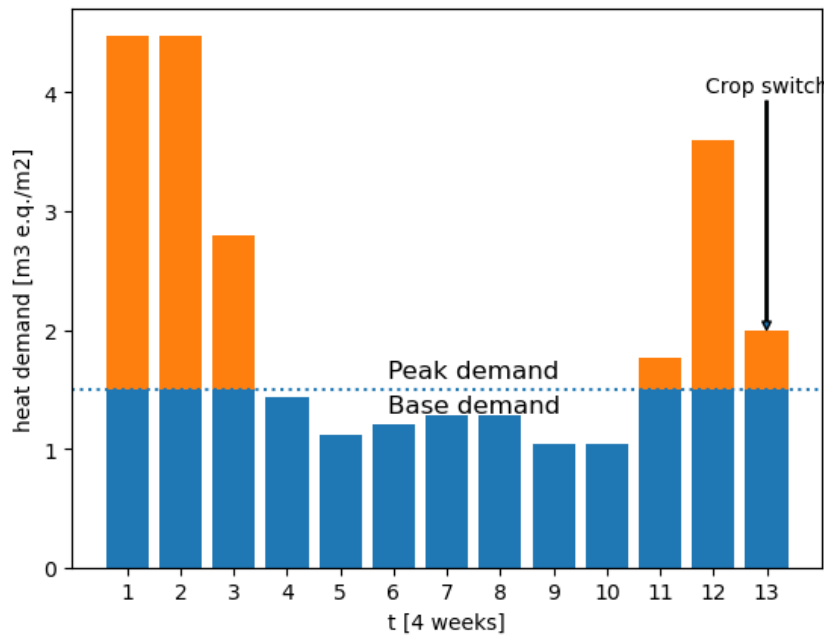


Figure 3: Bathtub curve of the heat demand of a tomato crop with boiler [13]. Heat demands are given in gas equivalent and are displayed in 4-week periods.

2.3.2. Light

A plant can grow by turning light into sugars through the process of photosynthesis. Crop growth is thus correlated with the amount it receives. However, the efficiency of the photosynthetic process varies per crop type and is even time-dependent. A greenhouse can artificially create additional light on top of the natural light to increase the growing speed of the crop, its size, or its fruit size.

Some plants are even dependent on the time window of lighting. Chrysants, for instance, need specific consecutive hours of light and darkness to open up their flowers.

2.3.3. CO₂

The photosynthesis process of a plant is, just like light, dependent on the concentration of CO₂. A greenhouse owner wants to increase its CO₂ concentration artificially when his lights are on,

to increase its efficiency. Most crops need this extra injection of CO₂ to become economically viable. Currently, CO₂ is often obtained as a side product of other processes. For instance, greenhouse owners can filter the air of their dispatched gas boilers, which contain high concentrations of CO₂.

The value of CO₂ for the horticulture sector creates an extra barrier to move away from fossil fuel energy. For other heat sources than fossil fuel CO₂ needs to be obtained externally, which is often a difficult process as they deal with the same sustainable transition.

2.3.4. Humidity

Controlling the humidity reduces the spread of viruses among the crops. It has, therefore, more to do with risk management than with a direct increase in output. The humidity is directly related to temperature via the humidity curve. Fans are used for better air distribution throughout the greenhouse. This better distribution results in a lower variability in microclimates.

2.4. Asset and commodity overview

Assets are machines present at a greenhouse that help control the climate parameters. An asset can be seen as a converter of energy that converts its input energy to a climate-controlling output energy. Modern greenhouses most often have access to these commodities via a distribution grid. The commodity is then delivered by an external supplier. In some cases, heat and CO₂ distribution grids also exist.

2.4.1. Heat generation

In this research, 4 ways of heat generation are considered, which are through the use of: Boilers, CHP units, P2H, and Geothermal.

Gas boilers are the most common heat source in the horticultural sector. Almost all greenhouses have a boiler. In some cases, boilers are used to account for all heat demand, and in almost all cases, they are at least used as backup. Because of their widespread gas boilers are always referred to as boilers. Other boiler types will be annotated by their input commodity.

CHP gas turbines are decentralized energy generators. Just like the boiler, they have as input gas, but besides heat, they also produce electricity. The main purpose of the CHP unit is to provide heat for the greenhouse. CHP gas turbines are always combined with a form of heat storage such that the moment of dispatch is less dependent on the moment of heat demand. Dispatch of the CHP unit is optimized to provide the electricity and CO₂ for the lighting and crops, respectively and to sell its excess electricity on the grid for the best price possible. Their flexible dispatch makes them a good ancillary service provider for the grid operator. CHP units have a ramp-up time of about 10 minutes and can only operate between 70 or 100 percent of their capacity.

There are two types of P2H assets that are considered: Heat pumps (HP) and E-boilers. Both assets turn electricity into heat and produce no side products. The difference between the two devices is that heat pumps have a higher efficiency and E-boilers have a higher generation capacity. The higher efficiency often makes heat pumps preferable to the E-boiler.

The last heat source is geothermal energy. Geothermal energy is often a shared asset because

of its high investment cost. Water is injected into a porous layer deep in the Earth's crust while water from that same layer is pumped upwards. Water in these deeper layers have a naturally high temperature because of the heat of the Earth's core. Heat from the pumped water can thus be extracted and used as a heat source.

A greenhouse in Westland is obliged to collect the amount of heat for which it has contracted; this has to do with the operation of the geothermal well.

2.4.2. CO₂ generation

Boilers and CHP produce CO₂ while burning gas. The outflowing air of the asset can be filtered and mixed with air in the greenhouse to increase the concentration of CO₂. The need for CO₂ can therefore have an influence on the dispatch of boilers or CHP units. There are even cases known in which boilers are turned on just for the CO₂.

For some greenhouses, there is also the possibility to buy the CO₂ externally. Air Liquide, for instance, delivers compressed CO₂ in big tanks to its customers [14]. There are also areas in which there is a CO₂ distribution grid. The CO₂ from these distribution grids often comes from industrial buildings that produce the CO₂ as a byproduct from their fabric processes. For instance, Westland has such a distribution grid that receives its CO₂ from the industry in the Port of Rotterdam [15].

2.4.3. Storage

Two types of commodities are known to be stored in greenhouses: heat and electricity. Electricity is stored in batteries; however, penetration of batteries in greenhouses is small, and they are often not used for their storage purpose, but for their reaction speed to provide short-term balancing services. Therefore, batteries will not be considered in this research as they are not associated with heat generation.

Heat storage is widely diffused in the form of water buffer tanks. A water buffer tank is a tank filled with water. The tank can be filled with hot water to store thermal energy. The buffer is used to remove the time-dependent factor in demand and generation patterns. Water buffers often have enough capacity to account for daily demands, but cannot deal with seasonal storage. The heat storage is incorporated implicitly in the rest of the research in the form of a time-independent daily heat demand. In other words, only cumulative daily heat generation is considered. This implicit incorporation can be done under the assumption that heat storage is present at each greenhouse and is large enough in capacity.

2.4.4. Lighting

Lamps transform the electricity into irradiance, which can be used for the plants. Two types of lamps can be distinguished: Son-T and LED. Son-T lights are, in theory, less efficient than LED as they generate more heat. However, heat can be used effectively in greenhouses and is not regarded as an energy loss. This makes them, in practice, as efficient as LED.

The benefit of LED is that the irradiance levels can be adjusted, giving them a huge benefit over Son-T, which can only be switched on or off. Not every greenhouse will have lighting, but electricity-intensive greenhouses mostly have.

2.4.5. Gridconnection

Excess electricity can be sold on the electricity grid, which forms the basis of the secondary income of the greenhouse. The connection to the grid consists of a physical and a contractual grid capacity. The physical capacity is the capacity that the physical can handle before overloading occurs. Contractual grid capacity is the agreement that the grower made about capacity use with the DSO. The grower has to pay for the size of the grid capacity.

2.4.6. PV generation

PV panels generate electricity using solar irradiance as an energy source. The penetration of PV energy in the Westland infra area is rather small. Factors for this include the competition of CHP units as decentralized electricity generators and the limited physical available area to deploy the PV panels. An increase in PV penetration can be expected as the capacity of CHP units decreases.

2.5. Associated greenhouse markets

2.5.1. Crop market and distinction

As mentioned, a distinction is made between ornamental crops and vegetable crops, which are categorized as flowers and vegetables in this research.

There is one important difference between the growing process of each of these categories. For vegetables, putting in more resources can result in a higher yield of the product, which is not the case for flower crops. For example, by injecting more light and CO₂, a tomato grower can produce more kilograms of tomatoes per square meter. Of course, there is a saturation of what a plant can produce, but the point is that it has the capabilities to react to the market price of the crops.

These market prices are heavily dependent on the harvest yield and the moment of the outdoor cultivation. These yields and moments of yields are very weather-dependent and can thus vary year to year. The tomato price drops at the moment that more tomatoes become available, which is highest at the harvest peak of the outdoor cultivation. Greenhouse can control the environment in their greenhouse to control the moment and amount of yield of tomatoes. For this environmental control, more lighting and CO₂ injection are needed, increasing the production cost. The extra revenues made by both higher prices and higher sales have to cover the extra production to increase the overall profit. In a year with low tomato prices, a tomato grower can choose not to turn on his lighting, as it is simply not worth the extra production cost.

The flower market differs from the vegetable market in three distinct ways. The first is that the flower market price is less dependent on the outdoor cultivation yield. Flowers are bought for their aesthetics; therefore, the quality of the product is very important. Enough quality can most often only be guaranteed in a greenhouse environment. Outdoor cultivation of flowers is thus a less common practice.

The second difference is that flowers can account for their production cost more easily in their selling price. Flowers are a luxurious product, and luxurious markets are often characterised by smaller selling quantities with a high profit per quantity. Because of this, the production cost is a smaller percentage of the total sales price than that for vegetable crops. Adding the same

increase in production cost will thus add more margin to a vegetable crop than it would do for a flower crop. For example, 50 cents extra for tomatoes that are normally 2 euros is a lot more than 50 cents added to 12 euro roses.

The last difference is that high prices occur in very specific time windows, making flowers less flexible in their moment of production. The higher prices occur because of an increase in demand and not because, as in the case of vegetables, a decrease in production. An increase in demand is caused by a cultural event like Valentine's Day or Mother's Day. These are moments in which the willingness to pay of consumers is highest. Flower growers try to plan flowers to be ready to harvest during these moments, making them less flexible in their environmental control.

2.5.2. Gas market

The prices of gas for a greenhouse consist of fuel cost, a grid fee for transportation of gas, and two governmental taxes, one for the commodity in general and one for associated CO₂ emissions when burning the gas.

The fuel gas price, excluding all extra costs, is for a small time scale constant. Variations on the price are sudden and often a result of geopolitical events. For instance, during the outbreak of the Russian-Ukrainian war price of gas rose significantly as a lot of gas was normally imported from Russia.

Fees associated with the distribution are not taken into account in this research, as they are not variable with the gas quantity. Greenhouses solely pay a fee for the gas capacity per hour to which they have access in a year. As this is an upfront fixed cost, it will not influence the dispatch of the assets using the gas.

For every quantity of gas used, two taxes are paid to the Dutch government, one for the commodity and one for the associated CO₂. The tax price for the commodity is stepwise variable, depending on the total amount of gas that is already consumed in that year. For CO₂ emissions, consumers pay a fixed price per commodity of 0.017 cents per m³ of gas used. The tax system is discussed more extensively in the appendix session to explain which tax prices are used for the model.

2.5.3. Day-ahead and intraday Epex market

The electricity market is different from other commodities due to its physical properties. The market consists of different time points, to trade your electricity with the purpose of ensuring supply and stability of the grid. In this research, the interaction with the short-term markets is important as they cause congestion problems on the network. There are 2 short-term electricity markets, the day-ahead and intraday [16].

In the day-ahead market, users can buy or sell their electricity for the next day in blocks of 15 minutes. The electricity price is decided by clearing the market

The intraday market has a different structure and is based on a pay-as-bid model. Users can bid for their consumption or production position at a certain price. Anyone willing to pay that price and provide the necessary production or consumption can complete that deal directly, independently of day-ahead prices.

2.5.4. Grid stability and Ancillary service markets

In medium voltage networks, it is important to track two parameters to ensure network quality these are line currents and voltages throughout the network.

Electrical lines have a maximum current at which they can operate. Going beyond this current will damage the lines due to the high temperatures.

A DSO is obliged to ensure the nominal voltage values of the network within a 0.05 p.u. limit because of the EN 50160 standard. For a 20 kV network, this means that voltage values need to be within 19 and 21 kV. Voltage drops in the network occur because of the line impedance of the network.

The frequency in a network is another important factor in network quality. It is, however, the responsibility of the Transmission System Operator (TSO) to maintain this and not that of the DSO.

Ancillary services are services in which electricity users consume or produce electricity with the sole purpose of improving the stability of the network. It is often a service that is called upon after the normal market mechanisms fail to provide this stability. Users on the decentralized grid can perform these services for the DSO or TSO depending on where the stability is needed and give a lot of insight into the dynamics between greenhouses and their role within the distribution network.

Two familiar services are re-dispatch [17] and frequency capacity [18], affr and mffr. Re-dispatch is called upon if line currents are getting to high. In such a case production is tried to be moved elsewhere, such that other lines in the network are loaded.

Frequency is extra capacity that can be dispatched that restore the frequency in the network. As this is back-up capacity, it cannot participate in other electrical markets at the same time.

Prices for ancillary services are often high. Network outages have huge economic damage, and thus, the willingness to pay for stabilizing the network is high.

Many greenhouses in the area of Westland Infra already participate in the ancillary service markets by offering the capacity of their lighting and CHP units. There are even cases in which a greenhouse bought battery systems specifically for these services.

2.5.5. Greenhouse control strategy

Figure 4 displays the physical and informational flow for dispatch control. The most important thing to note is that the people responsible for the crop are separated from the people responsible for the energy in the form of a crop and energy manager. The crop manager has priority and gives the constraints to the energy manager within which it can operate.

The crop manager receives weather data and data of market on which it sells its crops. Based on the characteristics of the crop the manager can now give his demands to the energy manager. These demands exist of the total demand of heat, the hours in which the lighting is applied, and the hours in which extra CO₂ is required. Also a cost curve of the light is given to the energy manager such that it knows to what cost it can turn off the light.

A lot of choices of the energy manager on the day-ahead market are made for a good position to anticipate in other, more lucrative energy markets.

Based on the state of charge of the heat buffer, the energy manager can decide the dispatch

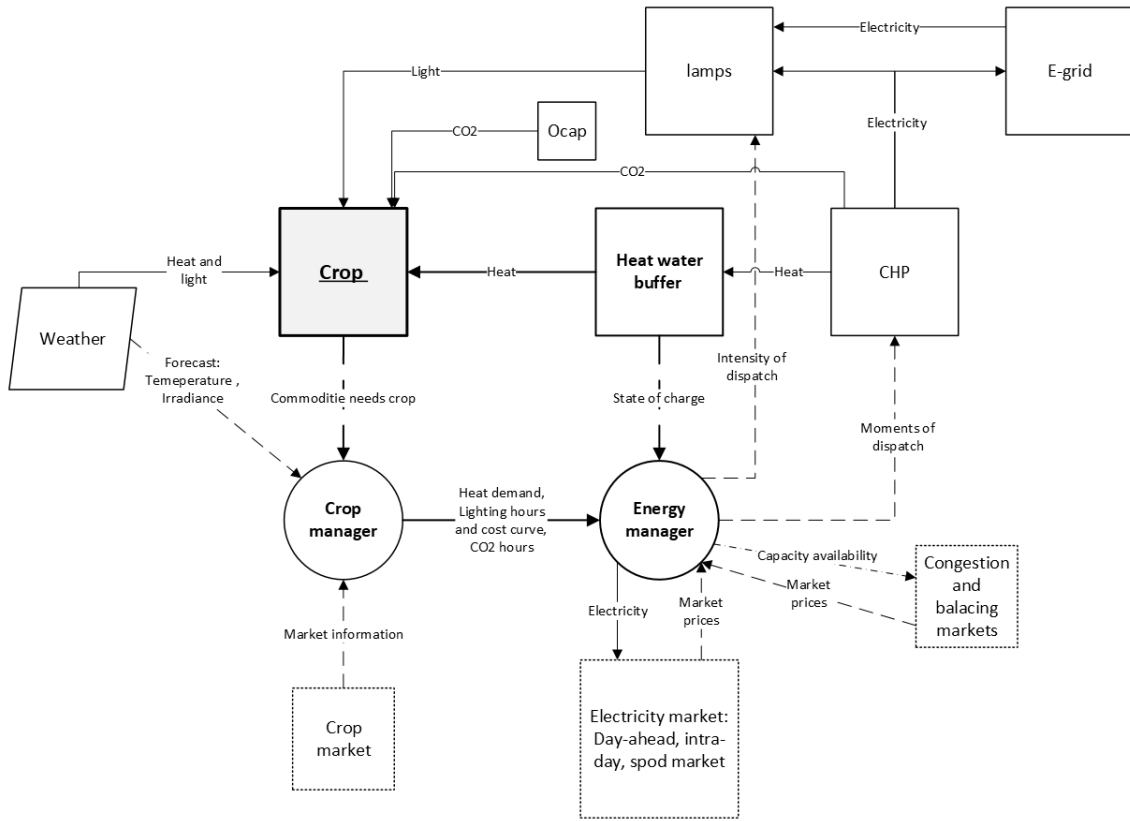


Figure 4: Commodity and information flow within a greenhouse together with the interaction with the external markets.

moment of the lamps and the CHP unit. If the heat buffer is full, the energy manager will sell its capacity to the TSO as a balancing mechanism.

In case of a more empty heat buffer, the energy manager will interact with the electricity market. Its goal is to produce heat for the lowest price possible. It will compare gas prices with the electricity day-ahead prices and decide on its bidding strategy. It sells in two time blocks for the best price on the day-ahead market. After the intraday market gives an indication of which spot prices to expect. If the spot prices are favorable, it strategically sells its position on the intraday market. During operation, it checks the buffer capacity and spot prices to decide to deviate from the electricity bid.

3. Model design

3.1. General model design

The goal of the model is to gain insights into how the energy transition will influence the stress on the distribution grid in a horticultural area. This will be done by simulating the network stress for 3 different future scenarios and comparing these with the current scenario.

The network stress is modeled in two separate steps, which combined form a multi-agent simulation model. The model is schematically displayed in Figure 5

In the first step, individual greenhouse agents are modeled to obtain their electricity interaction with the grid. This is done by controlling the dispatch of their assets to meet their demands.

The obtained grid exchange will then be used in the second step to calculate the network stress. For this research, a case study is provided by the DSO. The case study will be further discussed in the Chapter 'Case study'.

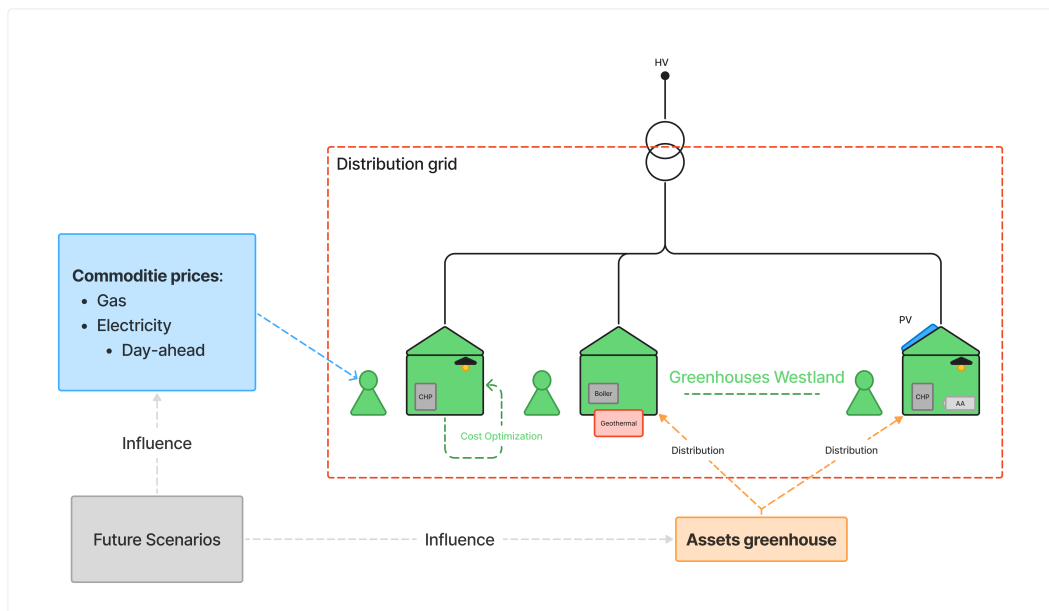


Figure 5: Schematics of the model including the agents, greenhouses and their assets, optimization and information flows.

The goal of the greenhouse agent is to minimize its cost while meeting the crop demand by dispatching its technical assets. It will do this by comparing the dispatch prices of the individual assets that are based on day-ahead electricity prices and gas prices. Intra-day markets are not considered as their dynamics are too complex for the research time. This is also the case for CO₂ production by the assets. The exact details on commodity pricing and dispatch control are discussed later in this chapter.

Three future scenario sketches are made to estimate the commodity prices and asset distributions in the future. The scenarios and associated values are discussed in Chapter 3.2. These scenarios will be compared with the current scenario that will also be described and modeled.

The model will be run for three different days, varying in wind, solar irradiance, and temperature. The days are explicitly chosen based on their weather conditions for two reasons. The first reason is that the days vary in wind and solar to highlight the role of renewable energy sources. The second reason is that the weather conditions had to be similar to what is expected in that month. This last reason has to do with the heat demand that is taken as a monthly average rather than a heat demand for a specific day.

The monthly average temperature is also the reason why is chosen for a daily simulation rather than a simulation longer than 24 h. A longer simulation will simply provide little extra insight and might deviate extra from the monthly average.

The 3 days and their characteristics are displayed in Table 4. Weather data is obtained via the KNMI website using the weather station of Hoek van Holland, which is near the Westland area [19]. Epex prices and weather conditions from these specific days will be used when running the model for the current scenario and will be the baseline for future scenarios.

Table 4: The three modeling days and their characteristics, including their average temperature $T[^\circ C]$, windspeed $V_{\text{wind}}[\frac{\text{m}}{\text{s}}]$ and solar irradiance $I_{\text{sun}}[\frac{\text{J}}{\text{cm}^2}]$

Annotation	Date	Season	$T[^\circ C]$	$V_{\text{wind}}[\frac{\text{m}}{\text{s}}]$	$I_{\text{sun}}[\frac{\text{J}}{\text{cm}^2}]$	Characteristic
Jan	Wed 24-01-2024	Winter	9.5	12.3	12.5	High wind, low solar
Mar	Tue 05-03-2024	Winter	6.3	2.4	12.8	Low wind, low solar
May	Mon 24-05-2024	Spring	17.6	2.5	124.8	Low wind, high solar

3.2. Future scenario's

3.2.1. Scenario sketches

Three scenarios are sketched for the horticultural sector to get insight into asset distribution among the greenhouses. The three scenarios are: Full Geothermal (Full Geo), Mixed Commodity (Mix Com), and Full P2H. Next to the future scenarios, a current scenario is assessed as reference material to validate the model and compare the future scenarios. The three scenarios are based on the scenario sketches of research done by Netbeheer Nederland into the future energy system of the Netherlands [20]. Their scenarios were based on which level the transition is shaped, bottom-up or top-down. The 3 scenario sketches would distinguish whether the transition choice is market-driven or collectively regulated, and if the orientation is national or internationally oriented. Currently, the energy infrastructure for the horticultural sector is gas-dominated and individually focused. The scenario sketches of this research will look into a scenario in which a specific energy carrier or technology is the dominant factor, as displayed in Table 5.

Table 5: Scenario sketches and their characteristics

Scenario	Dominant commodity	Dominant assets	Penetration geothermal
Current	Gas	Boiler, CHP	Low
Full Geo	Heat	Geo	High
Mix Com	Heat, Gas and electricity	CHP, HP, Geo	Medium
Full P2H	Electricity	Heat pumps	None

3.2.2. Current scenario

In the current scenario, the dominant energy carrier is natural gas. Gas is used by the CHP units to provide the greenhouse with heat and create electricity to be used for lighting or to sell on the electricity market. Geothermal energy has penetrated the market, but mainly for vegetable growers. For flower growers who are often more light-intensive, the business case of the CHP unit is a lot better than geothermal and thus lack final participation in the upcoming geothermal projects. Power to heat is only implied by early adapters that earn mainly from the electricity price volatility, such as negative electricity imbalance prices, and can be negligible in their total capacities.

3.2.3. Full Geothermal

The Full Geothermal scenario is a scenario in which transition is shaped top-down and investments are collectively regulated. Greenhouse owners have centralized their heat generation by collectively investing in geothermal energy. Large-scale heat distribution grids ensured access to geothermal energy by almost all greenhouses, accounting for almost all base heat demand in the area. Greenhouses without access are only small greenhouses that either have too little heat

demand or are too dependent on a CHP unit because of their lighting, and cannot invest in both technologies. Peak demand is met by a combination of boilers, heat pumps, or CHP unit.

3.2.4. Mixed commodity

The mixed commodity scenario is the scenario in which the transition is market-driven, but collective investments are still encouraged. Collectively shared heat generation is done only in areas where this is economically viable; therefore, penetration of geothermal energy is lower for this scenario than for the Full geothermal scenario. As the name suggests, base and peak generation have established a good balance between the available assets and energy carriers.

3.2.5. Full P2H

In the Full P2H scenario, electricity is the dominant energy carrier. Investments happen bottom up and individually; therefore, geothermal is disregarded. Heat pumps provide almost all base load for this scenario because of their high efficiency. CHP units are still present for lighted greenhouses, whereas unlighted greenhouses meet their heat demand with either boilers or large E boilers.

3.3. Greenhouse categories & asset profiles

Each greenhouse agent is put into a specific category based on the type of crop, the presence of lighting, and areal size of the greenhouse. The categorization is based on strategic research done by the municipality [15]. The 12 categories are displayed in Table 6.

Table 6: 12 different greenhouse categories existing of 2 types of crops, presence of lighting and 3 areal sizes.

Crop type	Lighting	Reference crop
Vegetable	No	Bell Pepper
Vegetable	Yes	Tomato
Flower	No	Anthurium
Flower	Yes	Chrysant
Areal sizes (A) [ha]		
2	5	10

The categories will help define which assets are present at the greenhouses and thus the options for flexibility. The presence of lighting adds a lighting demand for the greenhouses and will thus influence the presence of assets that generate electricity such as the CHP units. New technologies such as P2H and geothermal will occur more often at bigger companies than at smaller ones. The categories will also differ in control, as will be discussed later in this chapter.

3.3.1. Asset sizing, profile and distribution

Several asset profiles are established based on how a greenhouse owner meets their heat demand. A profile exist out of an asset for its base demand and one for its peak demand. The asset profiles are displayed in the Table 7.

Table 7: Asset profiles and the assets used to meet the load demands.

Asset profile	Base load	Shoulder peak load
Full CHP	CHP	Boiler
Geo CHP	Geothermal	CHP
Geo Boiler	Geothermal	Boiler
Geo HP	Geothermal	Heat pump
Full Electric	Heat pump	E-Boiler
HP CHP ¹	Heat pump	CHP
HP Boiler	Heat pump	Boiler
Full Boiler	Boiler	Boiler
Combi	Geothermal	CHP unit and Heat pump ¹

¹Separation of CHP unit and Heat pump in base load and peak load is less straightforward as it is dependent on the electricity used for lighting.

The distribution of the asset profiles among the greenhouse categories varies between the scenarios based on the scenario description of Chapter 3.2. The exact capacity of the heat sources, PV and lighting, per greenhouse category, can be found in the appendix in Chapter 7.1. The capacities are based on the performed interviews and [21].

3.3.2. Demand

Values for heat demand are based on the values found in the kwin. Kwin stands for "kwantitative informatie" (Quantitative information) and refers to the quantitative values provided by Wageningen University about different types of crops. These values were obtained by averaging data of several greenhouse owners throughout the Netherlands and provide economical and technical reference material.

The heat demand for the different crops is taken from the kwin [13] and is described in Table 8. Data in the kwin is described in gas equivalent and is translated to kWh using a factor of $9.77 \left[\frac{kWh}{m^3} \right]$ and a heat efficiency of 0.45 and 0.85 for the CHP unit and gas boiler, respectively. Data is given as an average daily heat demand for that month. A big assumption made in the model is that each greenhouse has enough thermal storage to meet daily heat demand. Therefore, daily demand is sufficient for our purposes, and hourly patterns are not needed.

The light demand of the crops can also be found in the same table as the heat demand, Table 8. It is given in the average daily lighting hours and was provided by a tomato and a chrysanthemum farmer, who also provided the light capacity per light hour for their crop. The light capacity are 0.66 and $0.57 \left[\frac{MWh}{ha^2} \right]$ for vegetables and flowers, respectively. The capacities are given in electricity consumption rather than light output. Of the lighting, heat generation is neglected, and it operates only at its maximum capacity.

Table 8: Heat and light demand per day of the different categories for the 3 sample months.

Category	Heat demand [MWh]			Light demand [h]		
	Jan	Mar	May	Jan	Mar	May
Paprika 2 ha	27.16	12.88	7.22	[-]	[-]	[-]
Paprika 5 ha	67.90	32.20	18.05	[-]	[-]	[-]
Paprika 10 ha	135.80	64.40	36.10	[-]	[-]	[-]
Tomato 2 ha	2.43	1.66	0.47	12	12	8
Tomato 5 ha	6.07	4.16	1.18	12	12	8
Tomato 10 ha	12.13	8.32	2.36	12	12	8
Anthurium 2 ha	22.54	13.04	3.56	[-]	[-]	[-]
Anthurium 5 ha	56.35	32.60	8.90	[-]	[-]	[-]
Anthurium 10 ha	112.70	65.20	17.80	[-]	[-]	[-]
Chrysant 2 ha	27.64	17.56	9.74	12	12	12
Chrysant 5 ha	69.10	43.90	24.35	12	12	12
Chrysant 10 ha	138.20	87.80	48.70	12	12	12

3.4. Commodity pricing and generation

3.4.1. Gas pricing

The current gas price is 0.337 euro per m^2 gas. The prices are directly taken from the Engie portal a gas supplier in the Netherlands. There are also variable tax cost associated with consumption of gas, one for the consumption itself and one for the associated CO_2 emitted. This results in a variable gas price of 0.557 euro per m^2 gas inclusive tax costs. There are also associated network cost with the use of gas however these are fixed and are thus not taken into account for the dispatch.

3.4.2. Epex pricing and extra electricity costs

Figure 6 show the hourly day ahead Epex prices for the three sample days. The data is obtained using the API of easy energy to access hourly historical Epex prices [22]. All days show an evening peak around 19:00 in agreement with the high demand of the residential sector during that hour. The January curve has a valley in the early morning corresponding with the high wind during those hours. The march curve is a relative flat curve corresponding to the small penetration of renewable energy at this day. The June line is a day with a lot of solar irradiance corresponding with the valley at the afternoon hours.

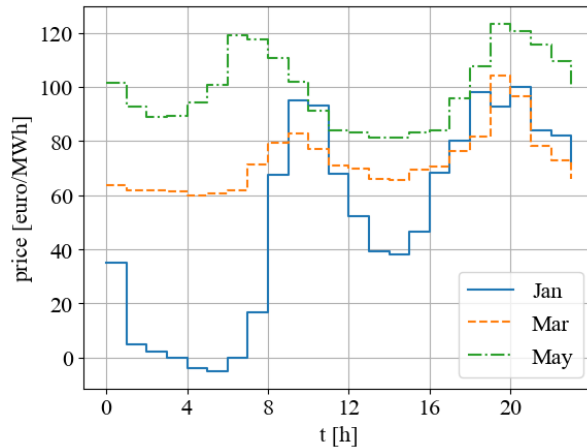


Figure 6: Day ahead Epex electricity price per MWh for the three sample days.

Associated max and minimum prices as well as there moment of occurrence are displayed in Table 9. Most notable is that they minimum for May occurs at a complete different time point that March and January.

Table 9: Minimum and maximum electricity prices for each of the sample days give in [€/MWh] plus the hours at which they occur.

	Jan		Mar		May	
	Price [€/MWh]	t [h]	Price [€/MWh]	t [h]	Price [€/MWh]	t [h]
Max	100.10	20	104.38	19	123.38	19
Min	-5.00	5	59.86	4	81.23	14

3.4.3. Governmental energy tax and distribution tariff

Energy taxes on both gas and electricity are defined by the government and are stated on the website of the responsible authority [23]. The system for both gas and electricity is the same and follows a tax scale system. For each scale, a different variable tax per energy quantity is defined. An average tax scale will be used for all greenhouses chosen based on average greenhouse use. For gas, an extra tax is included for CO₂ emission.

There are also commodity-associated grid tariffs [24]. For gas these tariffs are quantity independent and depend solely on expected gas capacity and a fixed annual cost, and thus will not be included in this research. This is not the case for electricity. In the Westland Infra area, grid consumers pay a fixed amount for the quantity they are using and an extra monthly fee for the maximum capacity they have used for that month. This latter one is quite a substantial amount of the grid tariff, but will not be taken into account in this research. This is because the maximum capacity is often used in intraday trading, a market that is not considered in this research.

All taxes and tariffs used in this research are displayed in Table 10.

Table 10: Energy taxes and tariffs in $[\frac{euro}{m^3}]$ for gas and $[\frac{euro}{MWh}]$ for electricity

Commodity	Energy tax	ass. CO2 tax	Grid tariff	Unit
Electricity	38.68	-	25.7	$\frac{euro}{MWh}$
Gas	0.2	0.017	-	$\frac{euro}{m^3}$

3.5. Assets representation of the greenhouse agent

The assets of the greenhouse are simplified to an input out put model. Fuel flows inside the asset with a certain energy, which is converted to another form of energy with a specific efficiency. The efficiency used for each assets are shown in table 11. For calculating the energy of one m³ of gas the $9.78 \frac{\text{kWh}}{\text{m}^3}$ is used, obtained from the CBS.

Table 11: Efficiencies used to calculate output values of the asset.

Asset	Input	Output	Efficiency
Boiler	Gas	Heat	0.85
CHP unit	Gas	Heat, Electricity	0.55, 0.4
Heat Pump	Electricity	Heat	4
Eboiler	Electricity	Heat	0.9
Geothermal	Heat	Heat	1

3.6. Dispatch control of greenhouse agent

The goal of the greenhouse agent is to reduce its cost whilst meeting its demand constraints. It does this by calculating and comparing the dispatch prices of the assets. The dispatch price for lighting is the cost to turn on the light for 1 hour and for the heat assets, this is the price to produce 1 MWh of heat. The control of the dispatch is shown in Figure 7.

The first step of the control is to calculate the generation cost of 1 kWh of heat for every hour of the day. In the case of a CHP unit, earnings from selling electricity on the grid are deducted from the fuel price to get its heat generation cost.

Base generation and peak generation are dispatched to meet the heat demand. First base generation is dispatched for the hours in which its dispatch price is lower than that of peak generation and the electricity constraint is not surpassed.

Then the peak generating unit is dispatched for the remaining heat demand or up to full capacity, upholding the electricity constraint. If the heat demand is still not met after dispatch peak generation, then base generation is dispatched again, but without comparing its price with peak generation.

There are 2 special cases in which the control is structured differently. The first are cases in which geothermal is the base generation source. In this case all the heat of the geothermal is used without comparing its price to the peak generation. The reason for this is that greenhouse owners are obligated to use the heat for what they have contracted. The second case is the dispatch of the e-boiler due to negative electricity prices. When negative dispatch prices occur, e-boilers will be dispatched before the heat pump as they can dispatch at a higher capacity.

Between every dispatch step, dispatch prices are recalculated. The change in dispatch price is caused by the network tariff cost. The cost are based soley on the consumption from the grid. It can therefore be cheaper to dispatch a heat pump during hours in which a CHP unit is already dispatch rather then dispatching it on the cheapest day ahead Epex price hours. The exact policy for updating the network cost is discussed later in this chapter in Chapter 3.6.5.

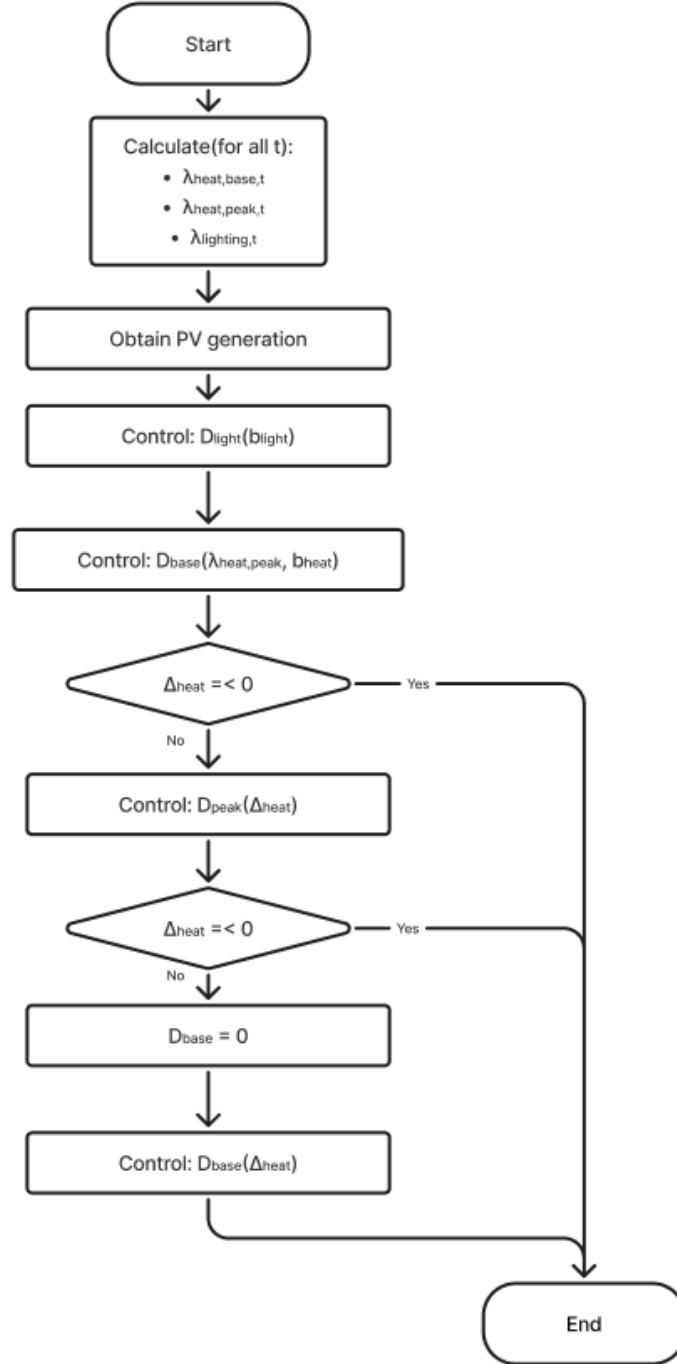


Figure 7: Dispatch control steps of the greenhouse agent in which: λ are the dispatch price per time instants, D_{asset} stands for dispatch policy, b is the light or heat demand constrain and Δ_{heat} the difference between heat demand and so far generated heat.

3.6.1. Policy: lighting dispatch

There are three input values for the lighting policy: hours to dispatch, dispatch price, and crop type. One assumption is that available grid capacity of the greenhouse is higher than the lighting capacity. Therefore, grid capacity will not be a constraint for lighting purposes and

does not have to be included in the policy for lighting dispatch.

For simplicity reasons is assumed that the lighting dispatch state is binary; it is either 'on' at maximum capacity or not at all. There is a different lighting policy for each crop type. Flower crop greenhouses have to dispatch their lighting in consecutive hours whereas tomatoes can choose when they dispatch there light.

For vegetable greenhouses dispatch price are sorted from low to high. After which lowest hours are picked equal to the hours of lighting needed.

For flowers the dispatch is more complex. One of the constrains is that light for these flowers is only dispatch between 4 and 21 such that they overlap with the natural daylight. First, a convolution product is done between the available dispatch prices and a block function of height 1 and a width equal to the number of dispatch hours for the hours in which there is total overlap with the time window. From the resulting array, the cheapest value is chosen to be dispatched, containing the 8 cheapest consecutive hours within the given time window.

Figure 8 shows a simplified diagram of the policy that is followed for the dispatch.

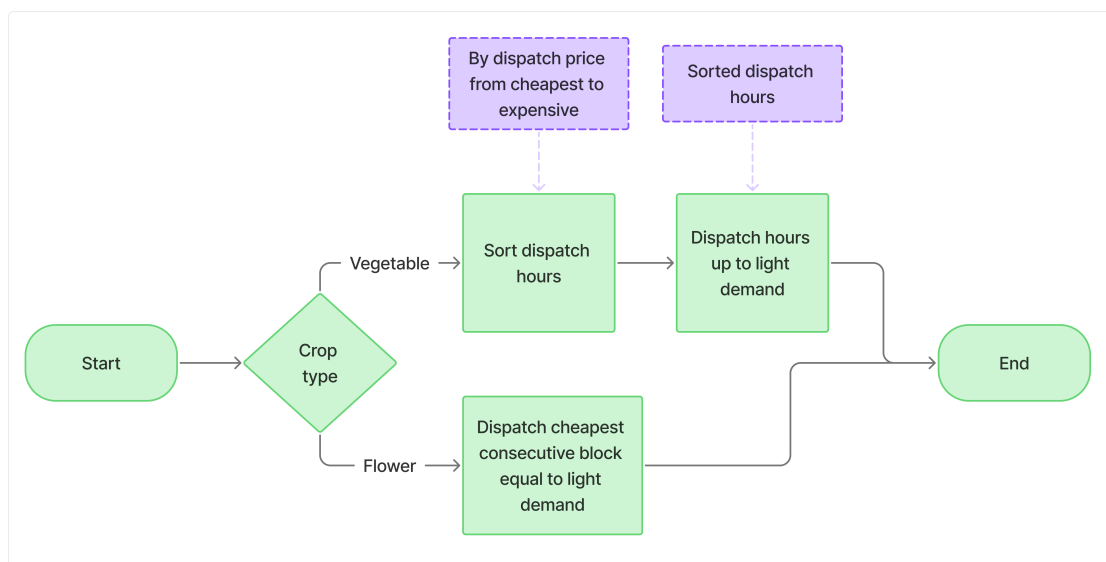


Figure 8: Simplified diagram of policy for lighting dispatch. Green blocks with continuous borders show the taken steps, and Purple blocks with dashed borders provide conditions under which steps are taken.

3.6.2. Policy: heatpump and eboiler dispatch

Heatpumps and eboilers policies are dispatched in a similar way as the lighting for vegetables. P2H assets dispatch according to the following steps:

- The first step in the policy of P2H dispatch is to check to what extent a P2H asset can dispatch at each hour based on grid consumption constrains and capacity constraints of the dispatch. This is done by assigning all hours a value between 0 and full capacity, which is stored in a separate array. If the asset is responsible for the base generation, it also compares its heat price with that of the peak generating heat asset. This comparison only happens in the first step of the dispatch model and only occurs for profiles that have a heat pump as base generation.

- The second step is to sort the dispatch based on their dispatch price from low to high.
- Then, in the third step is decided how many hours of heat-pump needs to be dispatched to meet the heat demand. This is done by integrating the dispatch array defined in step one, which is sorted according to step two, up until the point that the heat demand is met. All hours up to the boundary of the integral are dispatched or partially dispatched according to their availability; in all the other hours, the asset is not dispatched.

Figure 9 shows a simplified diagram of the policy that is followed for the dispatch of the P2H technologies.

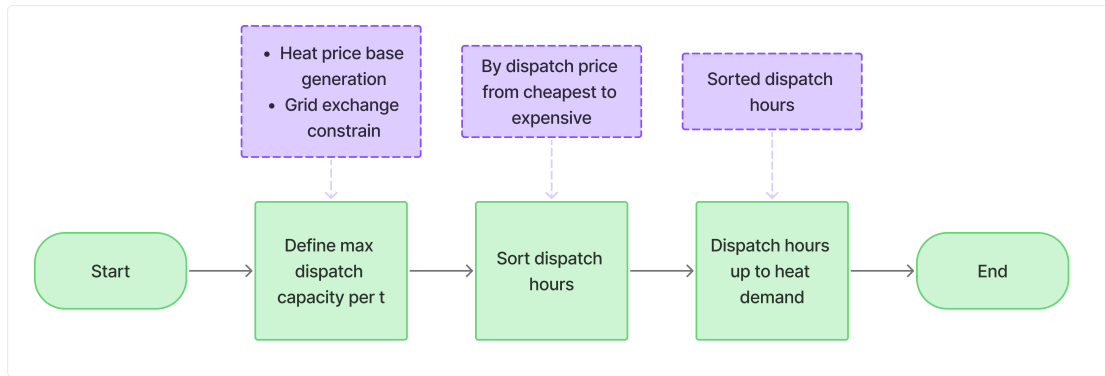


Figure 9: Simplified diagram of policy for heatpump and e-boiler dispatch. Green blocks with continuous borders show the taken steps, and Purple blocks with dashed borders provide conditions under which steps are taken.

3.6.3. Policy: gasboiler dispatch

The gasboiler dispatched is the simplest dispatch policy of all the assets. This because it has no interaction with the electricity grid making it time independent in its dispatch and price. Thus it simply dispatches for the first hours it can dispatch up to the point that heat demand is met, taking into account its maximum capacity.

Figure 10 shows a simplified diagram of the policy that is followed for the dispatch.

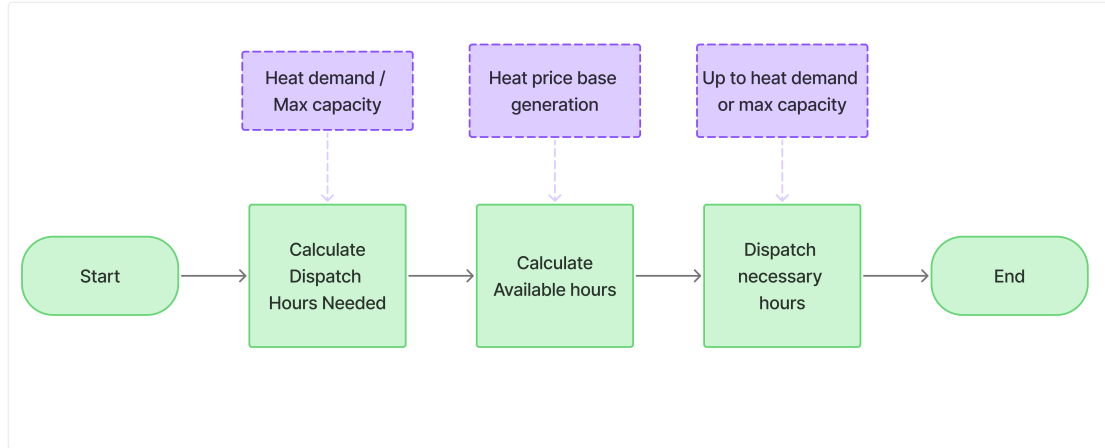


Figure 10: Simplified diagram of policy for boiler dispatch. Green blocks with continuous borders show the taken steps, and Purple blocks with dashed borders provide conditions under which steps are taken.

3.6.4. Policy: CHP dispatch

The CHP dispatch is the most complex of the assets as it has to follow specific policies to be in line with current operation. The first policy rule is that it dispatches for at least 3 consecutive hours. The second policy rule is that if more than 6 hours of CHP dispatch is needed, it has to dispatch in two blocks one from 00:00 to 15:00 and one from 15:00 to 24:00. The first policy rule has to do with on and off flipping of the CHP unit which is bad for the machine and the second has to do with strategic bidding to have a good position on the spot market. For simplicity is assumed that the CHP only operates at maximum capacity. Control of CHP dispatch happens according to the following steps:

1. The first step is to calculate the number of dispatch hours depending on the heat demand and maximum capacity of the CHP unit. If this is between 0 and 6 hours, the dispatch happens onefold in one consecutive block. If it is higher than 6, the dispatch happens in two blocks that dispatch in two different time frames. The next steps follow the control sequence for two blocks.
2. The second step is to create an associated array to calculate for which hours the CHP unit is allowed to dispatch, assigning these values a 1 and all other hours a 0.
3. Then a convolution between the array, created in step two, and a unit block is used to decide the maxim consecutive hours a CHP can dispatch within a given time frame. This is done by increasing the unit block by one and storing the time windows in which the convolution is equal to the width of the unit block and done until maximum dispatch hours is reach or the first iteration in which no convolution value is equal to the width of the unit block.
4. In the forth step the dispatch cost is calculated for the allowed time windows by summing and multiplying the dispatch costs. Of which only the cheapest dispatch cost and time window is stored for each window size.

5. The next step checks whether the dispatch hours needed are higher than the sum of the maximum hours. If this is true all maximum time blocks within the two time frames are dispatched. If not, all possible combinations between the first and second block sizes that are equal to dispatch hours are compared in dispatch cost, and the cheapest is dispatched.

For a single time block, the control is easier as the width of the dispatch block of the CHP unit is either equal to the dispatch hours needed or to the maximum width, depending on which of the two is higher. For this consecutive block size, the cheapest possibility is chosen to be dispatched.

Figure 11 shows a simplified diagram of the policy that is followed for the dispatch.

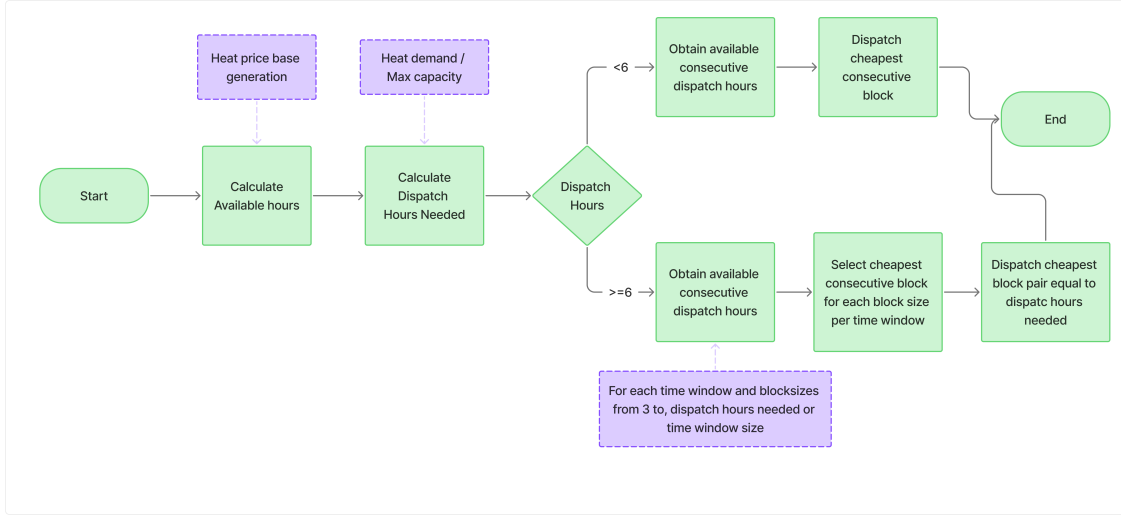


Figure 11: Simplified diagram of policy for CHP dispatch. Green blocks with continuous borders show the taken steps, and Purple blocks with dashed borders provide conditions under which steps are taken.

3.6.5. Calculating the dispatch price

The dispatch price is calculated by dividing the production cost by the total heat produced for that cost, see equation 1. Side products are sold on their specific market and is subtracted from the production cost. In the equation is $\lambda_{asset,t}$ the dispatch price at timepoint t and are $f_{asset,t}$, $\lambda_{fuel,t}$ and $\lambda_{tariff,t}$ the fuel consumption, associated fuel and tariff cost respectively. $p_{asset,side,t}$ is the production of a secondary product besides heat and $\lambda_{side,t}$ and $\lambda_{side,tariff,t}$ are represents the selling price and associated selling tariff. $E_{asset,heat,t}$ is the heat produced at time point t.

$$\lambda_{asset,t} = \frac{f_{asset,t}(\lambda_{fuel,t} - \lambda_{tariff,t}) - p_{asset,side,t}(\lambda_{side,t} - \lambda_{side,tariff,t})}{E_{asset,heat,t}} \quad (1)$$

The dispatch cost is actually, in cases associated with electricity, nonlinear, as they involve a discrete step of the tariff costs. There are only grid tariffs for electricity consumption and not for production of electricity, therefore the tariff is non linear at zero power exchange. For gas tariffs this problem doesn't exist as there is not such a thing injecting gas back in the network. The non linearity makes it tricky to calculate the actual tariff cost around the origin. To simplify

this step there is assumed, only in case of this calculation, that assets can only dispatch at full capacity and that the tariff between the point of dispatch and not dispatching happens linearly. Combining these assumptions results in equation as shown in Equation 2. In the equation $P_{i,grid,t}$ and $\lambda_{P_{i,tariff,t}}$ stand for the Power exchange with the grid and the grid tariff price respectively. The i indicates the power before full dispatch of the asset 0 or after full dispatch 1. The difference tariff cost is divided by the total heat produced by the asset at time point t indicated by $E_{asset,heat,t}$, resulting in the network tariff price at time point t indicated by $\lambda_{tariff,t}$.

$$\lambda_{tariff,t} = \frac{P_{1,grid,t}\lambda_{P_{1,tariff,t}} - P_{0,grid,t}\lambda_{P_{0,tariff,t}}}{E_{asset,heat,t}} \quad (2)$$

In other words the electricity tariff cost for every time point t is calculated before and after dispatch. The difference is divided by the total heat capacity at time point t resulting average tariff price between zero and maximum dispatch.

3.7. PV generation greenhouse agent

PV generation is simulated using a simple model in which the electrical output energy is the incoming solar irradiance times the efficiency of the module as discribed in [25]. The incoming solar irradiance is retrieved from the weather of the KNMI at Hoek van Holland [19]. The efficiency of the module is taken to be irradiance and module temperature depend as displayed in Equation 3.

$$\eta(T_m, G_{AOI}) = \eta(25^\circ\text{C}, G_{AOI})[1 + k(T_m - 25^\circ\text{C})] \quad (3)$$

Here an efficiency is calculate at standard module temperature of 25 degree Celsius that is only depended on irradiance which is multiplied by a factor which is dependable on a deviating module temperature. The first part of the equation is calculate using Equations 4, 5, 6 and 7. The Duffie-Beckman model is used to calculate the module temperature and is shown in Equation 8. All variables within the mentioned equations and there associated value can be found in Table 12. The "Tiger Neo N-type 54HL4R-B 420-440 Watt" is used as reference PV module for the associated values.

$$\eta(25^\circ\text{C}, G_{AOI}) = \frac{P_{MPP}(25^\circ\text{C}, G_{AOI})}{A_m G_{AOI}} \quad (4)$$

$$P_{MPP}(25^\circ\text{C}, G_{AOI}) = FFV_{OC}(25^\circ\text{C}, G_{AOI})I_{SC}(25^\circ\text{C}, G_{AOI})|_{FF=const} \quad (5)$$

$$I_{SC}(25^\circ\text{C}, G_{AOI}) = I_{SC}(STC) \frac{G_{AOI}}{G_{STC}} \quad (6)$$

$$V_{OC}(25^\circ\text{C}, G_{AOI}) = V_{OC}(STC) + \frac{nk_b T}{q} \ln\left(\frac{G_{AOI}}{G_{STC}}\right)|_{T=25^\circ\text{C}} \quad (7)$$

$$T_m = T_{amb} + \frac{G_{obs}}{G_{NOCT}}(NOCT - 20^\circ\text{C}) * \frac{9.5}{5.7 + 3.8w} \left(1 - \frac{\eta_{STC}}{\tau\alpha}\right) \quad (8)$$

Table 12: Variables and constants from the equation given in this section. Sources of the Book, Data sheet and Weather station are given by [25], [26] and [19] respectively.

Variable	Value	unit	Source
k	-0.0035	[-]	Book
FF	0.8	[-]	Data sheet
A_m	2.0	m^2	Data sheet
G_{NOCT}	800	W/m^2	Data sheet
G_{STC}	1000	W/m^2	Data sheet
$I_{SC}(STC)$	13.65	mA	Data sheet
$V_{OC}(STC)$	39.16	V	Data sheet
n	1	[-]	Book
k_b	$1.380 \cdot 10^{-23}$	JK^{-1}	Book
q		C	Book
η_{STC}	0.2152	[-]	Data sheet
$\tau\alpha$	0.9	[-]	Book
G_{AOI}	variable	W/m^2	Weather station
T_{amb}	variable	$^{\circ}C$	Weather station
w	variable	m/s	Weather station

3.8. Case scenario

3.8.1. Case Network

A 20kV medium voltage case grid is provided by the DSO, which is displayed in Figure 12. The grid is a meshed grid but is operated as a radial network by opening up the switches that connect two nodes. It consists of a coupling with the HV network operated by Tennet, via the purchase station. This distributes the 150 kV of HV grid to two separate transformers, which transform the 150 kV to 20 kV. The network behind each of the two transformers is annotated by a branch. Loads that are fed by "Distribution station A" belong to "Branch 1" and the loads that are fed by "Distribution station B" belong to "Branch 2". The distribution stations A and B will also be referred to as the main distribution station of branch 1 or 2. The branches can even be divided by subbranches, highlighted by the different colors in the figure, and are annotated by the first node in connection to the main distribution station. Branch 1 exist of subbranches: 2,3 and 8 with a total of 9 load, whereas branch 2 exist of subbranches: 2, 3, 4, 9 and 15 with a total of 20 loads. There is a clearly an uneven number of load distribution among branch 1 and 2 so higher stress can be expected in branch 2 then in branch one. Details about wire types and length are added in the appendix in Section 7.2, and information about the impedance values is presented in the result section in Section 4.2.

The DSO has not provided which category type is on which node. Therefore, the 29 loads are divided in categories based on their occurrence percentage in Westland [15], after which they are randomly distributed over the network. For this, the random shuffle function of the numpy library in python is used. In the categorization of the loads is ensured that every category occurs at least once. This results in the distribution as shown in figure 13. In the figure vegetables are annotated by a continuous green arrow line and the flowers by a pink dashed arrow line. The size of the greenhouse is noted in the arrow head and is given in hectares. The node circle

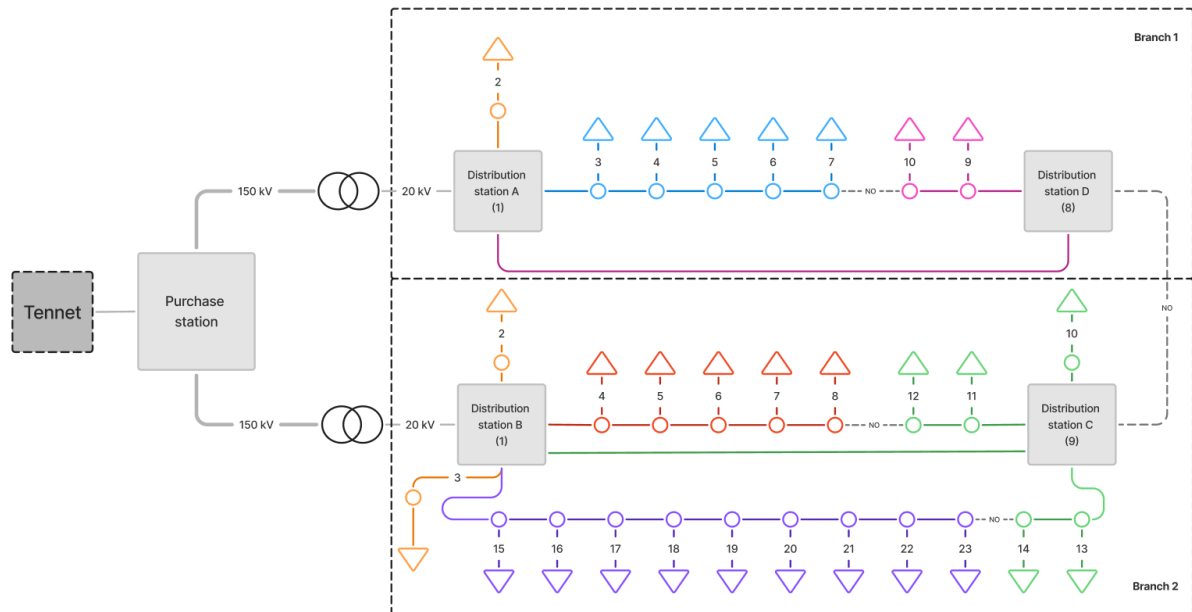


Figure 12: Case study as provided by Westland infra, consisting of 29 loads, displayed by the arrow; 4 distribution stations; a coupling point with the HV grid, and 2 transformers. The dashed lines in between nodes are lines that are normally open (NO), creating a disconnecting point, ensuring that the grid is operated as a radial network. The number at each arrow displays the node number.

shows wether the greenhouse has a lighting asset and by yellow colloring if lighting is present and uncolored circle if lighting is absent.

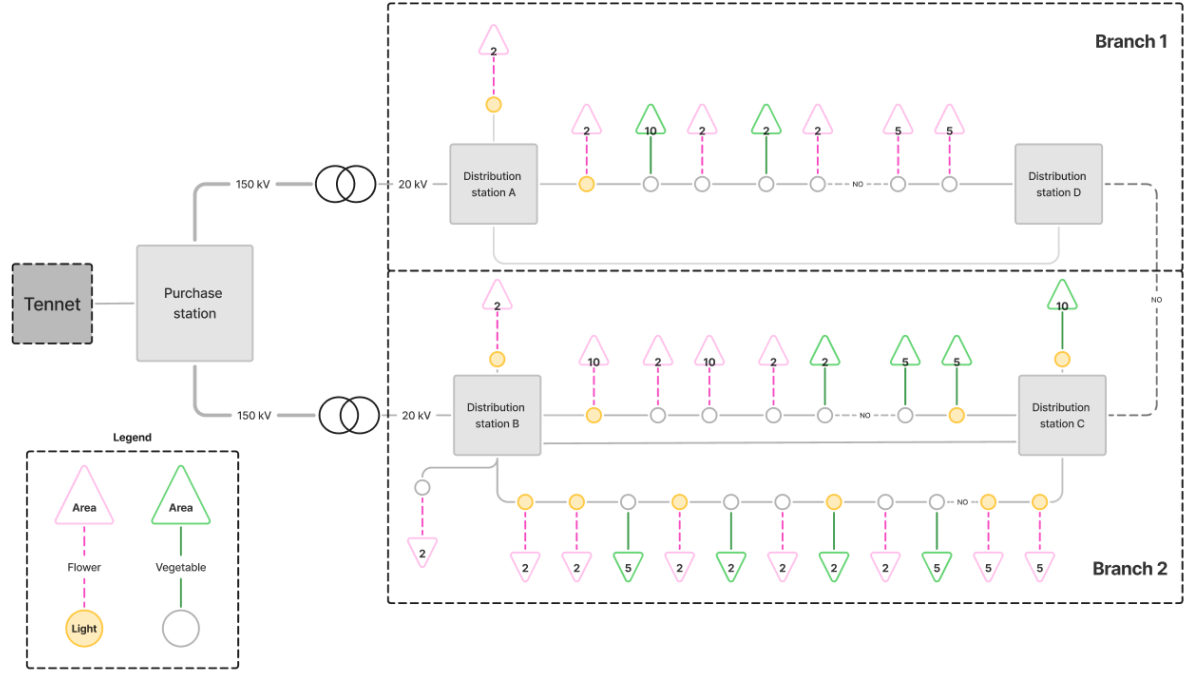
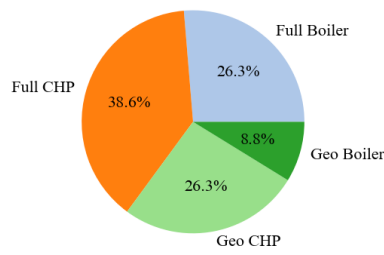


Figure 13: Distribution of the categories among the case network, in which: Type of crop is annotated by green continuous or pink dashed arrow line for vegetables and flowers respectively; area sizing is annotated in the arrowhead in hectors and lighting is displayed by a colored or uncolored node circle.

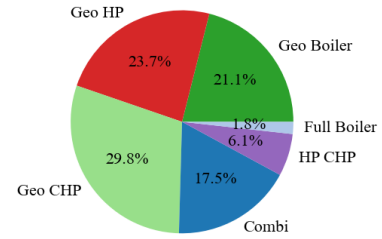
3.8.2. Profile distribution

Each asset profile, asset for base-load generation and peak generation is distributed differently among each scenario. The penetration of a given profile in a scenario is displayed as a pie diagram in Figure 14. The percentage are based on area rather than on number of greenhouses. This way there is more insight to what extend an profile could have affect on the network. In the current scenario (Figure 14a), 4 different profiles are central with either gas boilers, CHP units, or geothermal. The fact that boilers and CHP are present at every scenario highlights why gas is currently the dominant commodity, from the profiles more than 50% of the base generation is done by one of the gas assets.

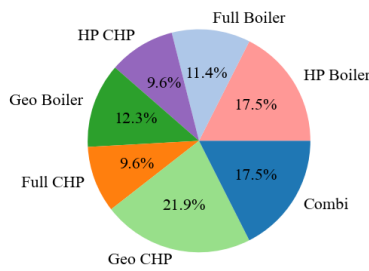
The Full Geo scenario has clear geothermal character, only 8% of the greenhouse areas doesn't have geothermal energy in their asset profile. Geotothermal energy is equally combined with either a HP or one of the two gas assets. The pie diagram for the mix comodity scenario, Figure 14c, shows an evenly distribution of the different profiles where all profile are around 10% or 20% of the greenhouse areas. The Full P2H scenario is the only scenario without geothermal and with a profile that is fully electric as can be observed in Figure 14d. P2H is present in 92% of the areal and the HP are combined with either a Boiler, CHP unit or Eboiler.



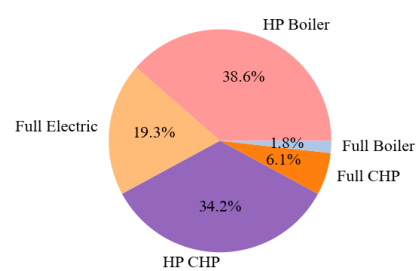
(a) Current scenario



(b) Full Geo scenario



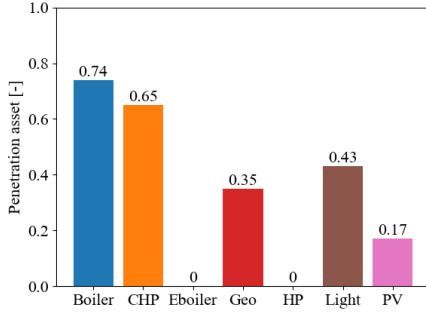
(c) Mix Com scenario



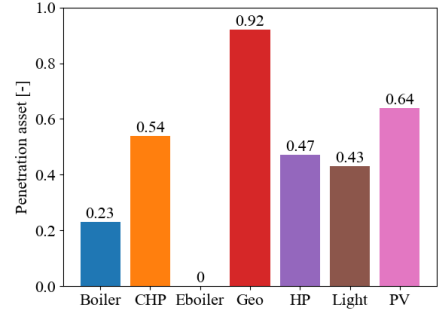
(d) Full P2H scenario

Figure 14: Pie diagram of the penetration of profiles among each scenario. The percentage are based on area of greenhouse.

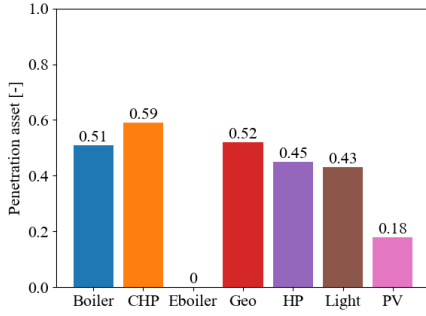
The penetration of the individual assets among the areal are also displayed as a bar-plot in Figure 15 to have a better oversight how often a assets occurs in each scenario. The penetrations of lighting and PV are also displayed in these bar graphs, information that is not visible on the pie graphs. Note that the percentage of lighting doesn't change among the scenarios as it is depend on the category distribution which stays the same over the scenarios. Furthermore the PV penetration is higher for the the Full Geothermal and P2H scnearios, Figure 15b and 15d and lower for the scenario that are still gas dominate, Figure 15a and 15c.



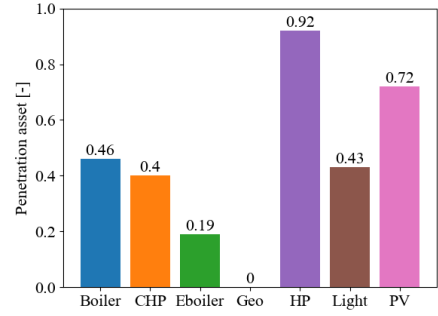
(a) Current scenario



(b) Full Geo scenario



(c) Mix Com scenario



(d) Full P2H scenario

Figure 15: Penetration bar plot of the asset among each scenario.

3.9. Electrical grid simulation

To simulate current flows and voltage levels, the model of this paper [27] is used. Input parameters of the model are node connections, cable types between nodes with their respective impedance and length values, and a load profile for every node. The load profile is obtained via the load, and all other information is provided through the case scenario. Most of the features of the model are not used as the loads cannot be controlled during operation. The model is solely used to calculate the current and voltage using a numerical approach. The model uses the nodal power injection and starting positions and calculates the voltage and current values in separate optimization steps. The obtained optimized value is the input for the other value, and the optimization procedures are repeated until both values are below an error value.

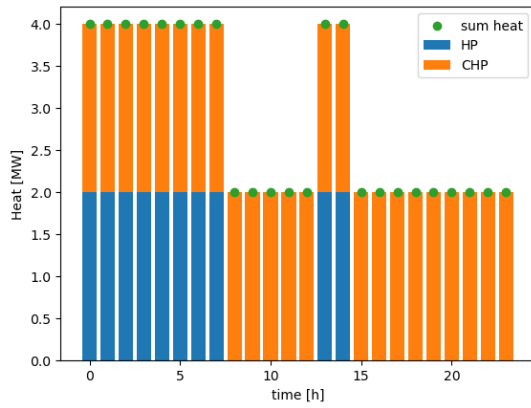
4. Model results and discussion

4.1. Greenhouse model

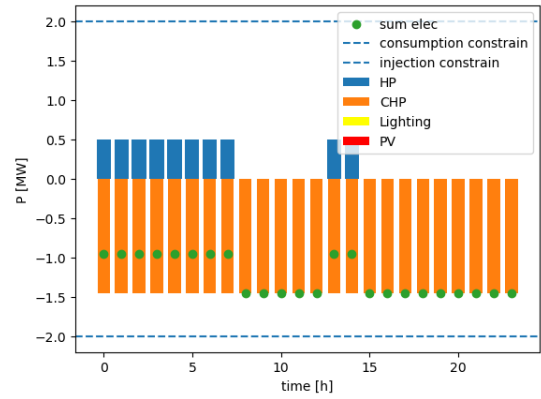
Figures 16, 17, 18 and 19 display 4 examples in which every croptype, area size, and month are represented. In each figure, a heatplot, an electricity and a price plot are shown. The plotted prices are the dispatch prices after dispatch and include the extra grid tariffs and governmental taxes.

Paprika

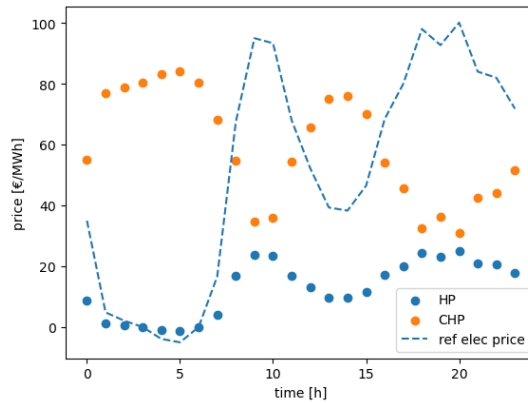
The first example is a Bell pepper greenhouse with a heat and light demand of January plotted in Figure 16. The greenhouse has an HP CHP profile and thus has an HP for its base load and a CHP for its peak load. The heat plot of the Greenhouse in figure 16a shows a dispatch of CHP for every hour and an HP dispatch during the first 8 hours during the first price valley and 2 hours of dispatch during 2nd price valley. Both assets can produce similar capacities of heat. Even though the HP is the base generation, more heat is produced by the CHP unit. This has two reasons: control order and price calculation. The control first dispatches the HP whilst comparing its price with the CHP unit. In the next step the CHP unit is dispatched to its fullest extent, after which leftover heat is met by HP unit for the hour it has not yet dispatched. Doing it this way ensures that the CHP unit covers most of the body of heat if prices are more favorable for the CHP unit. The price calculation includes an electricity tax for grid consumption. In the first step, no generation is yet present in the CHP unit; thus, the dispatch price includes the high network tariff. Figure 16c shows the prices with an already dispatched CHP unit. Now very low price can be observed for the heatpump, even better prices than for the CHP unit itself. A more balanced generation between HP and CHP units would have been better in this case. The electricity plot in Figure 16b displays the electricity consumption for each individual asset and the total grid exchange highlighted by the green dots. For all hours, a feed-in grid exchange can be observed, something which is expected with full CHP dispatch.



(a) Heat consumption



(b) Electricity consumption



(c) Dispatch price including tariffs and taxes after dispatch

Figure 16: Dispatch profile of 5 ha Bell pepper in January with an HP CHP profile, consisting of heat and electricity consumption per asset, and dispatch price of the assets including all extra variable costs.

Tomato

The next example is a 10 ha tomato greenhouse, plotted in Figure 17, with lighting and a Combi profile that has three assets: Geothermal for the base load and a combined HP and CHP unit for the peak load. In the heat plot a constant base heat generation of the geothermal can be observed. On top of the base generation a separate HP heat generation block and CHP can be observed. Notice that HP unit produces less heat per hour than the CHP unit. This has to do with the electricity constrain.

The electricity plot displays lighting dispatch at the same hours as the HP unit. The electricity consumption because of lighting is already enough to meet the constraint by itself. Therefore, there is little space for the HP to dispatch, and it thus dispatches only a small amount of its maximum capacity.

The dispatch of lighting is not a consecutive block, highlighting the difference with lighting in a greenhouse with flowers.

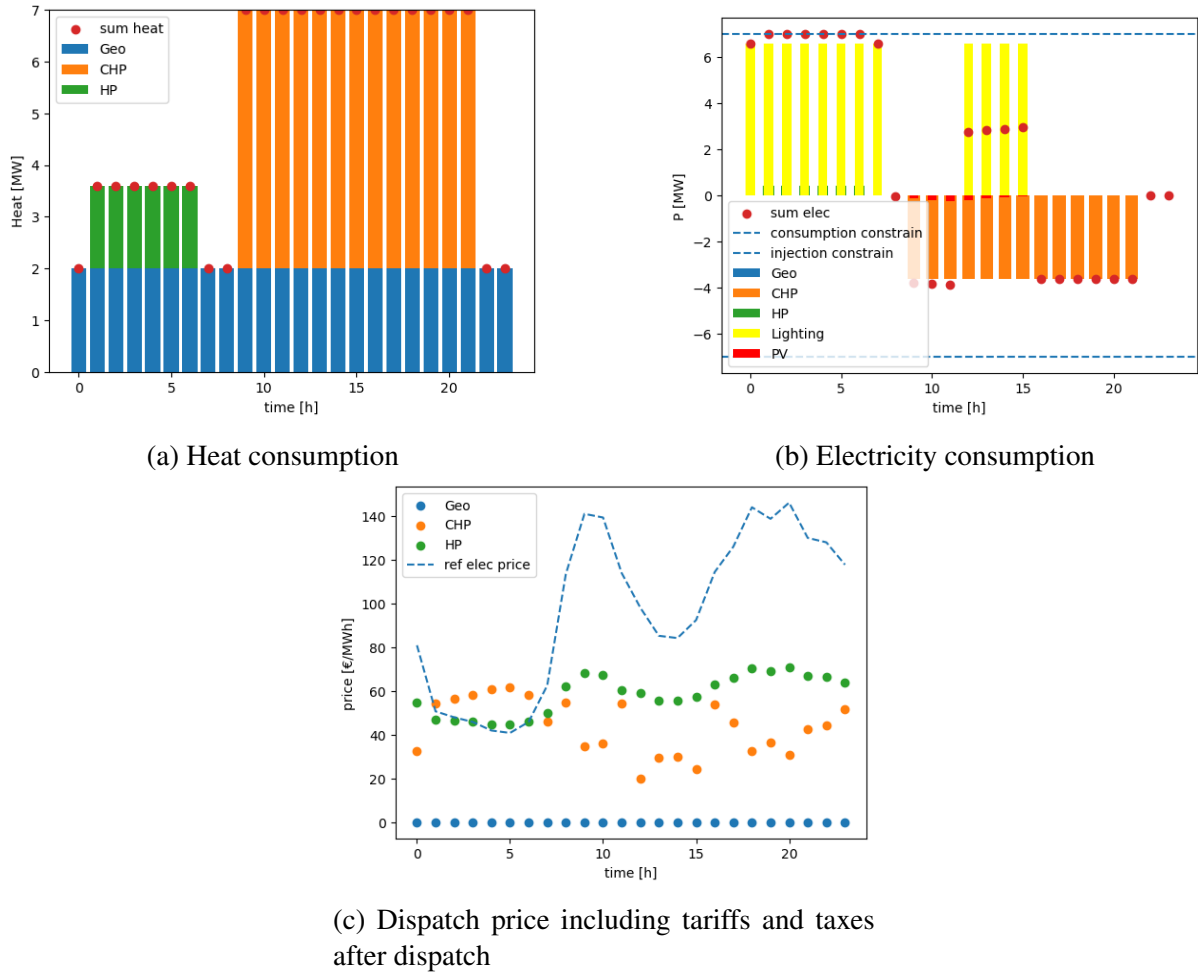


Figure 17: Dispatch profile of a 10 ha tomato greenhouse in January with a combi profile, consisting of heat and electricity consumption per asset, and dispatch price of the assets including all extra variable costs after dispatch.

Anthurium

A 5 ha anthurium greenhouse for the month May is displayed in figure 18. The asset profile is Full electric, meaning that the base load is generated by a HP and the E-boiler is used for peak load. No E-boiler dispatch is observed, and all heat is solely covered by the heat pump. This is in line with what is expected, the HP has a higher efficiency, and E-Boilers are always more expensive in dispatch price unless prices go negative, which is not the case for May. The difference in dispatch price is clearly observed in Figure 18.

Also, little PV generation can be observed in the electricity plot in Figure 18b. This shows how little the PV generation is compared to the other consumption and generation.

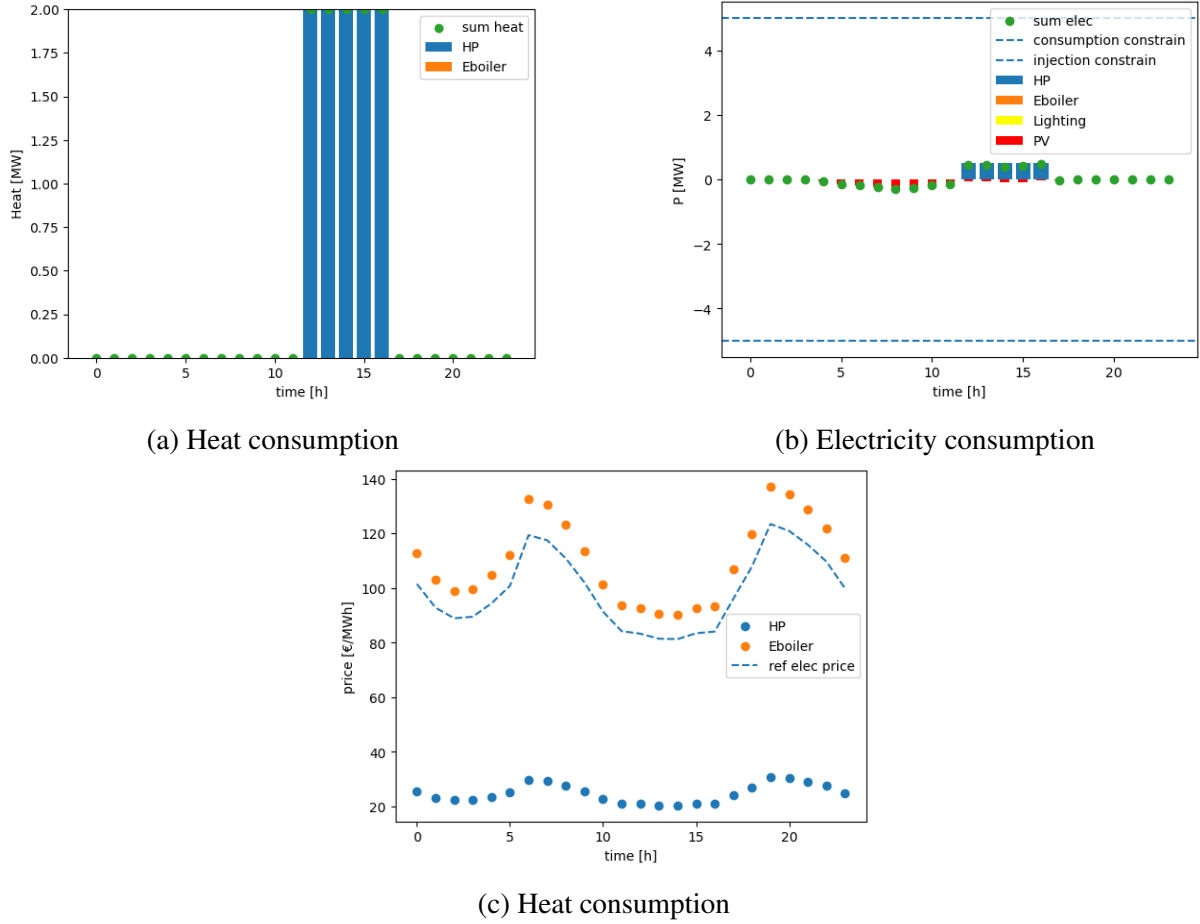


Figure 18: Dispatch profile of 5 ha anthurium greenhouse in January with a Full Electric profile, consisting of heat and electricity consumption per asset, and dispatch price of the assets including all extra variable costs.

Chrysant

The last example is a 2 ha Chrysant greenhouse in March with a Full CHP profile displayed in figure 19. The heat plot in figure 19a shows that only the CHP unit is dispatched. The electricity plot in figure 19b shows the 12 consecutive hours of lighting dispatch associated with Chrysant cultivation. The light dispatch is also clearly visible in the dispatch price of the CHP unit. For these hours, a clear drop is noticed in the price plot of Figure 19c. In these hours the CHP can compensate for the already dispatched light, reducing the cost of electricity grid tariff. In the same figure it is observed that the dispatch price for the CHP unit is cheaper than that of the boiler explaining why only the CHP is dispatched.

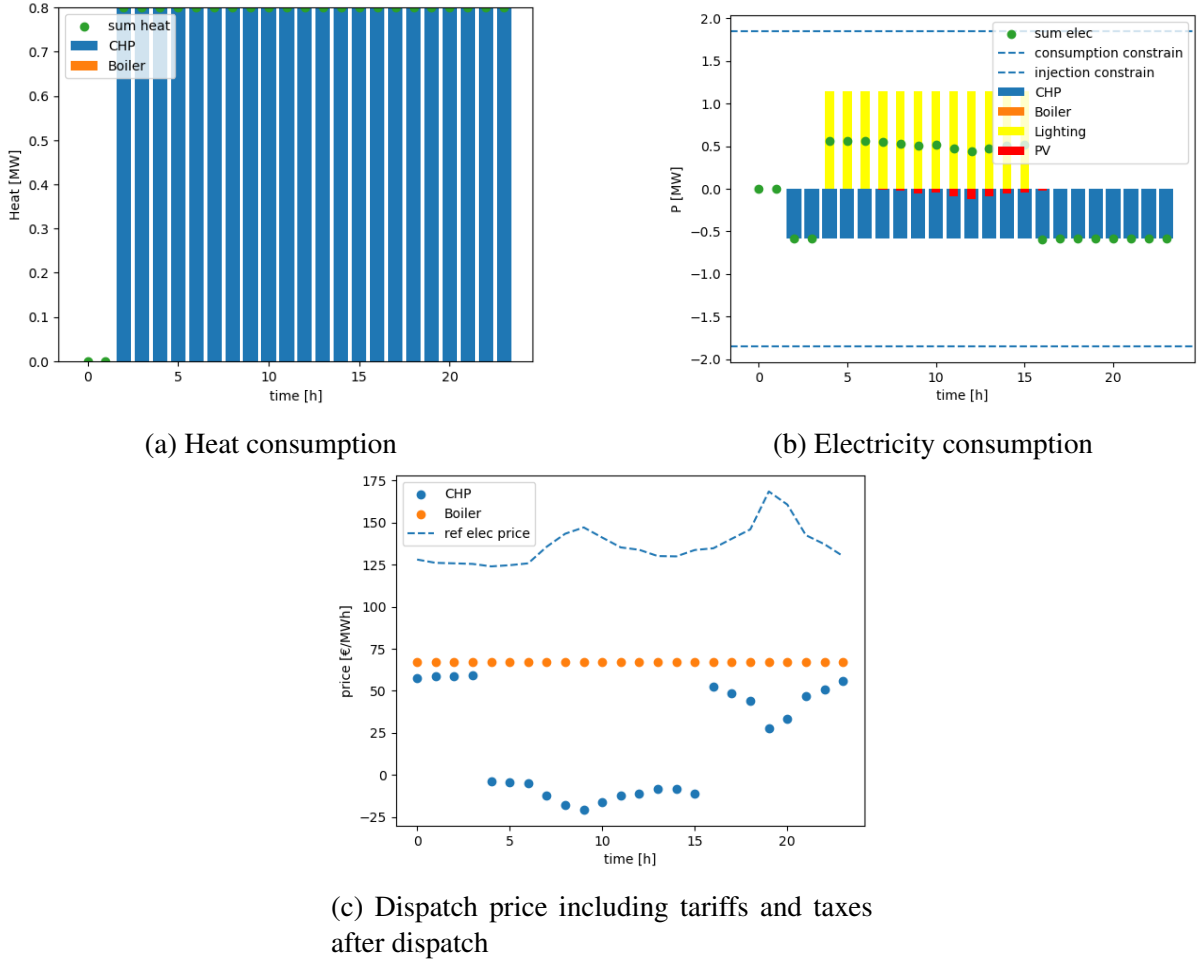
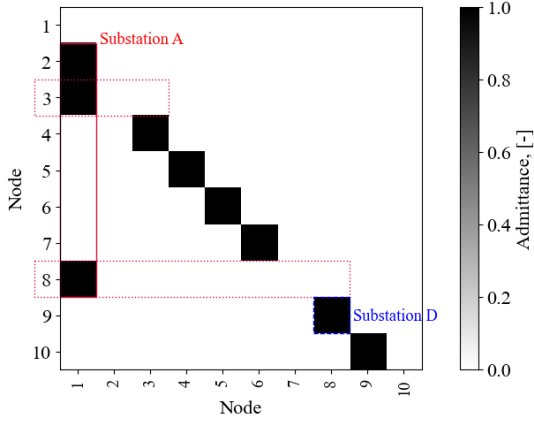


Figure 19: Dispatch profile of 2 ha chrysanth greenhouse in January with a Full CHP profile, consisting of heat and electricity consumption per asset, and dispatch price of the assets including all extra variable costs.

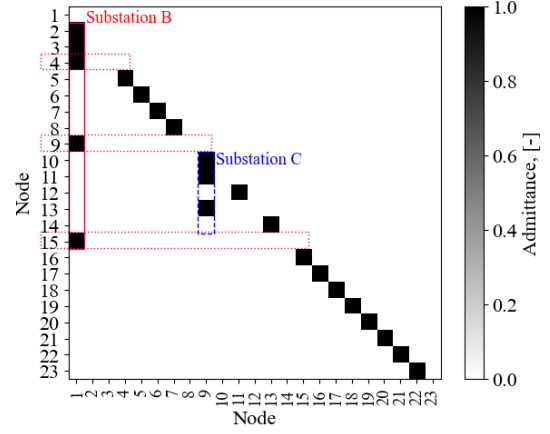
4.2. Network description

For the numerical network stress model a admittance and impedance matrix is needed that contains the necessary information of the network. The node connection is represented as a admittance matrix in figure20 for both branches. Both branches exist of a main distribution station, node 1 highlighted by the continuous red block, that is connected to other sub nodes or branches highlighted by the horizontal dotted red block. This first connection node of the subbranches will be used to name the subbranch in the rest of the report. In both branches a second distribution station is present highlighted in by the vertical dashed block in blue.

Figure 21 contains the same information but now every connection is color annotated to show its impedance value. Note that two values of impedance values occur: high values around 400Ω and low once around 100Ω . It is likely that the big difference in these values have an influence on voltage drop per subbranch. The high difference in resistance is an result of the difference in cable length as type of cable is the same for most of the network connection.

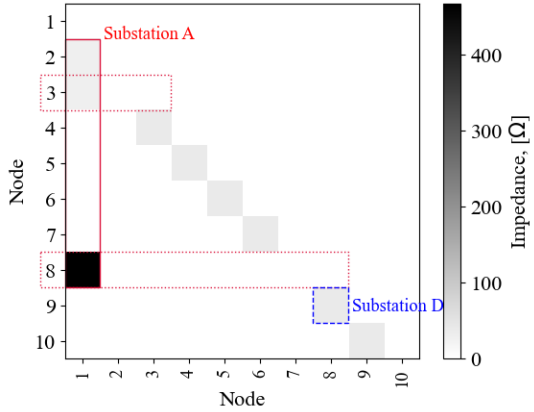


(a) Branch 1 with main distribution station A and its subnodes: 2 and 3, and sub branches 3 and 8

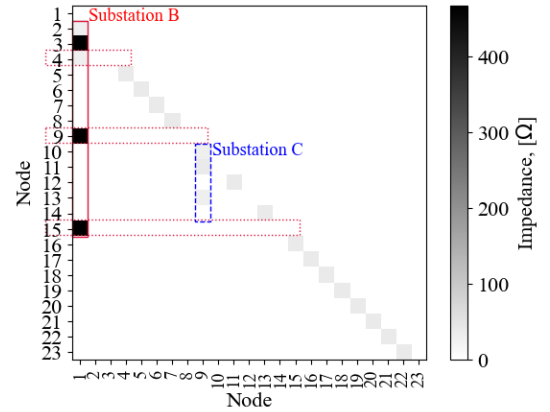


(b) Branch 2 with main distribution station B and subnodes 2 and 3, and subbranches 4, 9, and 15

Figure 20: Admittance matrix of the two branches of the case study network. The main distribution station and its sub branches are highlighted in red, by a continuous and dotted line respectively. Other substations are highlighted in blue by dashed line.



(a) Branch 1: with low line impedance for sub-branch 3 and a high for subbranch 8



(b) Branch 2: with low main line impedance for subbranch 2 and 4, and a high for sub-branch 3, 9 and 15, in the line connection with main distribution station

Figure 21: Impedance matrix of the two branches of the case study network. The main distribution station and its substations are highlighted in red, by a continuous and dotted line respectively. Other substations are highlighted in blue by dashed line.

4.3. Grid voltage of the case network

Voltage values at every node and time point need to be assessed to get insight into the stability of the network. Voltage values are taken to be stable if they are between 0.95 and 1.05 pu. of the nominal voltage of the network in this case 20 kV. The boundaries correspond to a high consumption and feed-in power, respectively. A boxplot can be made to get quick insight into a large quantity of data. In such a plot, only the magnitude of the values is taken into account,

and other information, such as the nodal location or time instances, is disregarded. This is thus a quick way to check whether voltage limits are surpassed and to get an idea of how often that happens. Figure 22 shows the voltage boxplots for the four scenarios and three months. Voltage values are given per nominal values in this case 20 kV. In each plot, boundary voltage values in the figures are highlighted as blue dotted horizontal lines across the graph at the 0.95 and 1.05 pu.

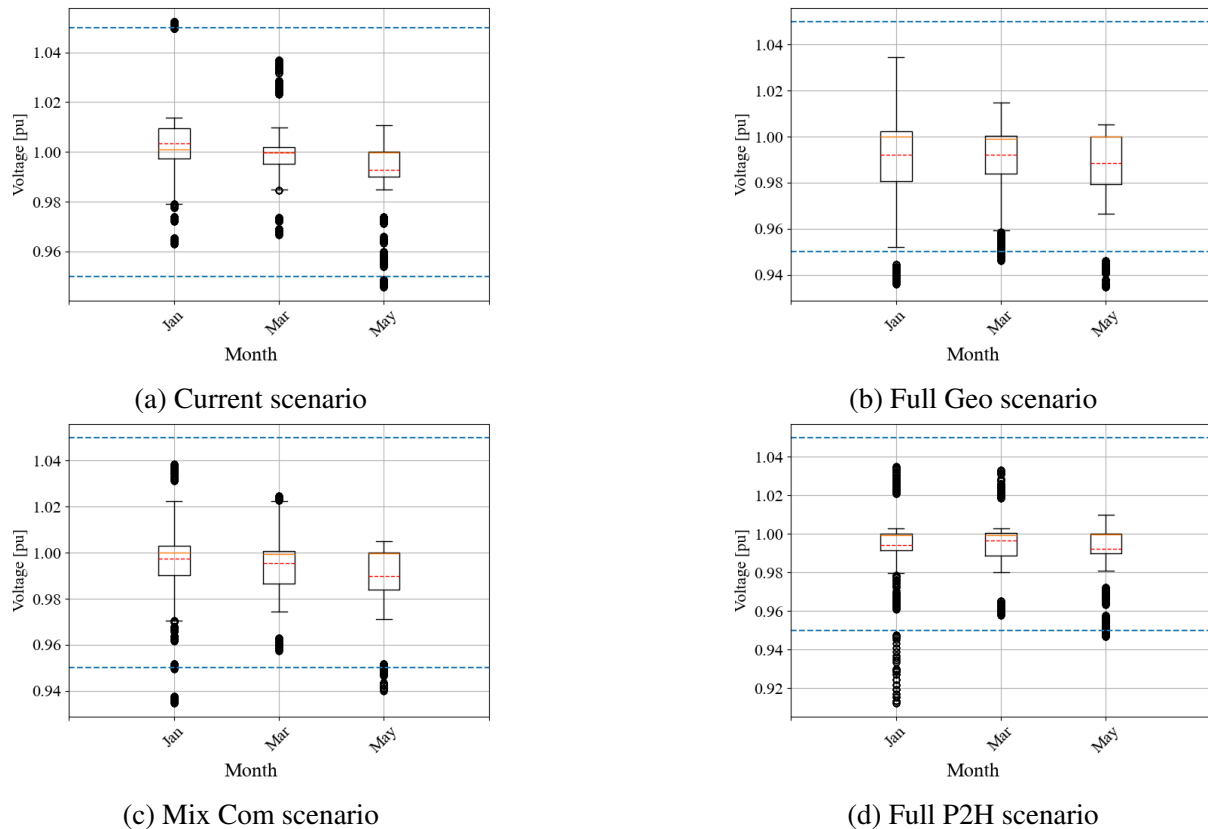


Figure 22: Voltage boxplots of the case network for all scenarios and months. Voltage values are in p.u. with a base voltage of 20 kV. The dotted line in the box of the boxplot resembles the average voltage value the dotted lines at 1.05 and 0.95 are voltage boundaries.

The boxplot consists of the 5 different features, mainly highlighting a boundary that showcases what percentage of datapoints fall inside of it. The first two features are the two horizontal lines in the box. These lines are the median and mean value of the dataset, highlighted by the continuous and dotted lines, respectively. The next feature is the edges of the box corresponding to the first and third quartiles of the dataset. The difference between the first and third quartiles is also called the inter-quartile range (IQR). The second-to-last feature is the whiskers of the boxplot. Their size is the last data point that falls inside 1.5IQR from the box edge. All data points outside the box and whiskers are displayed by the fliers. These can be associated with low-frequency occurring values.

For the current scenario (Subfig 22a) a decreasing voltage trend can be observed over the

months. The voltage value can be associated with power injection or consumption. A voltage value above nominal is associated with consumption, and a value below nominal is associated with nodal consumption. Naturally, in lines, a small voltage drop is expected because of losses in the line. The nodal power injection nature observed in January thus transitions to a more consumption nature if heat and light demand decreases in Mar and May. This is not case looking at the extreme values. January shows a lower minimum voltage then March and a higher than May.

In January single instances can be observed where voltage is above the upper limit. These data points are probably very time and position specific as they differ a lot from the the other observation, showcased by the large distance between the whisker and the fliers. March shows in contrast to January only values between the voltage limits. The third quartile has also moved down and more consumptions values are observed. In contrast to January and March, May shows voltage values below the lower limit. However in contrast to January more data points can be observed between the lower whisker and fliers. Another thing to notices in may is the median line that is near the is near the third quartile and near the nominal voltage. This means that for 25% of the data no voltage drop occurs which could mean that there is slight power injection in the lines but more likely that there is no power interaction at all, also giving a nominal voltage.

Other scenarios also surpass the voltage limit in January, however in contrast to the current scenario the lower limit is exceeded. Especially the Full P2H scenario shows low voltage values that are below 0.92 pu. Upper limits are not surpassed but injections points are observed. The Full Geo scenario is the only scenario that has data points surpassing the lower limit in March. The Mix Com and Full P2H scenario don't show any surpassing of the limit and are similar to the March value of the current scenario.

The characteristics described for May can also be observed for May in other scenarios. For example also May of the Full Geo scenario shows voltage values below the limit and median near the third quartile. There is however a difference in how far the limit is surpassed. Voltage values for Full Geo and Mix Com scenarios are even below 0.94 pu whereas for the current and Full P2H scenario voltage values are more nearer 0.95 pu.

Th last notable thing to observe that the minimum value of march is always the lowest for every scenario. For the Full P2H and Mix Com scenario January has the lowest value wheras the minimum voltage value of the the Full Geo scenario appear to be of the same hight.

4.4. Grid voltage of the case per network branch

Separating the data into two separate boxplots enables us to see which characteristics of the total boxplots can be assigned to which branch. Figure 23 displays the boxplots for each scenario and branch. The first things to observe are the small boxes for the first branch in comparison with the second branch. This has probably to do with the number of greenhouse in branch 1 compared to the amount of greenhouses in branch 2. As the number of greenhouses in branch 1 is so much lower, little voltage impact is observed because of the lower power consumption and injection. The contributions of these data points are mainly in narrowing the IQR of the boxplots of the overall network. Lower IQR values for the Full P2H scenario and the larger IQR values for the month of May cannot be observed in boxplot for branch 2. However, the

most important observations in the boxplots are the surpassing of the line limits and these can only be observed in branch 2 and therefore, only analysis on branch 2 is continued.

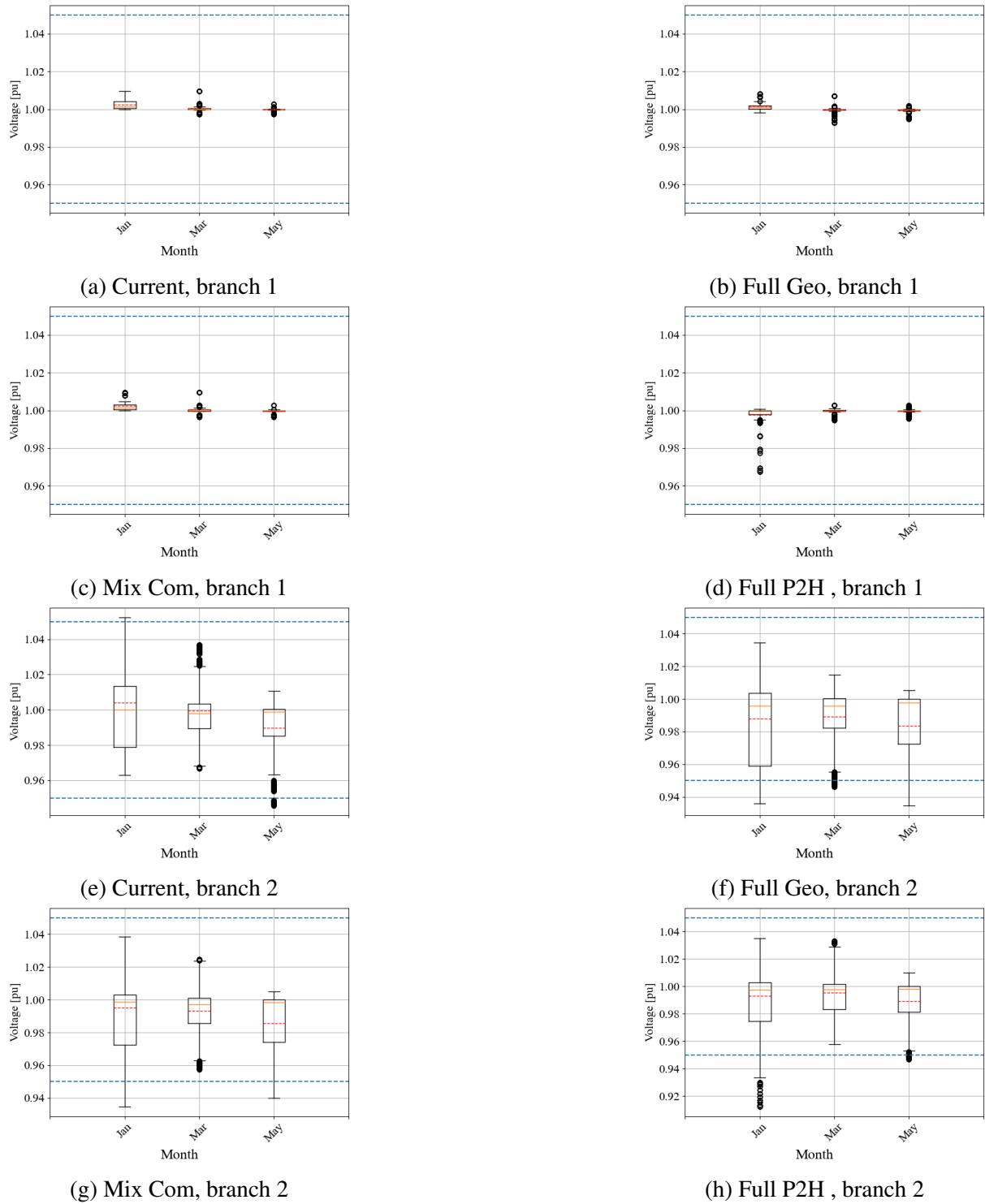


Figure 23: Voltage boxplots of the case network for all scenarios and months. Voltage values are in p.u. with a base voltage of 20kV. The dotted line in the box of the boxplot resembles the average voltage value; the dotted lines at 1.05 and 0.95 are voltage boundaries.

All data from branch 2 is plotted in a heatmap to get more insights into the time instants and specific location of the voltage values. The heatmap is plotted in figure 24 and displays the various nodes in the y-direction and time instances in the x-direction of the heatmap. The black horizontal line separates the nodes per subbranch. Nodes between two horizontal lines belong to the same sub-branch and are labeled on the right y-axis of the plot corresponding to the first node of the sub-branch. The values of the heat map are discretized into 5 distinct values: values exceeding the limits, $V < 0.95$ pu and $V > 1.05$ pu, values near the limit, $0.95 < V < 0.975$ pu and $1.25 < V < 1.05$ pu, and values where V is around the nominal value, $0.975 < V < 1.25$. There are two characteristics that can be observed for every graph.

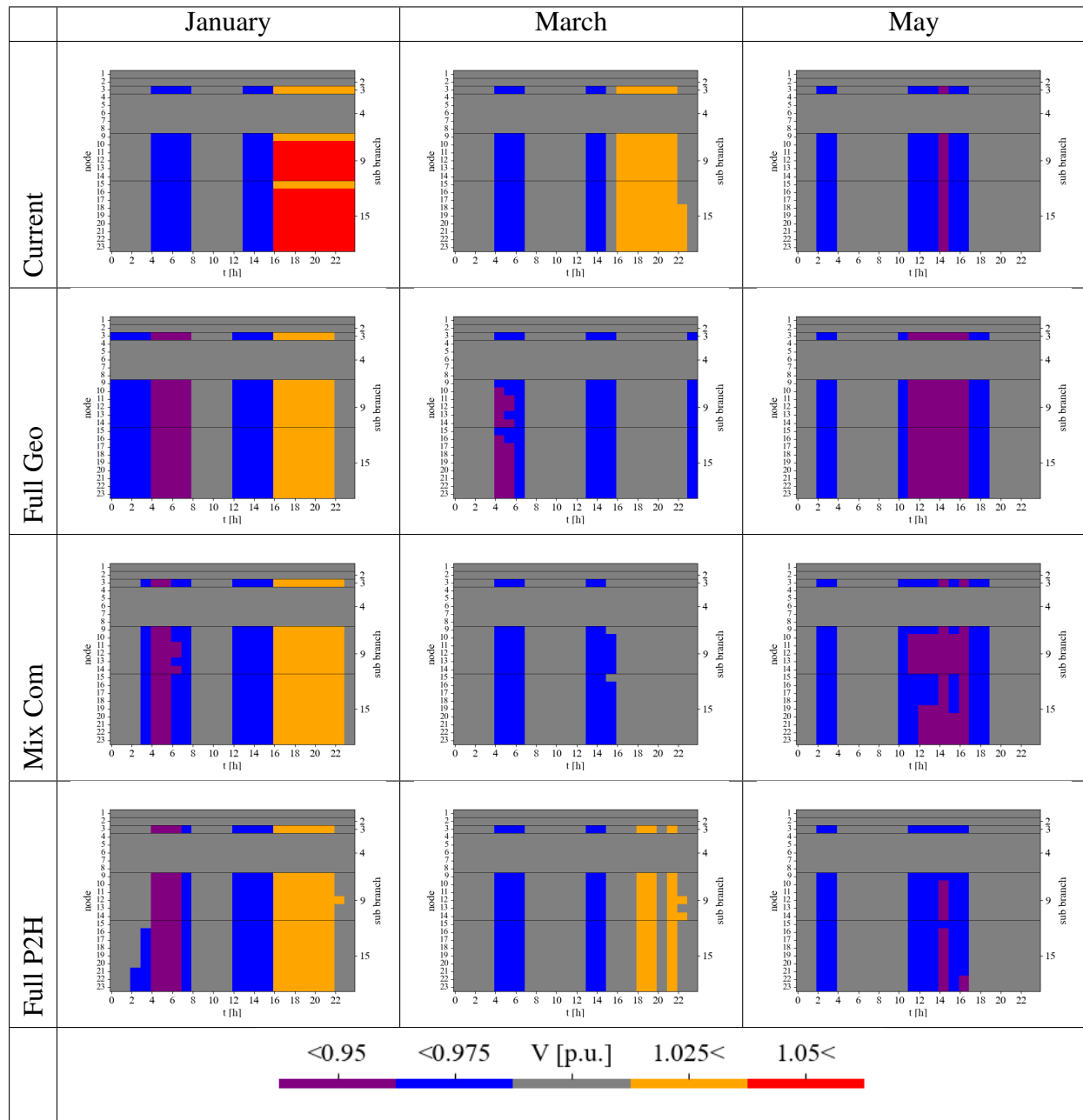


Figure 24: Voltage heatmaps for node and time points of branch 2 for every scenario and month. Voltage values are categorized in 5 boxes with boundaries (0.95, 0.975, 1.025, 1.05) pu.

The first thing is that within each months voltage drops and increase are observed in the same time frames for each scenario. For instance for January all voltage drops occur between mainly between 4 and 8 , and 12 and 16; voltage increase are only observed from 16:00 to midnight. Also if in over-voltage occurs in January this is between 4 and 8. Similar time frames can be observed in the other scenarios but with slightly different hours. The time windows occur because of the day-ahead epex prices that are high or low within these specific time frames. The high production hours occur after 16:00 when prices are high. Following the same reasoning voltage peaks should be expected between 8 and 12 however, a voltage increase to nominal is not observed. The voltage does however increase compared to the neighboring time frames hinting at lighting dispatch between 8 and 12 o'clock compensating for the CHP production. The second characteristic to observe is that there are only voltage activities within 3 sub-branches: 3, 9 and 15. Subbranches 2 and 4 don't showcase any voltage problems. This is due to the fact that these first 3 subbranches have a high line impedance connecting them with the substation which is not the case for the latter 2, as can be seen earlier in figure 21. Furthermore the first node of separate subbranches, for example node: 3, 9 and 15; displays the same voltage value for every time instances. This affect can be assigned to the way in which the voltage and current values in network are modeled and will be discussed further in the discussion section.

The next step is to verify or extend the observations from the boxplots with the heatmap. In the box plots for the current scenarios multiple voltage exceedings were observed for the months January and May. January displays a consistence over voltage after 16 o'clock. The single occurring fliers the voltage box-plots are multiple fliers occurring at a similar voltage value. The under voltage in may is a single instant at 14:00. The overvoltage in the Full Geo scenario is in a broader time frame then the other scenarios, however from the boxplot we know that voltage exceeding between 4 and 7 are probably much higher for the Full P2H scenario. Consumption is thus more concentrated for the Full P2H scenario then for the Full Geo one.

March shows the most stable values compared to the other months of the same scenario which is in agreement with the observations in the voltage box plot. Only the Mix Com scenario shows a small time window with over voltage. That specific heatmap also shows under voltage in the last hour of the day. That hour corresponds to the dropping tail of the electricity price. Where voltage values for May appear similar in the boxplot they are not in the heatmap. The Full Geo and Mix Com scenario exceed the lower voltage limit for way more time points whereas for the current and Full P2H scenarios this happens only for 1 or 2 hours respectively. Another interesting feature is the the voltage rise at 15 observable in the Mix Com scenario. This cannot be explained with the heat plot but might be observable within a electrical current plot of the branch.

4.5. Electrical current flow values at branch coupling

Now that the observations for voltage are made, they can be compared with values for the electrical current by analyzing the current running at the Tennet coupling points. First, the electrical

currents for the current scenario are analyzed, as this scenario has no P2H and therefore all exchanges can be assigned to the dispatch of CHP and Lighting. There is also a small penetration of PV, but its capacity is small in comparison with the lighting and CHP capacity; thus, its effect will be very limited. Line current values for the current scenario are displayed in Figure 25. Additionally, power input per time instance for each individual asset is plotted in a bar plot and shown in Figure 27.

For January, two peaks can be observed from 4 to 8 and from 13 to 16. Also, the first 4 hours can be associated with high values as they are of the same values as the second peaks.

There are also two clear moments in which current values are negative and thus injection occurs. These are from 8 to 12 and from 16 to midnight. These injection peaks correspond with the electricity prices also mentioned while discussing the heat plot. The first negative peak was not visible within that heat-plot probably because the associated injection is too low to cause a large enough voltage drop 24. The second negative peak was clearly visible in the heatplot and appears here as a flat line. This fact, together with the sudden drop at $t = 16$ h, suggests the lighting stops from that time point and CHP dispatches at maximum capacity, as these are also the most expensive hours to sell the electricity.

For March, the two positive peaks can still be observed, although the latter one has increased in size. The biggest difference between January and March can be observed in the negative peaks. The first negative peak has become slightly positive, and the second peak has become less flat and has slightly increased. The last hour of the day has even become positive.

In May, the valleys have shrunk so much that only two peaks are left, of which the first one has shrunk in size and has shifted to appear from 2 to 4. The second peak has further increased in size and spreads now from 9 to 17.

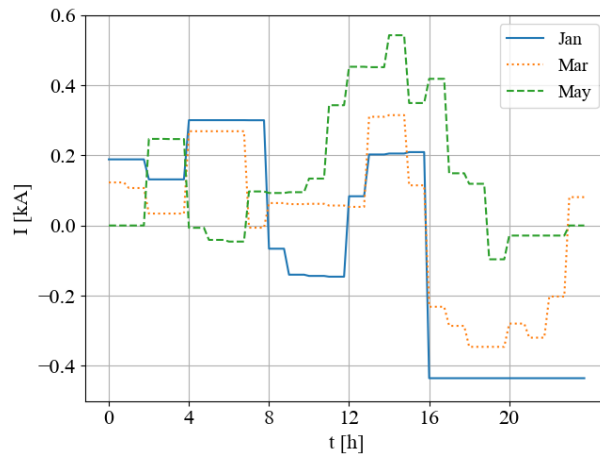
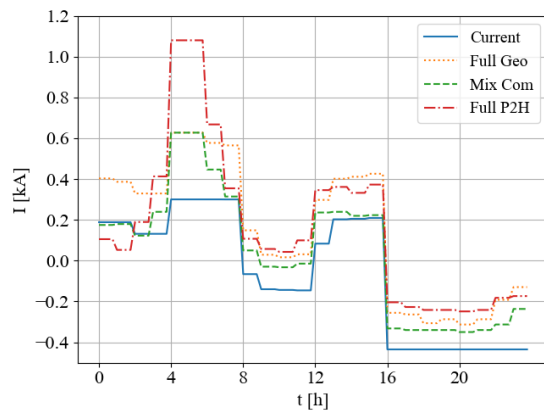


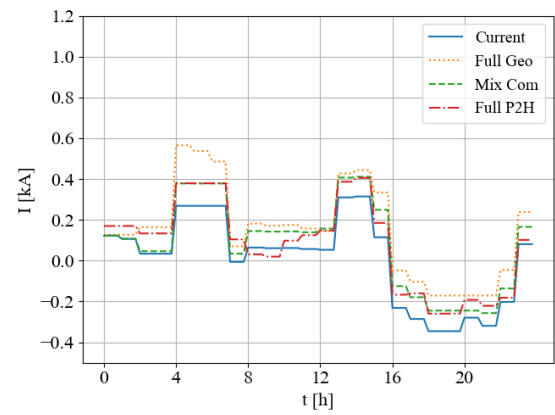
Figure 25: Electrical current plots of the current situation for the 3 sample days.

In Figure 26, the line current for each at the coupling with Tennet is shown for the months separately. In such a way the scenario can be easily compared. The most observable difference between the different graphs within the January plot (Figure 27) is the peak between 4 and 8. The peak is much higher for the future scenario compared to the current one. The bar dispatch plot (Figure 27) shows that the reason of this increase is different for the Full P2H scenario than for gas and Full Geo. For the Full P2H scenario the peak is associated with the dispatch of E-boilers. Within the full electric profile e-boilers account for the peak demand and are an

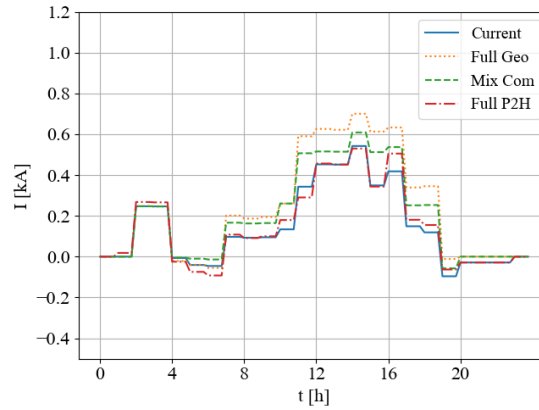
addition the the capacity of the heat pump to meet the heat demand. E-boilers can consume large quantities at a single time instant creating a large peak at the lowest prices. For the Mix Com and Full Geo scenario the peak is caused by both a dispatch in heat-pumps as well as an decrease in electricity production by the CHP units. This decrease in CHP dispatch is not observed for the current scenario probably because the role of the CHP units in the current scenario is to account for the base load whereas it in the future scenario it is more often used as peak generation. This effect is even clearer in the last 8 hours of the day. For the current scenario this is flat line where the CHP unit runs at full capacity whereas for other scenarios already drops in CHP dispatch can be observed because heat demand is already met by the primary source of heat. For both March and May similar plots can be observed for a each scenario. The role of Eboiler as peak generation shows a clear drop in current at the first peak in March and its shape resembles better that of the current scenario. For both these months the Full Geo scenario shows the highest values mainly because of lower dispatch of CHP.



(a) Current plot of January.



(b) Current plot of March.



(c) Current plot of May.

Figure 26: Current plot for the 3 months and scenarios measured at the coupling with Tennet. Plot displays current values in kA versus time in h.

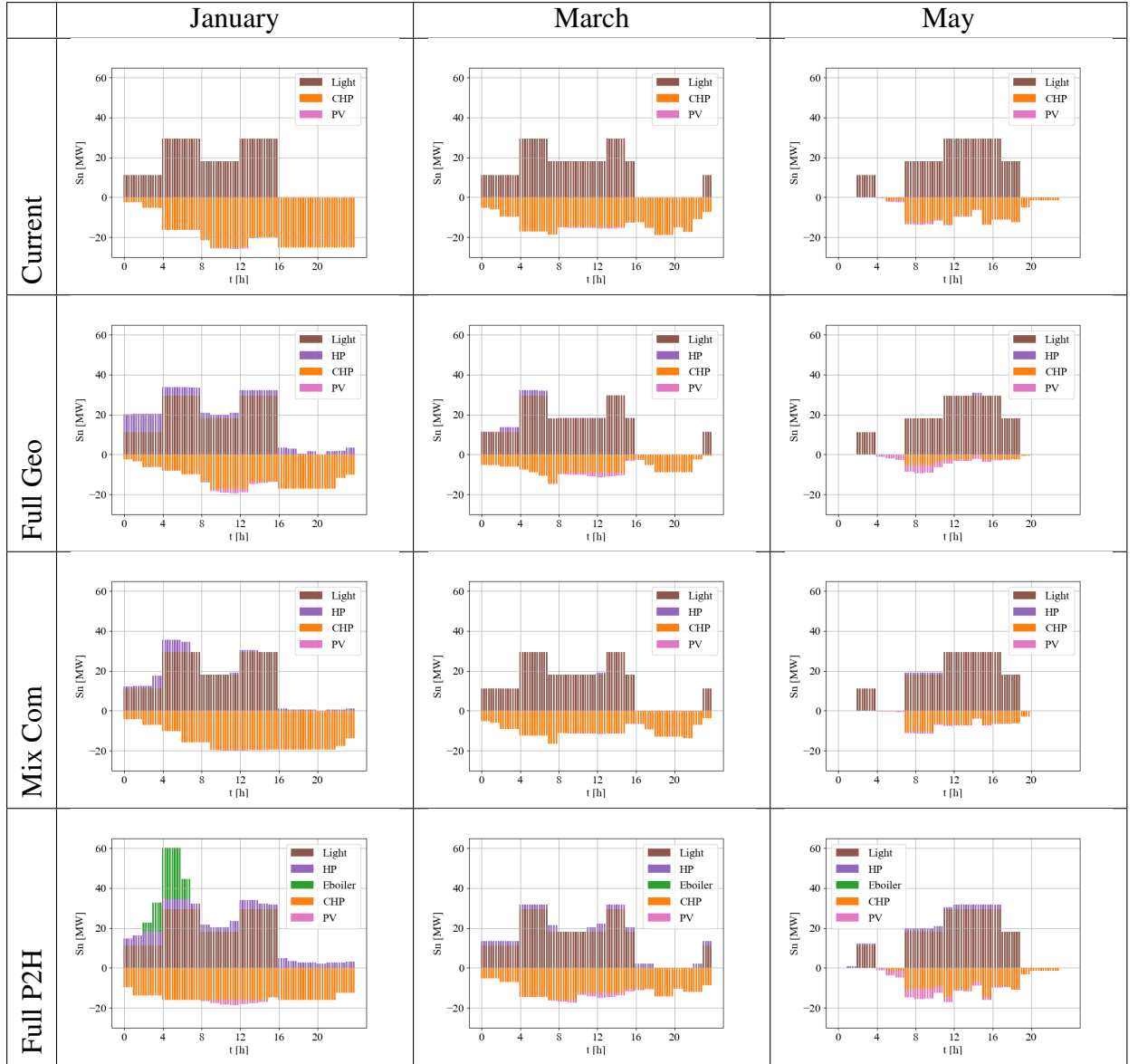


Figure 27: Asset electrical power consumption matrix for 3 sample days and 4 scenarios. Power values are give in MW.

4.6. Conclusion of the discussion

Combining the results that are obtained from the box and power plots shows us that the dispatch of CHP units and lighting is the dominant factor for network stress. The stress is mainly caused by a mismatch of dispatch hours by the CHP unit during the lighting hours. Extra penetration of p2h and geothermal for this model causes this mismatch to be stronger, as fewer CHP hours are available. In reality, a better agreement between the two assets is expected. Greenhouse owners are heavily penalized for the maximum peak they set each month. Most of the electricity costs are paid for this capacity fee rather than the network tariff price they pay per quantity. The incentive for low consumption exchange with the grid is thus higher. This is not the case for feed-in exchange with the grid. Greenhouses don't pay any network tariff for these. A better agreement will thus result in less network stress in windows 2 and 5 that can compensate for

each other. Another reason why agreement in reality happen is that during lighting hours often extra doses of CO₂ are required something that is also produced during CHP dispatch.

Problems specifically by P2H are only observed if P2H is the only available option for heat, and if the heat demand is high. In this scenario, the e-boiler will dispatch at the best electricity prices, causing network problems such as the high peak for the Full P2H scenario in January. However, two assumptions within the model enhance this problem that are not necessarily true. The first assumption is that day-ahead price patterns stay the same throughout the scenarios and the years, whereas in fact they will shift under the transition of Full P2H . The low prices observed in these time windows will probably be higher than stated. The other is the earlier-mentioned capacity penalty. This, in combination with the quite extensive available capacity for the full electric profile, will pose a difficulty for an e-boiler to dispatch solely at such a single instant.

The changing commodity prices can also have a negative effect on the stress of the electricity grid in case of P2H penetration. Currently, P2H can in dispatch price hardly compete with the dispatch of a CHP unit or even a boiler. Figure 28 shows such a price comparison between a HP Boiler profile in March. Especially the rising energy taxes by the government on CO₂ and resource will drive up the gas price changing this picture. Another good thing to notice is that network tariff for gas are fixed per year whereas they are variable for electricity. So even though in variable cost a heat pump cannot compete with the boiler in reality taking constant costs into account they might.

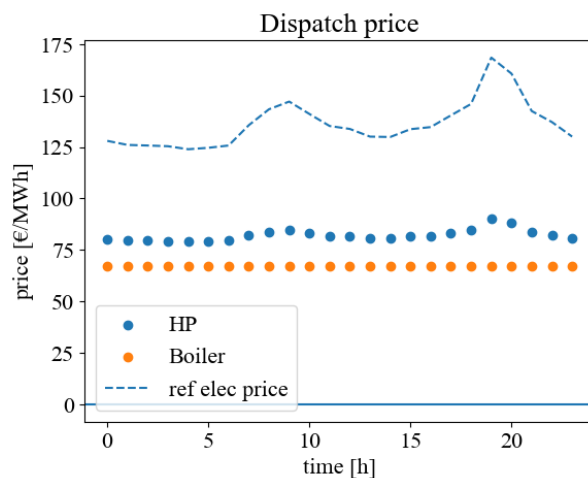


Figure 28: Dispatch price of a HP Boiler profile in March. Extra variable cost associated with the use of commodity are included in the dispatch price

The last thing to discuss are the similar voltage values that are observed nodes that are radial connected to the same node. As mentioned earlier this observation can be assigned to modeling approach used to estimated the parameters of the network. The network model is a numerical method in which nodal power injection is used for a first estimation of the current after which current and voltage are iterated until they have converged in which error is smaller than a certain value. This process is iterated two fold. First current is converged after which the found current is used as input value for to estimate the voltage, the found voltage values are

used to calculate the current values. In the last step of this process after both have converged the current is used to calculate the voltage values. However current values between the two nodes are used to calculate the voltage values of the node later in the branch. This way the same current is used for radial voltage drops, thus with an equal impedance a equal voltage drop is observed.

Improving this model is out of the scope of this research however it has some extensive effects on the observed heat-plots earlier. Especially the voltage drop in node 2 of branch 2 are incorrect. Current levels of this single small greenhouse are a lot lower than that of the other subbranches, but voltage drops are observed the same. It is therefore for debate to what extent the voltage values of radial nodes of the heatplot can be used. The model method does work for single lines so voltage values further in the line are more trustworthy.

5. Conclusion

This research has shown the effect of 3 different energy transition scenarios in greenhouses on the horticultural MV electricity grid, by modeling the greenhouse dispatch through its interaction with the day-ahead electricity market. First, it was shown that asset dispatch was also influenced by associated markets, lighting dispatch that depends on the type of crop, and CHP dispatch that strategically bids for the Spot and Ancillary service market. After this, 3 future scenarios were defined based on research done by Netbeheer Nederland: Full Geothermal, Mixed Commodities, and Full P2H. Asset profiles were created that are distributed over the future scenarios. All scenarios exceeded the voltage limits. However, the reference scenario showed feed-in voltage exceedings, whereas the other scenario only showed consumption voltage exceedings. The Full Geothermal scenario showed the worst voltage and current values as it surpassed the voltage limit for each of the three simulated days. The Full P2H showed that full electrification of the heat results mainly in high grid stress in colder months for a short period of time. The Mixed commodity scenario showed the best values of the three future scenarios, as there were no major voltage exceedings. The main takeaway is that the actual cause of the undervoltage is the drop in CHP dispatch that is normally compensating for the consumption of lighting. Transition to other heat sources will cause network stress as they phase out this dispatch, rather than problems that are caused by the technologies themselves. Only P2H shows new problems for large heat demand.

6. Recommendations

6.1. Future scenarios

One of the observations in this research was that, in most cases, P2H could not compete in price with the CHP units. However, this was under the circumstances that gas and electricity prices would stay the same. In reality, the change in these commodity prices would be a driver for renewable assets to diffuse in the existing market. The expected market price for a specific scenario should therefore be included to give a more realistic approach in dispatch. This can be done by researching under which price two assets are compatible and varying prices in multiple ranges above this compatible price.

6.2. Including extra electricity markets

Intraday markets should be included to have a complete overview of the exchange between a greenhouse and the medium voltage grid based on their heat demand. To include these markets, an extra modelling step is needed in which the intraday is simulated. Greenhouse owners can then decide, based on their available buffer heat capacity and heat demand left, if they react to intraday prices. For this, a multiday simulation is needed, which can only be done if there is also a day-dependent heat demand available.

These heat demands can be simulated using thermodynamic models. These models are more complex than regular buildings as evaporation dynamics need to be taken into account for realistic values.

6.3. Including electricity capacity tariff

Electricity tariffs in the Netherlands are more capacity-based than quantity-based. This means that exceeding the maximum capacity set in a month heavily influences its cost over the months. This is thus an important decision parameter to control the dispatch of the assets and should, in some form, be included. The maximum set by a greenhouse often occurs while interacting with intraday markets, as earnings are larger on these markets. Whilst including intraday market, this tariff cannot be neglected.

7. Appendix

7.1. Asset sizing

Tables 13 and 14 show the capacity values for the different asset profiles under the various categories. Occurring 0 values for CHP unit capacity means that the specific asset will not occur in the given category.

Table 13: Asset sizing under the different asset profiles and categories for the asset profiles: Full CHP, Geo CHP, Geo Boiler, and Full Electric.

Category	Full CHP		Geo CHP		Geo Boiler		Geo HP		Full E	
	CHP [MW]	Boiler [MW]	Geo [MW]	CHP [MW]	Geo [MW]	Boiler [MW]	Geo [MW]	HP [MW]	HP [MW]	E-boiler [MW]
Paprika 2 ha	0	6	0.4	0	0.4	6	0.4	0.135	0.135	3
Paprika 5 ha	2	15	1	2	1	15	1	0.445	0.445	7
Paprika 10 ha	4	30	2	4	2	30	2	0.9	0.9	15
Tomato 2 ha	1	6	0.4	1	0.4	6	0.4	0.135	0.135	3
Tomato 5 ha	2.4	15	1	2.4	1	15	1	0.474	0.474	7
Tomato 10 ha	5	30	2	5	2	30	2	0.9	0.9	15
Anthurium 2 ha	0.6	6	0.4	0.6	0.4	6	0.4	0.135	0.135	3
Anthurium 5 ha	1.5	15	1	1.5	1	15	1	0.445	0.445	7
Anthurium 10 ha	5	30	2	5	2	30	2	0.9	0.9	15
Chrysant 2 ha	0.8	6	0.4	0.8	0.4	6	0.4	0.135	0.135	3
Chrysant 5 ha	2.4	15	1	2.4	1	15	1	0.474	0.474	7
Chrysant 10 ha	5.5	30	2	5.5	2	30	2	0.9	0.9	15

Table 14: Asset sizing under the different asset profiles and categories for the asset profiles: HP CHP, HP Boiler, Full Boiler, and Combi.

Category	HP CHP		HP Boiler		Full Boiler	Combi		
	HP [MW]	CHP [MW]	HP [MW]	E-boiler [MW]	Boiler [MW]	Geo [MW]	CHP [MW]	HP [MW]
Paprika 2 ha	0.135	0	0.135	6	6	0.4	0	0.135
Paprika 5 ha	0.445	2	0.445	15	15	1	2	0.445
Paprika 10 ha	0.9	4	0.9	30	30	2	4	0.9
Tomato 2 ha	0.135	1	0.135	6	6	0.4	1	0.135
Tomato 5 ha	0.474	2.4	0.474	15	15	1	2.4	0.474
Tomato 10 ha	0.9	5	0.9	30	30	2	5	0.9
Anthurium 2 ha	0.135	0.6	0.135	6	6	0.4	0.6	0.135
Anthurium 5 ha	0.445	1.5	0.445	15	15	1	1.5	0.445
Anthurium 10 ha	0.9	5	0.9	30	30	2	5	0.9
Chrysant 2 ha	0.135	0.8	0.135	6	6	0.4	0.8	0.135
Chrysant 5 ha	0.474	2.4	0.474	15	15	1	2.4	0.474
Chrysant 10 ha	0.9	5.5	0.9	30	30	2	5.5	0.9

Table 15 shows lighting and PV capacities for every category. PV capacity values are obtained by averaging the PV capacities of greenhouse examples in the area for the given areal size. Lighting capacity was obtained through the conducted interviews.

Table 15: PV and lighting capacities for the different categories.

Category	PV [MW]	Lighting [MW]
Paprika 2 ha	0.6	[-]
Paprika 5 ha	0.8	[-]
Paprika 10 ha	1	[-]
Tomato 2 ha	0.6	1.32
Tomato 5 ha	0.8	3.3
Tomato 10 ha	1	6.6
Anthurium 2 ha	0.6	[-]
Anthurium 5 ha	0.8	[-]
Anthurium 10 ha	1	[-]
Chrysant 2 ha	0.6	1.14
Chrysant 5 ha	0.8	2.85
Chrysant 10 ha	1	5.70

7.2. Network parameters

For the case scenario, nodes are connected by 20kV 3x1x300 AL cables with an impedance of $0.1 + j0.11 \frac{\Omega}{m}$. Cable lengths are summarized in Tables 16 for the first and second branch.

Table 16: Cable lengths between nodes of the 2 branches. Lengths are given in meters.

(a) Branch 1

From node	To node	Length [m]
1	8	3148,58
6	7	265,78
9	10	265,78
8	9	265,78
3	4	265,78
5	6	265,78
1	3	205
4	5	265,78
1	2	205

(b) Branch 2

From node	To node	Length [m]
1	2	205
1	3	3148,58
1	4	205
1	9	3148,58
1	15	3148,58
4	5	265,78
5	6	265,78
6	7	265,78
7	8	265,78
9	10	205
9	11	265,78
9	13	205
11	12	265,78
13	14	265,78
15	16	265,78
16	17	265,78
17	18	265,78
18	19	265,78
19	20	265,78
20	21	265,78
21	22	265,78
22	23	265,78

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