Farming cooperation

A pathway to self-sufficiency in terms of energy use

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SUMMARY

Worldwide, amongst others, there are two major pressing issues regarding sustainability [1]. On the one hand, there is the global wide-spread use of finite fossil energy, and on the other hand there is the emissions of greenhouse gases (GHG's) such as CO_2 and CH_4. Within the aforementioned context, agriculture is a substantial consumer of fossil energy, and therefore contributes to both the depletion of fossil resources as well as the emission of GHG [1]. The aforementioned will have a substantial negative impact on specific local ecosystems, as well as the climate as a whole [2]. One of the technologies that is suggested as helpful to provide more renewable energy in the farming sector, is Anaerobic Digestion (AD). AD is already a proven technology [3], and the technology can harvest energy from several biomass sources, to produce biogas. A previous investigation by Pierie et. al [2] suggests that, in a theoretical farming cooperation (consisting of 12 farms) case, there is more than sufficient biogas to fulfil the cooperation's energy demand, but this study was conducted on a yearly basis. To the authors knowledge, the investigation done by Pierie et. al is lacking two important characteristics. First, it does not include other renewable sources to be used within the cooperative farming setting, as well as storage options [2]. Second, it lacks a model that can calculate demand and production on an hourly basis. The current model can only express whether there is enough production potential for a year, but not if this supply can actually meet demand on an hourly basis. To investigate whether there are more possibilities for this cooperation, a new hourly model will be constructed. This will be done using a new modelling methodology called Power Nodes. This investigation mainly consists of two parts: the investigation regarding the potential cooperation, but also whether Power Nodes is a suitable modelling methodology. Based on this, two research questions were formed:

Research question 1: To what extent can a cooperation of farms become self-sufficient in terms of energy use, and provide balanced energy to the national grid by using biogas production, together with other kinds of renewable energy technologies?

Research Question 2: Is the Power Nodes method a viable method to model a dynamic energy system that can calculate and display supply and demand on an hourly basis?

To find answers to both research questions, several methods and tools are used: a case study, literature research, a questionnaire, the aforementioned Power Nodes methodology, Excel, several validation technologies and a SWOT analysis. Three scenarios were constructed for the designed model, to answer the first research question. The first scenario helps to determine the current energy demand patterns. The second scenario helps to determine whether the AD unit from the previous investigation can suffice on an hourly basis as well. In the final scenario, it is investigated whether it is possible to become an energy provider, instead of just producing the own demand.

From the results of this investigation it was concluded that on an hourly basis, there was more than sufficient biogas available to fulfil the cooperation's own energy demand. Additionally, the results from scenario 3 suggest that the use of extra energy producing technologies can mean that the farming cooperation can become an energy provider. This requires the use of several balancing technologies, as well as energy carrier conversion technologies such as an electrolysis system. However, some practical implications arose: a H_2 storage system of 3000 26L storage tanks was required. Also, the incoming electricity stream going to the electrolysis unit was very unstable, and therefore difficult to utilize. The analysis of the Power Nodes methodology suggests a lot of possibilities and strong points for this methodology, such as user friendliness and strong visualization. However, some weaknesses were discovered as well. The use of Excel to model such a Power Nodes model is not the best option, due to limitations in calculation possibilities in Excel. Also, it was quite difficult to keep a good overview of information streams and connections between different nodes.

SAMENVATTING

Vandaag de dag zijn er, onder andere, twee grote problemen als het gaat om duurzaamheid. Ten eerste, het wereldwijde gebruik van fossiele brandstoffen, en daarnaast de bijbehorende emissies van broeikasgassen als CO_2 en CH_4. Binnen de hiervoor genoemde context is de landbouw een grootgebruiker van fossiele brandstoffen, en draagt daarom bij aan de broeikasgasemissies en de afnemende fossiele brandstofreserves. Bovengenoemde heeft een negatieve invloed op zowel lokale ecosystemen als het wereldwijde klimaat. Een van de technologieën die genoemd wordt om meer hernieuwbare energie te gebruiken in de agricultuur is de anaerobe vergisting van biomassa. Deze techniek wordt al veel toegepast, en zet verschillende soorten biomassa om in biogas. Een eerder onderzoek door Pierie et. al [2] laat zien dat door een theoretische coöperatie van boerderijen voldoende biogas geproduceerd kan worden voor de eigen energievoorziening. Dit onderzoek is echter op jaarbasis gedaan, en kan dus geen uitspraken doen of dit ook op uurlijkse basis zou kunnen werken. Daarnaast worden in dit onderzoek geen andere hernieuwbare energiebronnen gebruikt. Het huidige gebruikte model kan alleen laten zien wat er op jaarlijkse basis beschikbaar is en nodig is. Om te onderzoeken of er meer mogelijkheden zijn voor zo'n theoretische coöperatie, wordt er een nieuw model gebouwd wat op uurlijkse basis werkt. Het bouwen van dit nieuwe model wordt gedaan met een nieuwe modelleringsstructuur genaamd Power Nodes. Het onderzoek kan ruwweg in twee delen verdeeld worden: het onderzoek aangaande de coöperatie, maar daarnaast wordt ook onderzocht of Power Nodes een geschikte methode is om dit soort uurlijkse modellen te dimensioneren. Op basis van voorgaande zijn de twee volgende onderzoeksvragen geformuleerd:

Onderzoeksvraag 1: Tot in hoeverre kan een coöperatie van boerderijen zelfvoorzienend worden op energiegebied, en eventueel een stabiele energieleverancier worden aan het nationale energienet, door biogasproductie te combineren met andere hernieuwbare technologieën?

Onderzoeksvraag 2: Is Power Nodes een geschikte methode om een dynamisch energiesysteem te modelleren dat, op uurlijkse basis, vraag en aanbod kan berekenen en visualiseren?

Om beide onderzoeksvragen te beantwoorden, worden verschillende methodieken en tools gebruikt: een casus, literatuuronderzoek, een vragenlijst, de eerdergenoemde Power Nodes methode, Excel, verschillende validatietechnieken en een SWOT-analyse. Drie scenario's zijn gebruikt in het model om de eerste onderzoeksvraag te beantwoorden. Het eerste scenario hielp om het huidige energieverbruik op uurlijkse basis in kaart te brengen. Het tweede scenario onderzocht de eerdergenoemde biovergister en de mogelijkheden hiervan op uurlijkse basis. In het laatste scenario werd onderzocht of het mogelijk was om een energieleverancier te worden, in plaats van slechts aan de eigen energievraag te voldoen.

Uit de resultaten van het onderzoek bleek dat, op uurlijkse basis, meer dan genoeg biogas beschikbaar was om aan de eigen energievraag te voldoen. Daarnaast bleek uit de resultaten van scenario 3 dat het gebruik van andere hernieuwbare energiebronnen ertoe kan leiden dat de coöperatie een energieleverancier kan worden. Om te zorgen dat dit op een gebalanceerde manier gebeurt, zijn er aanvullende balanceertechnieken nodig en daarnaast technieken als elektrolyse. Helaas zijn er nog wel problemen aanwezig: een H_2 opslag van 3000 26L tanks bleek nodig. Daarnaast bleek dat de inkomende elektriciteitsstroom nog te wisselvallig was voor de elektrolyse om goed te gebruiken. Uit de analyse van de Power Nodes methode bleek dat er genoeg mogelijkheden en sterke punten zijn, zoals gebruiksvriendelijkheid en visualisatiemogelijkheden. Helaas zijn er ook minder sterke punten en bedreigingen, zoals het houden van overzicht in informatiestromen en verbindingen tussen verschillende onderdelen van het model. Daarnaast lijkt het erop dat Excel te weinig rekenmogelijkheden heeft om een groot Power Nodes model door te rekenen en te visualiseren.

1. INTRODUCTION

Worldwide, amongst others, there are two major pressing issues regarding sustainability [1]. On the one hand, there is the global wide-spread use of finite fossil energy. Fossil energy is used to produce most of the electricity, and fuels like diesel and petrol are still the prime fuels in transportation. On the other hand, the use of fossil energy is a major source of atmospheric greenhouse gas emissions, (GHG) such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Within the aforementioned context, agriculture is a substantial consumer of fossil energy, and therefore contributes to both the depletion of fossil resources as well as the emission of GHG [1]. In 2007, agricultural emissions of CH_4 and N_2O contributed to 53 and 41% of the national emissions of these GHG's. Besides, agriculture has a contribution of 7,5% to the national total emission of CO_2 [4]. Currently, the main focus in agriculture lies on the reduction of costs per unit, which in turn results in more intense land use, increased emissions of substances (global warming potential) and more specific production. However, the aforementioned will have a substantial negative impact on specific local ecosystems, as well as the climate as a whole [2].

Therefore, in 2013, the Netherlands has set national goals for renewable energy production and sustainable development [5]. On top of this, the dairy sector and the Dutch government have signed an agreement in which they express the desire to increase energy efficiency by 30%, to lower CO_2 emissions by 30% (compared to 1990), and to have a share of 20% in renewable energy [5], [6]. This is in line with Dutch national goals that also aim for an energy efficiency increase and energy savings of 30%, and a 20% share of renewable energy in 2020. However, most farmers still aim for intensifying their production, reducing production prices and increasing their scale. Investments in a more renewable way of producing are expensive, and difficult to earn back in the current business structure. Farmers can, together with other stakeholders (consumers, food-processing industry, governments, etc.), develop a revenue model that is more focused on environmentally friendly production [7].

One of the technologies that is suggested as helpful to provide more renewable energy in the farming sector, is Anaerobic Digestion (AD). AD is already a proven technology [3], and the technology can harvest energy from several biomass sources, to produce biogas. Biogas is a flexible and storable energy carrier [8]. However, there are limitations to the implementation of AD technology. The choice of sources, operational values, long transport distances for biomass and specific technologies have a huge impact on the sustainability of the AD process [2]. In the Netherlands, a lack of stable subsidies often results in unfeasible AD projects, as the investments and operational costs are substantial [2]. Pierie et. al suggest the use of Industrial Symbiosis to integrate and optimize and AD system. Industrial Symbiosis is a technique to show the physical flows of materials and energy in local systems using a systems approach [9]. In their article, Pierie et. al suggest a farming cooperation scale AD system, used together by 12 farms. The results suggest a possibility for self-sufficiency on an annual basis, but in the most optimal scenario, 92% of the needed energy (gas, electricity, fertilizers, diesel) is produced internally [2]. This suggests that the farming cooperation is not yet fully self-sufficient in terms of energy use. Also, the research aimed at providing results on a yearly basis. For a better investigation, results on an hourly basis are desired.

1.1 Gap in knowledge

To the authors knowledge, the investigation done by Pierie et. al is lacking two important characteristics. First, it does not include other renewable sources to be used within the cooperative farming setting, as well as storage options [2]. Second, it lacks a model that can calculate demand and production on an hourly basis. The current model can only express whether there is enough production potential for a year, but not if this supply can actually meet demand on an hourly basis.

Adding other renewable energy sources can help the cooperative farming setting to become fully self-sufficient in terms of energy use. As mentioned before, the current possible reduction in energy use is estimated to be around 92%, when compared to a reference case. Farms typically have additional space to house renewable electricity producers such as solar PV and wind turbines, without sacrificing available space. However, it is commonly known that these energy producers are intermittent [10]. When looking at a farming cooperation that wants to produce renewable energy together, fitting supply of intermittent energy producers to the actual demand within the cooperation is very difficult. Among others, hydrogen storage is mentioned as a method to store energy and balance the difference between electricity supply and demand [11]. However, to the authors' knowledge, no literature discusses the implementation of solar PV and wind turbine energy production, as well as hydrogen and battery storage, on a cooperative farming cooperation scale as discussed in Pierie et. al [2].

Within this research, a new calculation structure called Power Nodes will be explained, used and validated. This new approach is built around the metabolism concept, defined by Ayres in 1988 as "the whole integrated collection of physical processes that convert raw materials and energy, plus labor, into a finished product and wastes" [12]. The new Power Nodes structure uses a combination of methods; the Modular approach (division of the systems' pathway in smaller blocks), Material and Energy Flow Analysis (MEFA), to clarify the energy production system in order to accurately model it [13] and Life Cycle Analysis, to quantify and environmental impacts. A main advantage of Power Nodes is the fact that it can calculate on an hourly basis. However, this Power Nodes method has not yet been verified or validated, which is also a gap in knowledge.

1.2 Reading guide

Chapter 2 describes the research aim and research questions that were formulated based on the introduction and gap in knowledge. The third chapter describes the methodologies that were used to develop an answer to the research questions. In the fourth chapter, the model that was designed is discussed. Chapter 5 discusses the used farming cooperation case, together with the three used scenarios. The sixth and seventh chapter explain results: chapter 6 discusses the model outcomes, and chapter 7 discusses the Power Nodes validation. Chapter 8 houses the discussion and the ninth chapter elaborates on the final conclusions. After the references (chapter 10), the appendix of this report can be found in chapter 11.

2. RESEARCH AIM AND RESEARCH QUESTIONS

This section will first describe the research aim. Additionally, the main research questions will be listed, together with relevant sub questions.

2.1 Research aim

The aim of this research is to investigate whether it is possible to produce all required energy (electricity, gas, fuel) for a farming cooperation by using renewable energy, in a balanced way. For example, it can be interesting to see if it is possible to implement other energy providing technologies (solar PV, wind), in the currently investigated sustainable farming cooperation [2]. To do this, the aim is also to investigate what kind of storage can be a possible technology to balance the supply of renewable energy and the energy demand of the theoretical farming cooperation.

Additionally, there is a second aim within this research. The recently developed Power Nodes method has not been validated or verified yet. Besides using this methodology to model the dynamic energy system mentioned above, a second aim is to validate this new and untested methodology.

2.2 Research questions

Based on the research aim described in section 2.1, the following main research questions were developed, together with relevant sub questions:

Research question 1: To what extent can a cooperation of farms become self-sufficient in terms of energy use, and provide balanced energy to the national grid by using biogas production, together with other kinds of renewable energy technologies?

Sub question 1-1: What does the yearly energy demand (electricity, heat, fuel) of a typical farm look like, together with the hourly demand patterns?

Sub question 1-2: What does an hourly production pattern look like for relevant renewable energy producers (solar PV, wind turbines, Anaerobic Digestion), and how can this be modelled?

Sub question 1-3: What are the possibilities for modelling (hourly variable) storage of different energy carriers (electricity, fuel)?

Sub question 1-4: What are the possibilities for modelling biogas upgrading?

Sub question 1-5: What are the options to fulfil the heat demand (CHP, regular gas boiler)?

Sub question 1-6: Can the farming cooperation become an energy provider if demand is fulfilled?

Research Question 2: Is the Power Nodes method a viable method to model a dynamic energy system that can calculate and display supply and demand on an hourly basis?

Sub question 2-1: How does the Power Nodes methodology operate?

Sub question 2-2: What methods are available to validate and verify the Power Nodes method?

Sub question 2-3: What method(s) is/are the best way to validate and verify the Power Nodes method?

3. METHODOLOGY

In this section, the methodologies to answer the main research questions are described. To answer main research question 1, all described methodologies will be used, except the validation techniques and SWOT analysis. To answer research question 2, mainly literature research will be used. First, the use of a case study is described. Furthermore, additional methodologies are described: literature research, questionnaire, the new Power Nodes methodology, Excel, validation techniques, SWOT-analysis, and the system boundaries of this study are explained, to clarify the scope of the study. Finally, the expression of results will be briefly discussed as well.

3.1 Case study

For this research, a case study is conducted. Previous work by Pierie et. al [2] investigated whether a farming cooperation consisting of 12 farms, can work together to produce their own energy by means of anaerobic digestion. A main result from this investigation was that on a yearly basis, sufficient biogas can be produced to fulfil the cooperation's energy demand. However, the question that arises is whether this annual production of roughly 1,2 million cubic meters of biogas is sufficient to fulfil the hourly energy demand. The case is situated in the surrounding agricultural area around Groningen. Local biomass is used in the previous work by Pierie et. al, characteristics like these will be the same in this investigation. The exact characteristics of the farming cooperation case are more extensively described in section 5.1. For extra information regarding the case, please refer to the previous investigation by Pierie et. al [2].

3.2 Literature research

Literature research will play an important role in this research. First, literature research was used to investigate the current situation with regards to the topic of this research. It was also used to gather the information and data for other technologies that are used in this research, and not yet modelled as Power Nodes. Some technologies are already modelled in Excel, literature research was used to understand which Power Nodes already exist and can be used. To answer main research question 2, literature research is also important to find out which techniques are available to validate and verify the designed model.

3.3 Questionnaire

Unfortunately, initial literature research proved that there is a lack of hourly energy demand patterns for both agricultural farms and dairy farms. Therefore, a questionnaire is used to retrieve necessary data from both agricultural and dairy farmers. This data will then be used to construct relevant hourly demand patterns. The three kinds of energy demand patterns are all constructed in the same way. For both types of farms, the demand consists of two parts: the energy consumption of the household, and the energy consumption of the farming business. For the households of both farms, the available demand patterns provided by Liander [14] can be used. However, the patterns for the business-related demands have to be manually created. In the questionnaire, both agricultural and dairy farmers are asked to view their opinion on how the energy use is divided over the day (hourly) and over the year (monthly). By doing this for electricity, heat and fuel, an hourly estimate can be made for both agricultural and dairy farms. A more elaborate description of the demand patterns can be found in section 4.2.1. For both the agricultural and dairy farms the filled in questionnaires are averaged and adjusted (to compensate for business size). The averaged questionnaires for both dairy farms and agricultural farms can be found in the appendix under 11.1, for extra clarification.

3.4 Power Nodes

Below, in figure 3-1, an overview of the Power Nodes methodology is displayed. Every sub-module of the entire model, e.g. a wind turbine, is modelled as a separate model in a Power Node. The node itself has a predetermined layout, to improve clarity. The separate sub-module should be able to function on its own. In this methodology, a forced merit order is active. The connection between Power Nodes is called the Net Load Signal (NLS), which is the structure in which the separate sub-modules connect to each other. First, demand is placed, to create an energy demand in the beginning of the process. This demand is then displayed using the outgoing, negative NLS, which then travels to the next Power Node. The next nodes are energy production nodes, that all produce energy and add this positive signal to the previous negative demand signal. After this, there is a possibility for storage or curtailment to act and bring any positive signals (overproduction) down to 0, or bring any negative signals (demand) up to 0. If, in the end, an NLS is 0, there is no demand or overproduction, the system is in balance. The forced merit order means that (following figure 3-1 below) production node 1 is able to add to the NLS before production node 2. This is not important for two production nodes that simply produce as much usable energy as possible, but it can be of importance when storage or curtailment nodes are added.

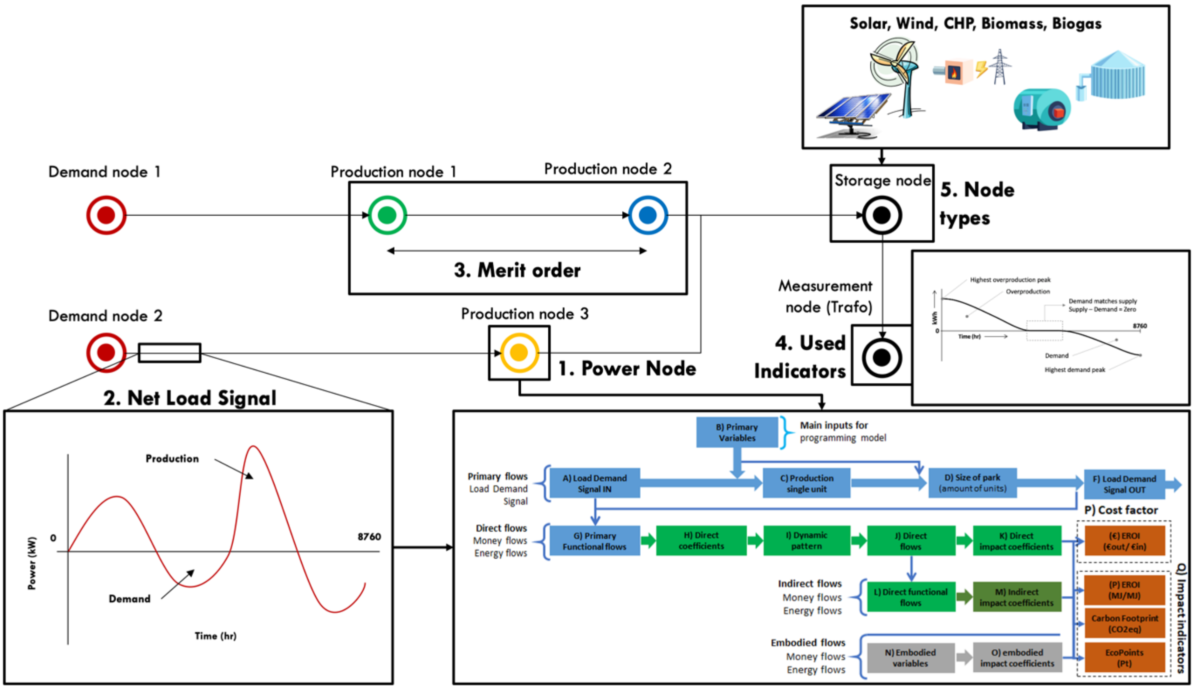


Figure 3-1. An overview of the Power Nodes methodology [15].

When the NLS has travelled through all the relevant nodes, the final NLS arises. This final NLS shows the end result of the Power Nodes working together. As explained before, the goal is to get this NLS to be fully 0 throughout all the hours of the year, as this means that the system is in balance. To better display this final NLS, the choice was made to show the results in the form of a Load Demand Curve, which simply takes all the final NLS signals from each hour and sorts them from high to low (see 4. in figure 3-1 above). The LDC provides a clearer overview of the results, as it is a fluent line that is easy to read. The LDC is further described below, in section 3.8. There are numerous types of nodes available (demand nodes, production nodes, storage nodes, conversion nodes, upgrade nodes, etc.). When using the Power Nodes methodology, new separate nodes can be designed and built, and implemented in an existing model without any major design changes. This immediately displays one of the charms of Power Nodes: the nodes are only connected via the NLS. Therefore, adding new nodes can be easily done by simply placing it where it is required, and rerouting the incoming and outgoing NLS'es. In chapter 4, the designed model is explained, which provides more clarity on the

Power Nodes methodology. From this chapter it will also become clear which nodes are used and how they interact together. For more information, please refer to the (currently unpublished) work of Frank Pierie et. al [15].

3.5 Excel

The above-mentioned Power Nodes methodology will be used to model the entire energy system in Excel. The expectation is that Excel can provide more than sufficient calculation possibilities, as well as visual possibilities, while remaining user-friendly and clear. The main goal is to model the entire system in one file, with a design that makes it a generic model. An overview sheet will be used, that can make navigation through the model easy and organized. Additionally, a planning sheet will be modelled that houses all the main variables that can be altered. Furthermore, each Power Node will be modelled in a separate sheet.

3.6 Validation techniques & SWOT Analysis

In this section, the used validation/verification techniques are briefly described. Also, the use of a SWOT analysis is described and how they can work together to result in an extensive description of possibilities and dangers for the designed model or the used methodology. This will be the main contribution to answer research question 2.

3.6.1 Validation techniques

To validate and verify the designed model and the Power Nodes methodology, several techniques will be combined. Robert G Sargent describes several validation techniques in his article that are applicable to the Power Nodes methodology and the designed model using this methodology [16]. In this case, the decision was made to use the following validation techniques: Comparison to Other Models, Face Validity, Structured Walkthrough, Traces, and Extreme Condition Tests. All used techniques are briefly described below. For more, information regarding these techniques, please refer to the article written by Sargent [16].

Comparison to Other Models: Various results or outcomes of the designed model are compared to other existing, validated models. When these results or outcomes are comparable to outcomes of other validated models, this provides evidence that the results or outcomes of the designed model are valid.

Face Validity: In this technique the methodology of Power Nodes and the designed model can be tested by asking a knowledgeable person (that is familiar with the methodology or subject of the designed model) to have a look. For example: is the logic used in the model or methodology correct, and are the model's input-output relationships reasonable?

Traces: The behavior of a specific part of the model (e.g. a variable) is traced from the beginning to the end to determine its effects within the model, and to see whether these effects are correct.

Extreme Condition Tests: In this technique, extreme conditions are simulated to see if the designed model acts to these conditions in the way it should. For example, if the capacity of a storage system is set to 0, the storage system is not able to store and discharge anything. Or, if the capacity of a solar panel is set to a certain maximum production capacity, it is not able to produce more than this set capacity. By performing this technique for as many extreme conditions as possible, the model can be tested extensively for extreme conditions.

3.6.2 SWOT-analysis

A SWOT (Strengths, Weaknesses, Opportunities, Threats)-analysis is a useful tool to identify possibilities and dangers within a company, tool, model or methodology. By using the above-mentioned validation and verification techniques and the model itself, results will arise that show (future) possibilities and (future) dangers for the used methodology. These results will be structured in a SWOT analysis framework. Based on the SWOT-analysis results, it will become clearer where the Power Nodes methodology can still be improved.

3.7 System boundaries

Below, in figure 3-2, a visualization of the system boundaries of this research is shown, where the visualization shows that the focus of this research lies on technical feasibility. Even though they are highly relevant, both economic feasibility and sustainability are outside the system boundaries of this research. Of course, indicators of sustainability might be relevant during analysis (e.g. amount of fossil fuel saved). This research will focus on a specific case (described as the 'cooperation'), over the period of 1 year (365 days). This cooperation of farms has a certain energy demand, that will consist of three types of energy: electricity, heat and fuel. To meet these demands, energy will be produced via several technologies. For every hour, there will either be a surplus or shortage of one or more types of energy, which will need balancing to make demand (from the cooperation) meet the supply (from various technologies). Necessary input materials for the AD system, such as biomass, are not included in this research, as they have already been investigated in previous research [2]. Also, the remaining materials after biogas production (digestate) are not included in this research. If there is a surplus or shortage of energy in the end, this has to come from or go to a (national) grid. If this is the case, the cooperation is not (fully) self-sufficient. However, if there is a connection to a national grid needed, the exact characteristics are not investigated in this research (only the amount of energy that has to go to or come from the grid). The main focus is to become as self-sufficient as possible, and any remaining demand from or supply to the national grid should be implemented as smoothly as possible.

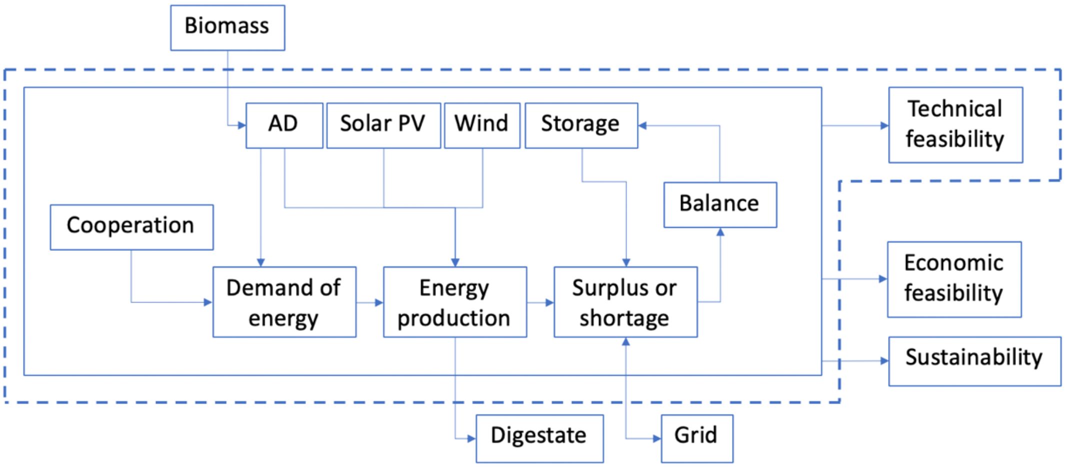


Figure 3-2: A visualization of the system boundaries of the conducted research.

Data requirements:

For this research to succeed, some data is required to adequately model the situation. First, the annual energy demands of the farming cooperation are needed, as well as the hourly demand patterns. The previous research has already provided for annual demands, and the hourly demand patterns will be constructed by consulting agricultural and dairy farmers by use of a questionnaire. Unfortunately, specific hourly energy demand patterns are available for average households, but not for specific farms. Therefore, the use of a questionnaire will hopefully be sufficient to construct adequate energy demand patterns. Besides the energy demand patterns, there are other relevant data requirements. For the used technologies (e.g. a wind turbine, CHP, solar PV panels), technical specifications are required to model these technologies properly. As most of the used technologies are widely described in literature [3], [8], [10], this is not expected to be an issue. When specific technical specifications are not available, a well-educated estimate can be made based on the available literature.

3.8 Expression of results

Due to the fact that there are two main research questions to be answered, there will also be two separate expressions of the results. The main goal of the designed model is to show to what extent the cooperation of farms is able to fulfil its own energy demand (main research question 1). As described in section 3.4, the way to express this is using the aforementioned Load Demand Curve and Net Load Signal graphs. They are shown below in figure 3-3. The NLS (after it has been through all relevant nodes that can influence this NLS), shows for each hour whether there is overproduction, demand, or balance in the energy system. This is done for all 8760 hours in the year, which can result in graphs that show the variation. However, it can become difficult to see what the extremes are and how important these extremes are for the energy system. This is where the LDC comes in. the LDC is simply the NLS, but then sorted from the highest value (highest overproduction peak) to the lowest value (highest demand peak). In the middle, all values that are zero show the hours in which demand and supply are in balance. By showing the results this way, the variation from hour to hour is lost, but it becomes a lot clearer what the extremes are and how important they are. Hence, the goal is to get the LDC curve to be zero as much of the time (indicating self-sufficiency) and as 'flat' as possible, indicating low variety in energy demand and overproduction.

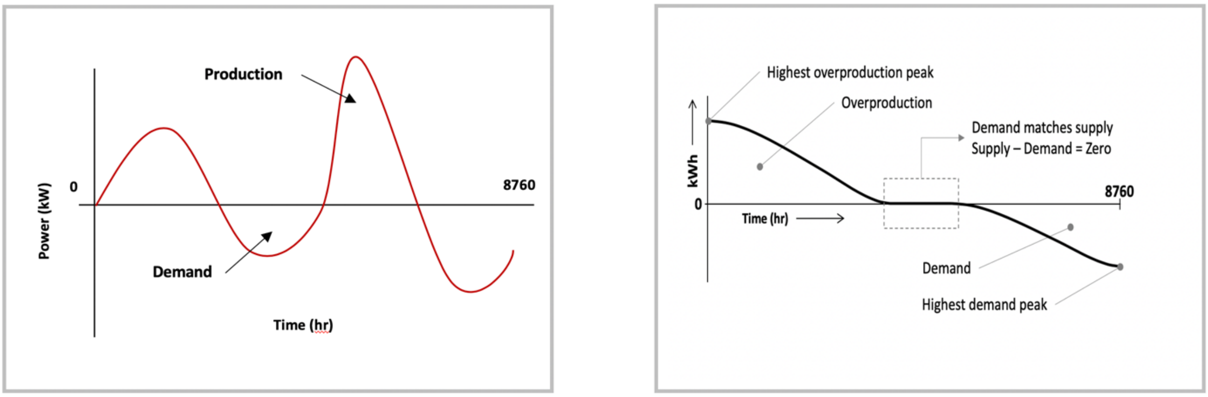


Figure 3-3. Visualization of the NLS (left) and LDC (right) results.

These NLS and LDC graphs will show the main results of each scenario, however there will also be side results that vary per scenario. These results can, for example show the production pattern of a production technology, or the charge state of a storage technology. Depending on the importance of the result itself, it will be shown in the results section or in the appendix.

To answer main research question 2, a SWOT analysis based on the above-mentioned validation and verification techniques will be used, to display strengths, weaknesses, opportunities and threats. The outcome of this SWOT analysis forms the basis for answering main research question 2.

4. MODELLING

In this section, the designed and used model will be described. First, a conceptual model of the aforementioned farming cooperation will be discussed, to explain the main structure and characteristics of the farming cooperation case. Out of this, the different types of system components will follow, and these will be described individually to explain their main functions and possibilities. The model itself was extensively validated by using the described validation techniques. From this validation, the validation of the Power Nodes methodology automatically followed.

4.1 Conceptual model

To better understand the design of the farming cooperation's energy system, a conceptual model was created. The goal of this model is to provide an overview in which the main connections between system parts become clear. Also, this conceptual model can act as a 'front page' for the final Excel model, to make navigation through the model easier. The full conceptual model is shown in figure 4-1.

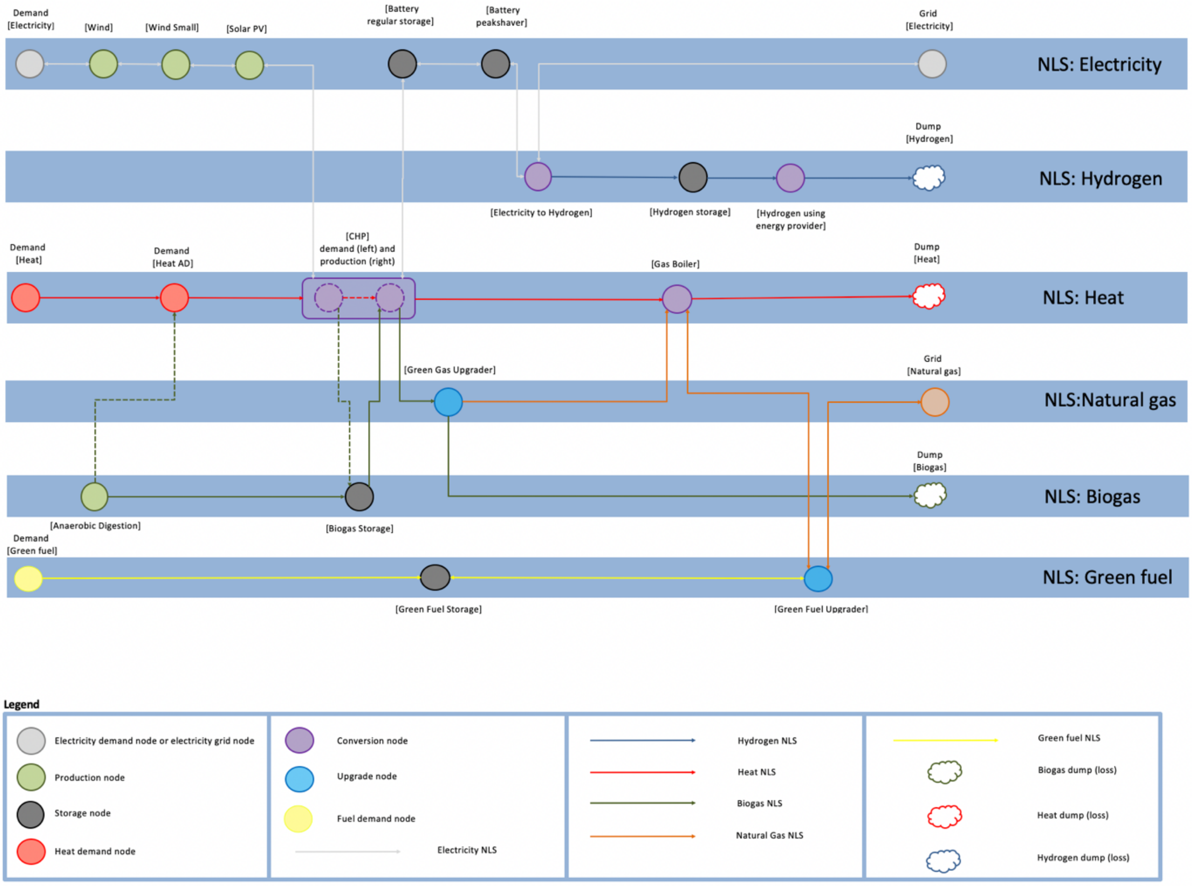


Figure 4-1. The designed conceptual model of the energy system proposed for the farming cooperation.

The arrows indicate the flow of an NLS. For example, the grey arrows form the path that the electricity NLS takes. Arrows that are two-directional indicate that, in reality, the energy can flow either way (for example electricity can come from the grid or flow to the grid). The blue bars visualize a general area of a certain energy carrier, for example electricity. Sometimes, an energy carrier interacts with a technology that also uses a different energy carrier (e.g. CHP). In situations like this, the arrow briefly flows from one blue bar to another. However, the color of the arrow still indicates the energy carrier form. In the end, it should always return to the blue NLS bar it refers to. There are two types of arrows: solid arrows and dotted arrows. Solid arrows represent a physical energy flow in reality, where a dotted arrow represents an information flow. In some occasions, information flows are required for sub-models to work properly.

As can be seen in figure 5-1, there are several types of nodes. These nodes are more elaborately described in the next section. In principal, each node describes a specific technology. One exception is the CHP. The CHP requires information from the biogas storage to know how much biogas is available to use. At the same time, the biogas storage wants to know from the CHP how much biogas it will take from the storage. This results in a feedback loop that Excel is not able to work with. Therefore, the CHP was divided in two parts. As can be seen in figure 4-2, there is a specific node for the theoretical demand of the CHP. This theoretical demand is there to tell the biogas storage how much biogas is theoretically wanted by the CHP. This is visually shown by the green dotted arrow in figure 4-1 and 4-2. As a response, the biogas storage can tell the CHP how much biogas is available to use. This is visually shown by the green arrow in figure 4-1 and 4-2 that goes into the CHP production node. The CHP production node then consumes biogas, and the remainder is sent away via the outgoing green arrow. At the same time, the electricity NLS and heat NLS also flow through the CHP, because the CHP is needed to produce heat, and it produces electricity as a by-product.

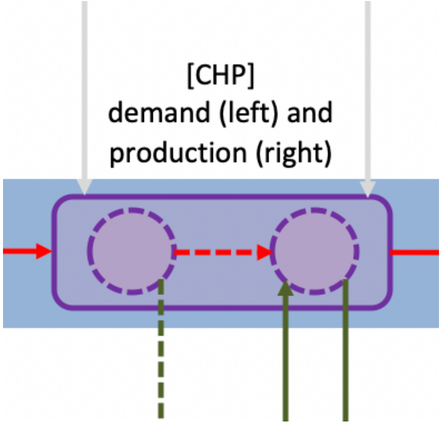


Figure 4-2. A cut-out of the CHP node from figure 4-1.

4.2 Nodes used in this model

As can be seen in figure 4-1, there are several types of Power Nodes used in this model. First, there are multiple demand nodes, that all show a specific type of energy demand of either the farming cooperation or a production technology. Second, there are several production nodes, that all house a technology that produces energy in a certain fashion. Additionally, there are storage nodes that house a storage technology that can be used to balance energy supply to the grid or to the farming cooperation. Conversion nodes are also part of this model. A conversion node converts energy from one entity into another. Finally, upgrade nodes are present, that upgrade an energy carrier into a more concentrated form. In the next sections 4.2.1 to 4.2.5, all used nodes will be described.

4.2.1 Demand nodes

In this section, all four of the modelled demand nodes are specified. There is a demand node for each of the three energy carriers (electricity, heat, and fuel) and there is a heat demand node for the Anaerobic Digestion system. In order to properly investigate the possibilities for an energy system in a farming cooperation, the energy demand of this cooperation has to be determined. Based on the questionnaires (section 3.3) that were conducted among farmers, the demand patterns for both the agricultural and dairy farms were made. The averaged questionnaires for agricultural farms and dairy farms can be found in the appendix under 11.1.

4.2.1.1 *Electricity demand*

The electricity demand (indicated as ‘1’ in figure 5-1 in the next section) is divided over four parts: the farm demand and the house demand of both an agricultural farm, as well as a dairy farm. This is due to the fact that these four demands all have their own demand pattern. The house patterns are based on the available patterns from Liander [14], and the farm patterns are based on the averaged questionnaires. These four demand patterns are then multiplied with the corresponding annual electricity use (indicated as ‘4’ in figure 5-1), which results in a yearly electricity use in an hourly pattern. These patterns are then multiplied with the number of farms, resulting in a total yearly electricity use, divided in an hourly pattern. This hourly demand pattern is then the starting point for the rest of the energy system model. The resulting electricity demand pattern will be displayed in scenario 1, section 6.1. The most important variables are listed below in table 4-1. For all the variables and their accompanying values, please refer to the appendix under 11.2.

Table 4-1. Most important variables in the electricity demand node.

Variable	Value	Unit
Total annual electricity demand	402000	kWh/a
Total number of farms	12	farms

4.2.1.2 *Heat demand*

The heat demand (indicated as ‘3’ in figure 5-1 in the next section) is divided over four parts: the farm demand and the house demand of both an agricultural farm, as well as a dairy farm. This is due to the fact that these four demands all have their own demand pattern. The house patterns are based on the available patterns from Liander [14], and the farm patterns are based on the averaged questionnaires. These four demand patterns are then multiplied with the corresponding annual heat use (indicated as ‘4’ in figure 5-1), which results in a yearly heat use in an hourly pattern. These patterns are then multiplied with the number of farms, resulting in a total yearly heat use, divided in an hourly pattern. This hourly demand pattern is then the starting point for the rest of the energy system model. The resulting heat demand pattern will be displayed in scenario 1, section 6.1. The most important variables are listed below in table 4-2. For all the variables and their accompanying values, please refer to the appendix under 11.2.

Table 4-2. Most important variables in the heat demand node.

Variable	Value	Unit
Total annual heat demand	417984	kWh/a
Calorific value gas	35	MJ/Nm_3

4.2.1.3 *Fuel demand*

The fuel demand (indicated as ‘2’ in figure 5-1 in the next section) is determined slightly different when compared to the two other energy demands. Only the fuel used for farming practices is taken into account. Therefore, there are only two different annual fuel demands (dairy farm and agricultural farm). These two (indicated as ‘4’ in figure 5-1), are then multiplied with the demand patterns based on the questionnaires, resulting in a fuel demand pattern for a dairy farm and agricultural farm. These patterns are then multiplied with the number of farms, resulting in one total yearly fuel use, divided in an hourly pattern. The resulting fuel demand pattern will be displayed in scenario 1, section 6.1. The most important variables are listed below in table 4-3. For all the variables and their accompanying values, please refer to the appendix under 11.2.

Table 4-3. Most important variables in the fuel demand node.

Variable	Value	Unit
Total annual fuel demand	1100500	kWh/a
Calorific value diesel	42	MJ/L

4.2.1.4 Anaerobic Digestion heat demand

Due to the fact that the AD unit requires a lot of heat [17], this is significant for the total heat demand of the system. Therefore, it is taken into account via a separate sheet. The sheet first calculates how much heat in total is used by the AD unit, via the total biogas production and the heat use per Nm^3 of biogas produced. This total amount of heat use is for the entire year. Next, a heat demand pattern is created by looking at the difference between the outside temperature and the internal temperature inside the AD system. The difference between these, for a certain hour, is converted into a fraction of the entire year. This demand pattern is then multiplied by the annual heat demand, resulting in a heat demand NLS for the AD unit. For more information regarding calculations, please refer to the Excel model. The most important variables are listed below in table 4-4. For all required variables and the accompanying used values, please refer to the appendix under 11.2.

Table 4-4. Most important variables in the AD heat demand node.

Variable	Value	Unit
Digester temperature	42	Degrees Celsius
Heat use digester	1,92	MJ/Nm$_3$

4.2.2 Production nodes

In this section, all the modelled production nodes are specified. There are four production nodes modelled: a large 2 MW wind turbine, a smaller 15 kW wind turbine, a solar PV panel, and an Anaerobic Digestion unit.

4.2.2.1 Wind turbine (2MW)

The wind turbine requires several parts to be modelled correctly. First, it requires a power curve that shows the production of the 2 MW wind turbine as a function of wind speed. Additionally, it requires input data that delivers an hourly wind pattern, to use together with the power curve to determine the hourly production of the wind turbine. Besides these, additional variables (e.g. hub height, cut-in speed, cut-off speed, rated speed) are required for the calculations. The most important variables are listed below in table 4-5. All required variables and the accompanying used values, the wind pattern and the power curve are shown in the appendix under 11.2.

Table 4-5. Most important variables in the Wind turbine (2MW) node.

Variable	Value	Unit
Power output	2	MW
Rated speed	15	m/s

First, the wind turbine sheet uses the wind speed as an input value. However, this wind speed is measured at a certain height. Therefore, the wind speed has to be corrected to the height of the turbine hub. This corrected wind speed is then used as an input for the turbine production calculations. Based on the corrected wind speed, the cut-in speed, cut-off speed, rated speed, turbine efficiency and reformer efficiency, the model calculates a production for that specific hour. This process is then repeated for all hours. The result is an hourly production pattern for a 2 MW wind turbine. For more insight in the specific calculations, please refer to the Excel model.

4.2.2.2 *Wind turbine (15 kW)*

For the 15 kW wind turbine (indicated as ‘13’ in figure 5-1 in the next section), the process is exactly the same as the above-mentioned 2 MW wind turbine. However, the wind speed has to be corrected for a different hub height, and the power curve is different. The resulting calculation method is exactly the same, so please refer to section 4.2.2.1 for more information. The most important variables are listed below in table 4-6. All required variables and the accompanying used values, the wind pattern and the presumed power curve are shown in the appendix (unfortunately, the exact power curve of the EAZ wind turbine was unavailable, so a comparable one was used).

Table 4-6. Most important variables in the Wind turbine (15kW) node.

Variable	Value	Unit
Power output	15	kW
Rated speed	8,5	m/s

4.2.2.3 *Solar PV*

The general strategy for modelling the solar PV panel (indicated as ‘12’ in figure 5-1 in the next section) is roughly the same as the wind turbine. First, a solar irradiation pattern is required as input data for the production calculations. Based on the maximum output, panel efficiency, inverter efficiency, and the surface area per panel, the model calculates a production for that specific hour. An important assumption is that it is assumed that the panels are at an optimum angle each hour of the day to harvest incoming irradiation. In reality, this is not the case. The model could be further specified by adding this feature. This process is then repeated for all hours. The result is an hourly production pattern for a solar PV panel. For more information regarding calculations, please refer to the Excel model. The most important variables are listed below in table 4-7. All required variables and the accompanying used values and the solar irradiation pattern are shown in the appendix under 11.2.

Table 4-7. Most important variables in the solar PV node.

Variable	Value	Unit
Power output	340	Wp
Panel efficiency	19,8	%

4.2.2.4 *Anaerobic Digestion*

The Anaerobic Digestion (AD) unit (indicated as ‘7’ in figure 5-1 in the next section) is modelled relatively straightforward. An important assumption is that it is assumed that the AD unit produces biogas at a constant rate each hour. In the model, an annual production of 1203886,8 Nm^3 of biogas was assumed (based on the investigation of Pierie et. al [2]). However, the NLS’es in the entire model work with kWh, rather than Nm^3. Therefore, the annual biogas production should be converted to kWh per year. To do this, an assumption was made. Most of the calorific value of biogas comes from the methane content [18]. As a result, the methane content of the biogas was further investigated. By using the methane content of the biogas, the methane calorific value and a conversion factor to go from MJ to kWh, it was possible to convert the annual biogas production in Nm^3 into kWh. The model then uses a regular hourly pattern to divide the total annual biogas production in kWh into hourly production. For more information regarding these calculations, please refer to the Excel model. The most important variables are listed below in table 4-8. For all required variables and the accompanying used values, as well as the assumed stable production pattern, please refer to the appendix under 11.2.

Table 4-8. Most important variables in the AD production node.

Variable	Value	Unit
Annual production	1203886,8	Nm_3/a
Methane content	56	%

4.2.3 Storage nodes

In this section, all the modelled storage nodes are specified. There are five storage nodes modelled: a regular battery, a battery with a peak shaving function, a hydrogen storage, a biogas storage, and a green fuel storage.

4.2.3.1 Regular battery storage

The first storage module that is modelled is a regular battery storage (indicated as '14' in figure 5-1 in the next section). The battery storage has a certain storage capacity. In the module, there are two important actions distinguished. First, there is a certain amount of charge possible each hour, as well as a certain amount of discharge. These two together, combined with the amount stored in the previous hour (charge state), adds up to the charge state. This charge state actually shows how much energy is stored in the storage in the end of an hour. The amount that can be charged depends. There are multiple things that can restrict the amount of charge possible (charge capacity, amount of incoming energy that is available to be charged, or the space left in the storage for charged energy). Additionally, the same can be said for discharge (discharge capacity, amount of energy that is available for discharge (including a maximum depth of discharge), or the amount of energy actually needed for discharge). Charging and discharging is done with a certain efficiency, so some is lost during the process (charge and discharge efficiency). Additionally, a self-discharge efficiency is taken into account. There is a certain percentage of the charge state that is lost each hour due to self-discharge. Of course, the amount of self-discharge depends on the size and type of storage. For each hour, the goal of the storage is to get the incoming NLS to be zero. So, if the incoming NLS is positive, it tries to store all the energy so that the outgoing NLS goes to zero. On the other hand, if the incoming NLS is negative, the battery tries to discharge as much energy as needed to change the NLS to zero. All the storage modules calculate in kWh's. For more information regarding calculations, please refer to the Excel model. The most important variables are listed below in table 4-9. For all required variables and the accompanying used values, please refer to the appendix under 11.2.

Table 4-9. Most important variables in the regular battery storage node.

Variable	Value	Unit
Capacity	25	kWh
Start stage	0	kWh

4.2.3.2 Battery peak shaver

The battery peak shaver module (indicated as '17' in figure 5-1 in the next section) is roughly the same as the regular battery. There is still a charge state, a charge and discharge possibility, a charge and discharge efficiency and self-discharge. However, the main difference lies in the way this module is managed. An extra feature is added to the peak shaving battery, called a charge and discharge threshold. Basically, if the incoming NLS is above the charge threshold, the storage charges all the excess energy above this charge threshold. As a result, the outgoing NLS is peak shaved with the charge threshold as the maximum (as long as the battery has sufficient storage capacity). The same goes for the discharge threshold. If the incoming NLS is below the discharge threshold, the battery is told to release energy to add to the NLS, resulting in an outgoing NLS that is smoothed with the discharge threshold as a minimum (as long as the battery has sufficient charge to discharge). For more information regarding calculations, please refer to the Excel model. The most important variables are listed below in table 4-10. For all required variables and the accompanying used values, please refer to the appendix under 11.2.

Table 4-10. Most important variables in the battery peak shaver node.

Variable	Value	Unit
Capacity	2400	kWh
Start stage	500	kWh

4.2.3.3 *Hydrogen storage*

For the hydrogen storage module (indicated as ‘15’ in figure 5-1 in the next section), the process is exactly the same as the regular battery, even though it stores hydrogen instead of electricity. The hydrogen has one added feature. In this research, it is not decided how any excess energy is delivered to the grid or energy demands. Therefore, the choice was made to store all excess energy in the form of hydrogen, as it can be used in multiple ways (add to AD system, inject in gas grid, use as vehicle fuel, use as gas turbine fuel to produce electricity) [11], [19]. There is no module modelled that uses this hydrogen, therefore the choice was made to model an extra feature in the storage itself, that shows how much hydrogen can be taken out each hour at a steady rate. In case this value is chosen above what is possible, a graph shows the possible shortage. For more information regarding calculations, please refer to the Excel model. The most important variables are listed below in table 4-11. For all required variables and the accompanying used values, please refer to the appendix under 11.2.

Table 4-11. Most important variables in the H_2 storage node.

Variable	Value	Unit
Capacity	100000	kWh
Start stage	23000	kWh

4.2.3.4 *Biogas storage*

For the biogas storage module (indicated as ‘8’ in figure 5-1 in the next section), the process is exactly the same as the above-mentioned regular battery storage, even though that the type of energy carrier is completely different. For more information, please refer to section 4.2.3.1. For more information regarding calculations, please refer to the Excel model. The most important variables are listed below in table 4-12. For all required variables and accompanying used values, please refer to the appendix under 11.2.

Table 4-12. Most important variables in the biogas storage node.

Variable	Value	Unit
Capacity	0	kWh
Start stage	0	kWh

4.2.3.5 *Green fuel storage*

For the biogas storage module (indicated as ‘11’ in figure 5-1 in the next section), the process is exactly the same as the above-mentioned regular battery storage, even though that the type of energy carrier is completely different. For more information, please refer to section 4.2.3.1. For more information regarding calculations, please refer to the Excel model. The most important variables are listed below in table 4-13. For all required variables and accompanying used values, please refer to the appendix under 11.2.

Table 4-13. Most important variables in the green fuel storage node.

Variable	Value	Unit
Capacity	6500	kWh
Start stage	250	kWh

4.2.4 Conversion nodes

In this section, all the modelled conversion nodes are specified. There are three conversion nodes modelled: a CHP, a gas boiler and an electrolysis system to convert electricity into H_2.

4.2.4.1 CHP

The first heat provider that is modelled in this system is a CHP (indicated as '5' in figure 5-1 in the next section). In this system, the CHP was modelled to be heat-driven, as the main function of the CHP is to produce heat. As a by-product, electricity is produced. There are two important efficiencies in the CHP: the efficiency of heat production and the efficiency of electricity production. The CHP starts with an amount of biogas. Part of this biogas is converted into heat, a part is converted into electricity, and a part is lost. In this case, the electricity production efficiency also distinguishes the amount of biogas used to produce heat. In short, only three efficiencies are important for the function of this CHP. For more information regarding calculations, please refer to the Excel model. The most important variables are listed below in table 4-14. For all required variables and accompanying used values, please refer to the appendix under 11.2.

Table 4-14. Most important variables in the CHP node.

Variable	Value	Unit
Capacity	255	kWh
Electrical efficiency	35	%
Heat recovery efficiency	80	%

4.2.4.2 Gas boiler

In case the CHP is not able to provide all of the heat demand, a backup is put in place by means of a traditional gas boiler (indicated as '6' in figure 5-1 in the next section). This gas boiler uses upgraded green gas or natural gas as fuel, and only acts in case the CHP is not able to deliver all the desired heat. In reality, green fuel is never used as a fuel, due to the fact that if there is green gas available, this means that there was no shortage of biogas to the CHP. Therefore, the CHP has already fulfilled all the heat demand. In case the CHP is given a smaller capacity then needed at some points, the gas boiler can still act on green gas while the CHP had no shortage in biogas. The gas boiler model is relatively straightforward: there is only one production efficiency, and the gas boiler is steered by the desired heat demand. For more information regarding calculations, please refer to the Excel model. The most important variables are listed below in table 4-15. For all required variables and accompanying used values, please refer to the appendix under 11.2.

Table 4-15. Most important variables in the gas boiler node.

Variable	Value	Unit
Capacity	0	kWh
Thermal efficiency	75	%

4.2.4.3 *Electricity to H_2: Electrolysis*

The electrolysis technology (indicated as ‘16’ in figure 5-1 in the next section) is also modelled relatively straightforward. It has a set capacity, and there is only one efficiency that acts as the conversion efficiency. All the incoming electricity is put into the electrolysis process, and the resulting hydrogen is sent towards the hydrogen storage. In case there is more electricity coming in than the electrolysis system can handle, the excess electricity is sent to the grid. If there is more hydrogen produced than the storage can store, the excess hydrogen is ‘dumped’. In reality, this will most likely mean it is burned, as there is nowhere to take it. For more information regarding calculations, please refer to the Excel model. The most important variables are listed below in table 4-16. For all required variables and accompanying used values, please refer to the appendix under 11.2.

Table 4-16. Most important variables in the electrolysis node.

Variable	Value	Unit
Capacity	645	kWh
Conversion efficiency	70	%

4.2.5 Upgrade nodes

In this section, all the modelled upgrade nodes are specified. There are two upgrade nodes modelled: a green gas upgrader that upgrades biogas to green gas, and a green fuel upgrader, that upgrades green gas or natural gas to green fuel.

4.2.5.1 *Green gas upgrader*

The green gas upgrader (indicated as ‘9’ in figure 5-1 in the next section) is modelled relatively simply, comparable to the electrolysis technology described in section 4.2.4.3. It has a set capacity, and is able to upgrade that capacity each hour. There is only one efficiency that acts as the upgrading efficiency. If there is more biogas than the green gas upgrader can upgrade, it is ‘dumped’. In reality, this means that it is most likely flared. For more information regarding calculations, please refer to the Excel model. The most important variables are listed below in table 4-17. For all required variables and accompanying used values, please refer to the appendix under 11.2.

Table 4-17. Most important variables in the green gas upgrader node.

Variable	Value	Unit
Capacity	600	kWh
Upgrade efficiency	95	%

4.2.5.2 *Green fuel upgrader*

The green fuel upgrader (indicated as ‘10’ in figure 5-1 in the next section) is modelled exactly the same as the green gas upgrader, with one addition. The green fuel upgrader has to upgrader sufficient fuel to cover the fuel demand, so there is a backup connection to the national gas grid. In case the green gas production is not sufficient to cover the fuel demand, natural gas is taken into the process to produce sufficient fuel. For more information regarding calculations, please refer to the Excel model. The most important variables are listed below in table 4-18. For all required variables and accompanying used values, please refer to the appendix under 11.2.

Table 4-18. Most important variables in the green fuel upgrader node.

Variable	Value	Unit
Capacity	300	kWh
Upgrade efficiency	85	%

5. CASE AND SCENARIOS

In this section, the characteristics of the farming cooperation case are explained. Additionally, the three used scenarios are elaborately described. The first scenario is the base scenario that reveals the exact hourly energy demands of the cooperation. The second scenario is the reference scenario that uses the same characteristics as the previous investigation by Pierie et. al [2], to see if the farming cooperation can fulfil its own energy needs on an hourly basis as well, rather than just on an annual basis. In the third scenario, additional renewable energy producers are added to investigate whether the farming cooperation can become a stable energy provider.

5.1 Farming Cooperation case

Within this research, a theoretical farming cooperation that consists of 5 dairy farmers and 7 agricultural farmers is used (based on Pierie et. al [2]). The number of farms in the cooperation was determined by the number of feedstocks needed in their theoretical farming case. As this investigation goes further into the case they developed, the choice was made to stick to the same cooperation of 5 dairy farms and 7 agricultural farms. There will be one AD system to produce biogas with the material remains of all farms included, as well as materials coming from outside the cooperation. All the manure that is used in the AD unit comes from the cooperation. In their article, Pierie. et al described that biomass is used that comes from the local government and water board. The same size AD unit is used, so the same annual biogas production can be assumed. However, Pierie et. al work on an annual basis, so there are no hourly patterns available. Therefore, the hourly energy demand patterns are taken from literature and constructed based on the answers of questionnaires filled in by local farmers. What the previous investigation by Pierie et. al does not include, is the extra production of energy by means of other renewable energy technologies. In this theoretical farming cooperation case, it will be investigated whether it is possible for the farming cooperation to become an energy provider to the environment. In the figure below (figure 5-1) an overview of the designed scenarios is given. Three main scenarios were designed. The first scenario was used to determine the current energy demands. In the second scenario, the goal was to determine whether the annual investigation by Pierie et. al [2] can also function on an hourly basis. In the third scenario, the goal was to see if the cooperation can become an energy provider.

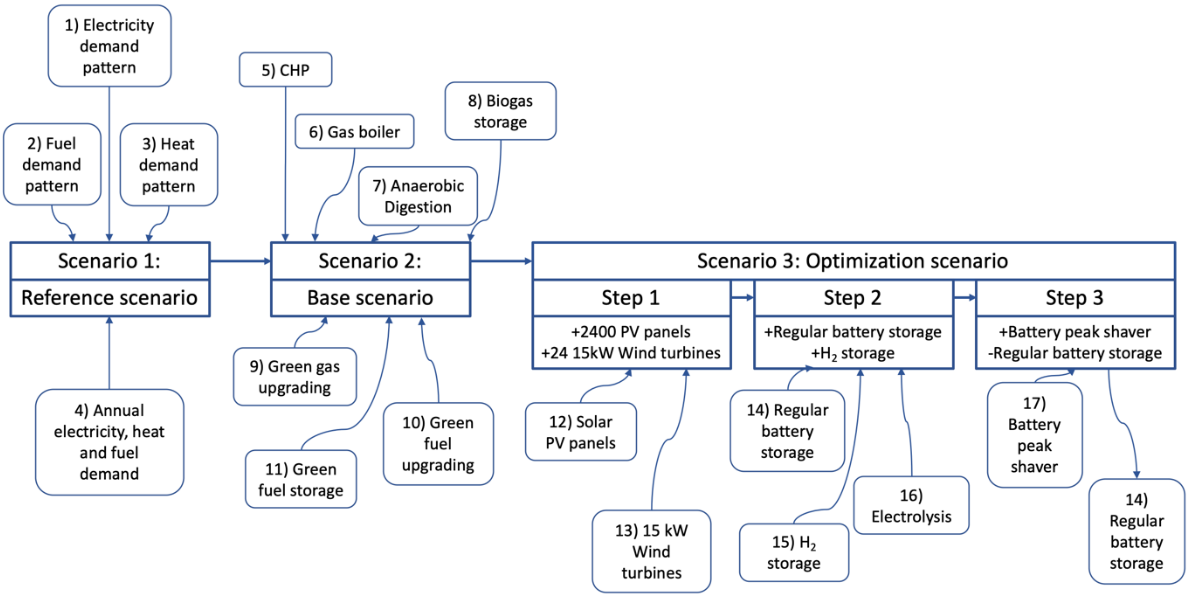


Figure 5-1. Visualization of the three scenarios used.

5.2 Scenario 1: Reference scenario

This is the first scenario that was run in the model. The goal of this scenario is to provide insight in the current energy demands of the farming cooperation. Therefore, only the energy demand sheets are active. In this scenario, the cooperation of 12 farms (5 dairy, 7 agricultural), all have an electricity, heat and fuel demand (for more info, please refer to section 4.2.1). The total added demands are then viewed in three NLS'es and three LDC's. Each of these will be shown in the results section in a separate graph. Based on these results, capacities of other technologies in the next scenarios can be chosen. A visualization of this scenario, together with scenarios 2 and 3 can be seen above, in figure 5-1. Additionally, in figure 5-2, an overview of the previously seen conceptual model is shown, but this time it is indicated which parts of the model are active for the specific scenario. In scenario 1, the nodes highlighted with the green dotted box are active. The active nodes are listed below as well, in table 5-1.

Table 5-1. Overview of the active nodes in the first scenario

Node	Total demand / Capacity	Unit
Electricity demand	402000	kWh/a
Heat demand	417984	kWh/a
Fuel demand	1100500	kWh/a

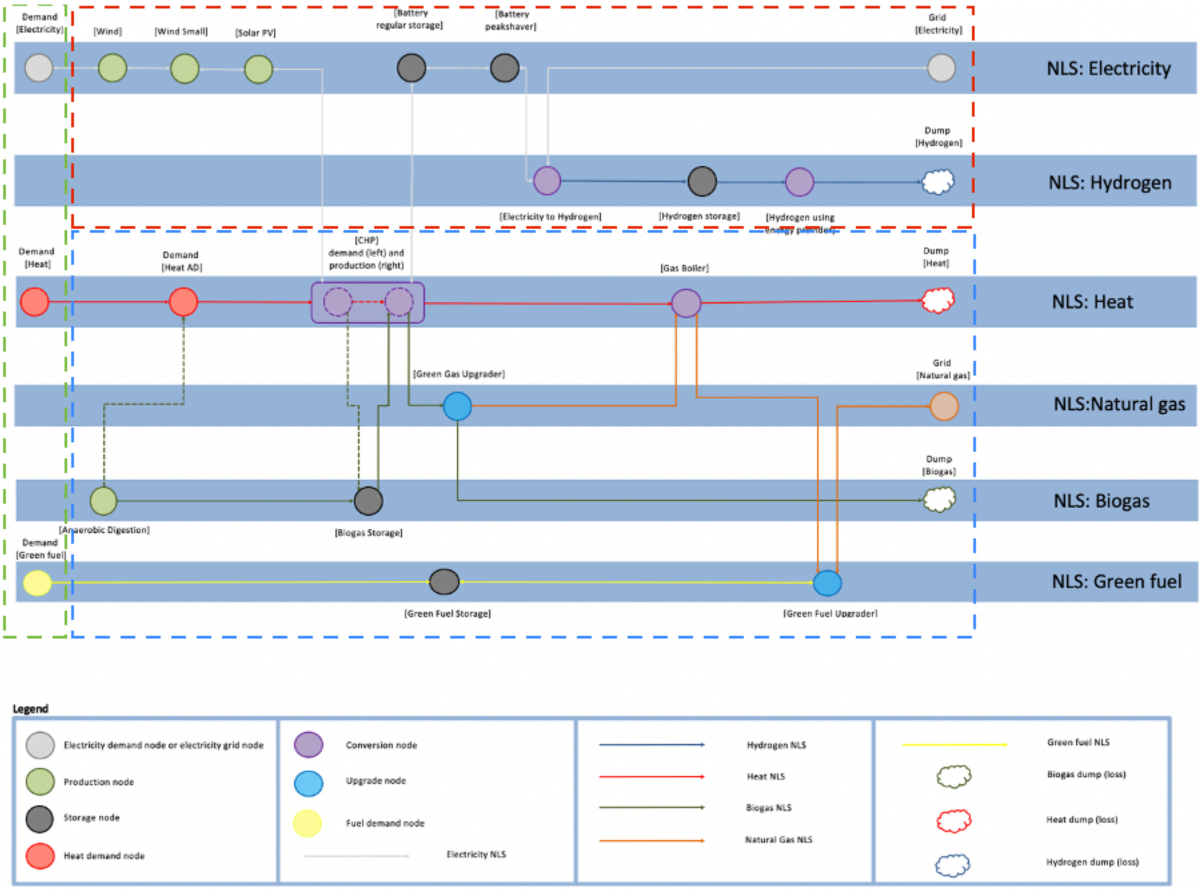


Figure 5-2. Visualization of parts of the model used in the various scenarios.

5.3 Scenario 2: Base scenario

The second scenario is referred to as the base scenario. The goal of this scenario is to see if a single AD unit can provide enough biogas to meet all the energy demands within the farming cooperation.

Pierie et. al [2] already proved that the annual biogas production is sufficient on a yearly basis. However, this scenario is there to check whether the annual biogas production is sufficient to fulfil the needs of the cooperation on an hourly basis too. In this scenario, besides the three regular energy demand nodes, there is a fourth demand node active, that houses the heat demand needed in the AD unit. This demand is simply added up to the regular heat demand. Besides, there is an AD-unit active that calculates the hourly biogas production. A heat-driven CHP is activated to produce the desired heat demand (by means of biogas), and a byproduct of this CHP is electricity. As a backup, there is a gas boiler that can be powered by natural gas as a backup, in case necessary. Additionally, there are several other nodes active that can work with a possible surplus in biogas. In case the CHP does not consume all the biogas, a green gas upgrader is added to upgrade all the remaining biogas to green gas. Besides the green gas upgrader, a green fuel upgrader is added that can upgrade green gas and natural gas to green fuel. Finally, a green fuel storage is added that can store green fuel for when the cooperation needs it. A visualization of the base scenario can be seen in figure 5-1. Additionally, in figure 5-2, the nodes highlighted in the green and blue dotted boxes are active. In table 5-2, an overview of the added active nodes in the base scenario is given.

Table 5-2. Overview of the newly added active nodes in the second scenario. The nodes in the previous scenario are also still active.

Node	Demand / Capacity	Unit
AD heat demand	642072,96	kWh/a
CHP	255	kWh
Gas boiler	0 (active but not used)	kWh
Green gas upgrader	600	kWh
AD production	1203886,8	Nm_3/a
Biogas storage	0 (active but not used)	kWh
Green fuel storage	6500	kWh
Green fuel upgrader	300	kWh

5.4 Scenario 3: Optimization scenario

The third and final scenario is called the optimization scenario. The goal of this scenario is to see if the farming cooperation can become an energy provider to the region. The scenario is divided into three steps. Each step is sequential to the previous step. In figure 5-2, the nodes highlighted in the green, blue and red dotted boxes are active.

5.4.1 Step 1

In the first step of the optimization scenario, 200 solar PV panels per farm are added, as well as two 15 kW wind turbines. The goal of this step is to understand how much excess electricity is produced, and what influence this excess production has on the outgoing electricity NLS and final LDC. A visualization can be seen in figure 5-1. In table 5-3, an overview of the added nodes in the first step of scenario 3 is given.

Table 5-3. Overview of the newly added active nodes in the first step of the third scenario. The nodes in the previous scenario are also still active.

Node	Amount	Unit
Wind turbine (15kW)	24	Turbines
Solar PV panels	2400	panels

5.4.2 Step 2

As a sequential next step, a regular battery system is installed that can take care of the final electricity demand that was left over after step 1. The remainder of the electricity is then converted into hydrogen, by using an electrolysis system. The hydrogen is stored in the hydrogen storage, and the storage can deliver a steady amount of hydrogen each hour. A visualization can be seen in figure 5-1. In table 5-4, an overview of the added nodes in the first step of scenario 3 is given.

Table 5-4. Overview of the newly added active nodes in the second step of the third scenario. The nodes in the previous scenario are also still active.

Node	Amount	Unit
Regular battery storage	25	kWh
H_2 storage	100000	kWh
Electrolysis	1100	kWh

5.4.3 Step 3

In the final step of the third scenario, the regular battery is replaced by a battery peak shaver. The goal of this battery peak shaver is to smoothen the NLS that comes into the electrolysis system, in order to bring down the capacity of this system. The same hydrogen storage as before is used. A visualization can be seen in figure 5-1. In table 5-5, an overview of the added or altered nodes in the second step of scenario 3 is given.

Table 5-5. Overview of the newly added active nodes in the third step of the third scenario. The nodes in the previous scenario are also still active.

Node	Amount	Unit
Battery peak shaver	2400	kWh
Electrolysis	645 (altered compared to step 2)	kWh

6. RESULTS: MODEL OUTCOMES

In this section, the results of the model are described, according to the scenarios described in the previous chapter. A division is made in the results. Main results are described in the scenarios, to explain the important characteristics. Side results are shown in the appendix, as they are nice to know but not essential to understand the important results. Per scenario, a clear indication is provided between the main results and side results by means of an overview table. In the end, the results of a sensitivity analysis regarding this model are discussed as well.

6.1 Reference scenario

The goal of this scenario was to provide insight in what the current energy demands are within the farming cooperation. Therefore, the focus lies on the three NLS'es and three LDC's that show the hourly electricity, heat and fuel demand. There are no side results in this scenario. An overview is provided below, in table 6-1.

Table 6-1. Overview of main results and side results of scenario 1.

Scenario 1: Reference scenario		
Main results:	Location	Figure
NLS electricity demand	Results	6-1
LDC electricity demand	Results	6-2
NLS heat demand	Results	6-3
LDC heat demand	Results	6-4
NLS fuel demand	Results	6-5
LDC fuel demand	Results	6-6
Side results:	Location	Figure
-	-	-

6.1.1 Electricity demand

Below, the NLS (figure 6-1) and resulting LDC (figure 6-2) are shown of the electricity demand in scenario 1. From the NLS, it is clearly visible that the total electricity demand of the cooperation is substantially higher in the winter months. What is clearly visible as well, is the division of electricity demand over the 12 months. This is due to the fact that most of the annual demand is taken by the farming practices. The demand patterns for the farming practices are made per month, resulting in this visibility. This will be further described in the discussion in section 8.

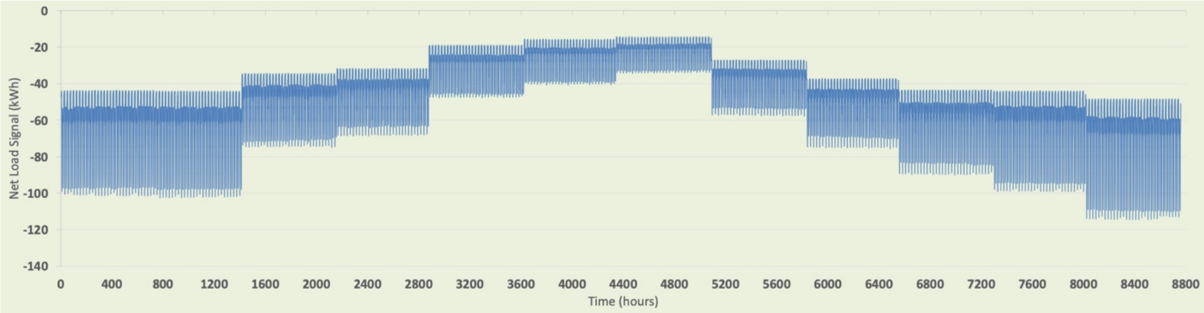


Figure 6-1. NLS of the electricity demand in scenario 1: reference scenario.

The LDC curve below clearly shows that there is a demand for all hours of the year, with peak demands of almost 115 kWh. Both graphs provide a clear representation of what the current electricity demand is. The peak demands of 115 kWh result in a required grid connection capacity of 115 kWh, while 75% of the time (6570 hours), the demand is only 60 kWh. As a result, the grid capacity has to be oversized for only a fraction of the hours in which it actually uses the maximum capacity.

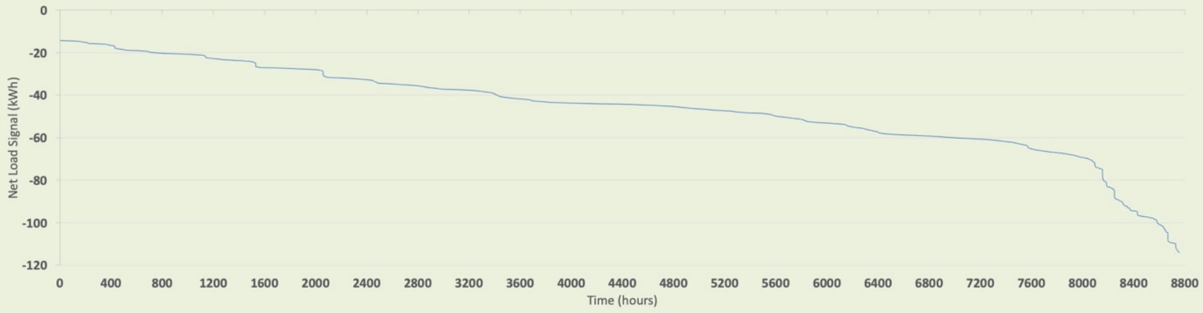


Figure 6-2. Resulting LDC of the electricity demand in scenario 1: reference scenario.

6.1.2 Heat demand

Below, the NLS (figure 6-3) and resulting LDC (figure 6-4) of the heat demand in scenario 1 are shown. In this scenario, the heat demand consists only of the heat demand of the farms (as described in section 4.2.1.2), as the AD system is not yet active. The NLS from the heat demand below shows a similar result when compared to the electricity demand. The demand for heat is a lot lower in the warmer periods of the year, which is logical due to the Dutch climate. However, in the winter months, the spread in heat demand over a day seems larger. This is most likely due to the fact that we lower the use of heating systems during the night. On the other hand, in the summer months, the variation over the day seems a lot smaller when compared to the electricity demand. This is probably due to the fact that the summer temperatures result in almost no heat demand, during day and night.

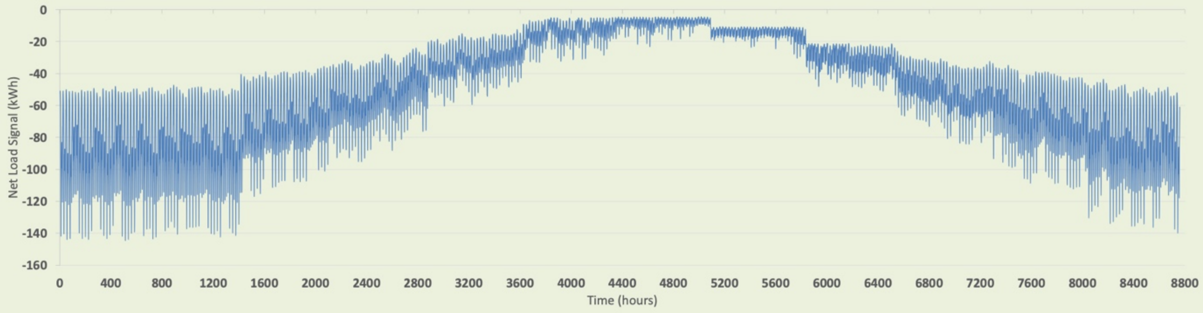


Figure 6-3. NLS of the electricity demand in scenario 1: reference scenario.

From the LDC curve below, it is clearly visible that for each hour in the year, there is still a heat demand in the cooperation. The peak heat demand is found around 145 kWh. As can be seen in figure 6-4, there is quite a steep drop-off in the last +-100 hours, requiring an extra 25 kWh heat capacity. The other +-8650 hours, the heat demand capacity is within 120 kWh. Comparable to the electricity demand, this results in a heating capacity which is over capacitated to make sure that all heat demand can be met. Both graphs show a clear representation of what the current heat demand is in the cooperation.

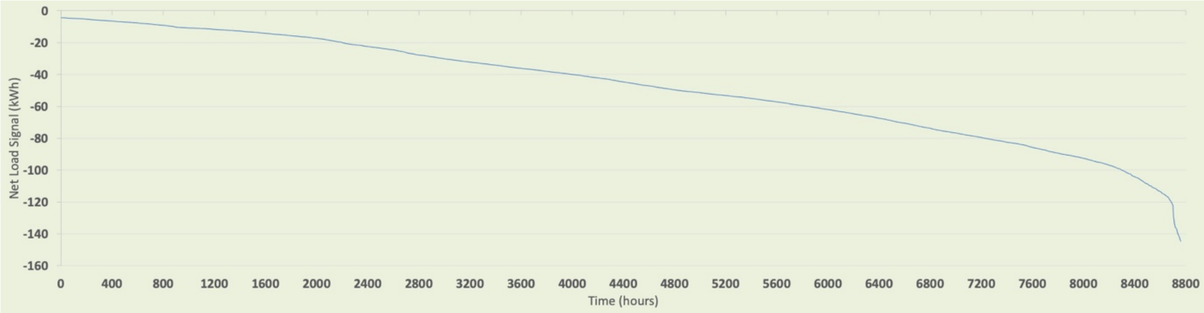


Figure 6-4. Resulting LDC of the electricity demand in scenario 1: reference scenario.

6.1.3 Fuel demand

Below, the NLS (figure 6-5) and resulting LDC (figure 6-6) of the fuel demand in scenario 1 are shown. The NLS that was constructed based on the hourly fuel demand clearly shows that there is a demand every 24 hours, which complies with how the demand pattern was constructed. Also, the peaks in fuel demand in April/May and October are logic, as these are periods in which especially agricultural farms use a lot of fuel to run equipment that is used to work on their lands[20].

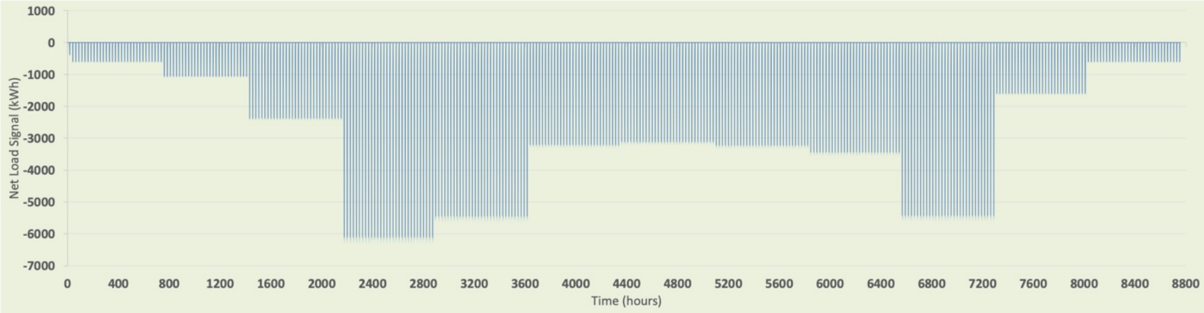


Figure 6-5. NLS of the fuel demand in scenario 1: reference scenario.

From the LDC curve below in figure 6-6, some extra proof is found that the fuel demand is only there for one hour every day, and 23 hours of no demand. This is shown below by the blue line which shows zero for about 8400 hours of the 8760 hours in a year. The maximum demand peak lies at around 6000 kWh (so, for one month in the year, the daily fuel consumption lies around 6000 kWh). This complies to the average results of the questionnaires. Both graphs show a clear indication of what the current fuel demand looks like.

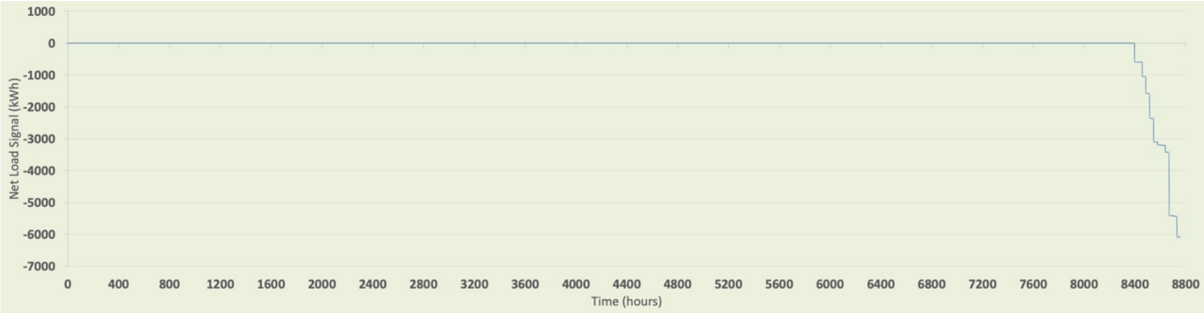


Figure 6-6. Resulting LDC of the fuel demand in scenario 1: reference scenario.

6.2 Base scenario

The goal of this scenario was to find out if the annual biogas production that was investigated by Pierie et. al [2] to be sufficient on a yearly basis, is sufficient on an hourly basis as well, to cover the full energy demand of the cooperation. For the main results, the focus lies on the NLS'es and resulting LDC's of electricity, heat, fuel and natural gas. There are several side results, that concern the CHP, AD unit, green fuel upgrading unit and green fuel storage. These are shown in the appendix, as they are not directly relevant for the explanation of the main results. An overview is provided below, in table 6-2.

Table 6-2. Overview of main results and side results of scenario 2.

Scenario 2: Base scenario		
Main results:	Location	Figure
NLS electricity	Results	6-7
LDC electricity	Results	6-8
NLS heat	Results	6-9
LDC heat	Results	6-10
NLS fuel	Results	6-11
LDC fuel	Results	6-12
NLS natural gas	Results	6-13
LDC natural gas	Results	6-14
Side results:	Location	Figure
CHP production pattern	Appendix	11-3
AD production pattern	Appendix	11-4
Green fuel upgrading production pattern	Appendix	11-5
Green fuel storage charge state	Appendix	11-6

6.2.1 Electricity

Below, the NLS (figure 6-7) and resulting and initial LDC (figure 6-8) of the electricity demand in scenario 2 are shown. The NLS below clearly shows that the electricity demand is now easily fulfilled most of the year, by the CHP. The CHP is heat driven, which means that the produced electricity (as a by-product) can't be adjusted in the CHP. There are some hours in the year left in which the electricity demand is not yet fulfilled. However, on most other hours there is that much surplus, that a storage function is expected to easily cope with the remaining electricity demand.

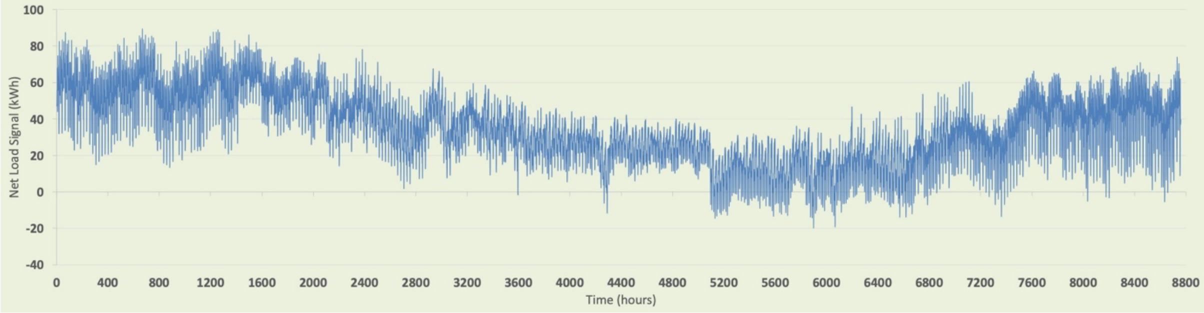


Figure 6-7. NLS of electricity in scenario 2: base scenario.

The graph below (figure 6-8) represents the initial electricity demand from the reference scenario (indicated in red) and the resulting electricity LDC in the new base scenario. The LDC shows that currently, in most hours (+-8400) there is an overproduction of electricity, and there are still some hours (+-300) where there is some electricity demand left. This indicates that the electricity production from the CHP alone is enough to fulfil the electricity demand of the cooperation.

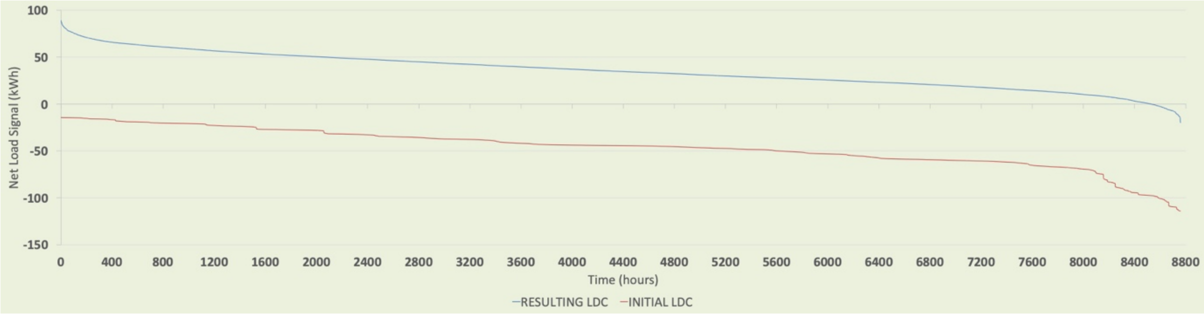


Figure 6-8. Resulting and initial LDC of electricity in scenario 2: base scenario.

6.2.2 Heat

Below, the NLS (figure 6-9) and resulting and initial LDC (figure 6-10) of the heat demand in scenario 2 are shown. It is important to say that in this situation, the used AD system also adds a heat demand to the total. In the red line (initial heat demand from reference scenario), this is not yet shown, as it is a result from the reference scenario. However, the blue line in figures 6-9 and 6-10 indicate that, even when adding the digester heat demand to the equation, the CHP is more than able to fulfil the entire heat demand using biogas. The total heat demand is covered by the CHP, as can be seen in the appendix in figure 11-3, in the CHP production pattern graph. This shows the total heat production by the CHP, so including the heat demand of the AD. In reality, it might be the case that there is a different technology than the CHP to cover the AD heat demand, but to make the investigation less complicated, it is modelled to be within the CHP's capacity.

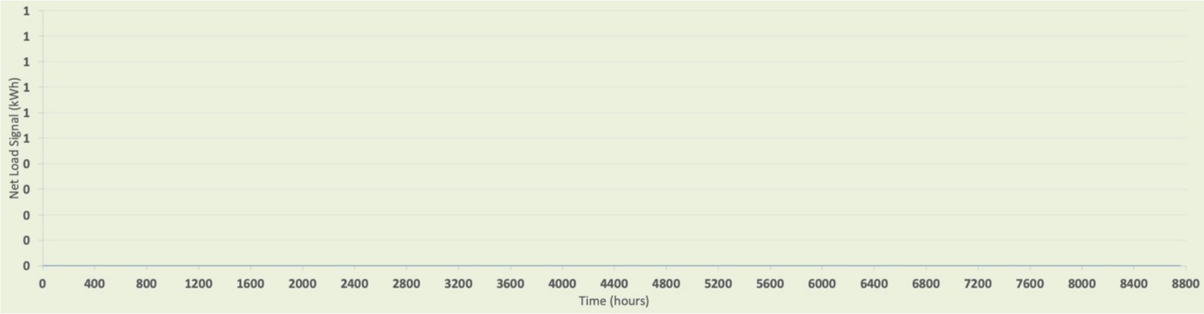


Figure 6-9. NLS of heat in scenario 2: base scenario.

Due to the higher heat demand in the winter months, a lot of heat is produced by the CHP. As a result, a lot of electricity is also produced as a by-product. This electricity is visible in the NLS of figure 6-7. The electricity production by the CHP has resulted in extra stability problems in the electricity NLS.

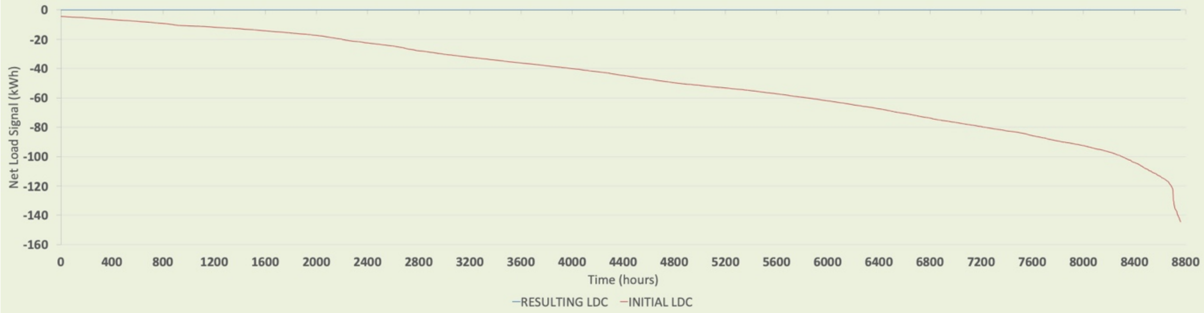


Figure 6-10. Resulting and initial LDC of heat in scenario 2: base scenario.

6.2.3 Fuel

Below, the NLS (figure 6-11) and resulting and initial LDC (figure 6-12) of the fuel demand in scenario 2 are shown. From the NLS it becomes clear that the hourly fuel demand for the entire year is covered (as the NLS is completely zero). In figure 6-12, the resulting LDC for fuel is also zero, showing a clear difference with the initial LDC in the hours of the days when fuel was desired.

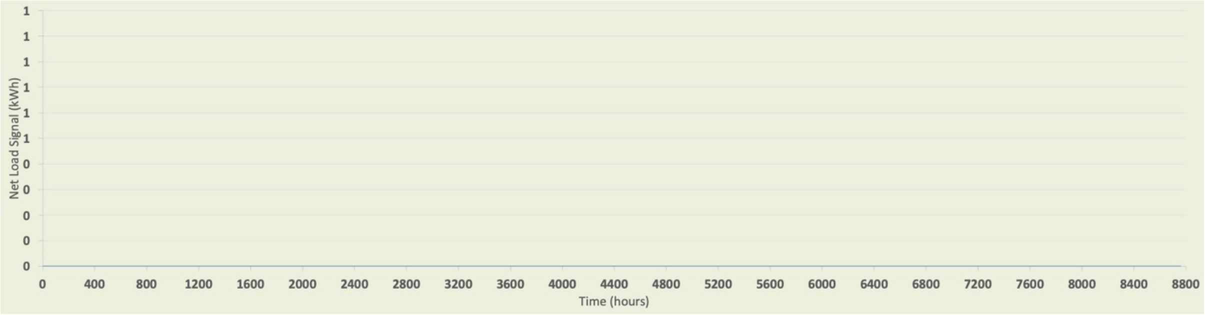


Figure 6-11. NLS of fuel in scenario 2: base scenario.

In this scenario, a fuel upgrader with a maximum capacity of 300 kWh was used, together with a storage of 6500 kWh. The assumption that was made indicates that the farmers fill up their machinery once each day, so the storage can be relatively small (a 6500 kWh diesel tank holds roughly 550-600 liters). If the decision is made to fill up the machinery less often (once a week, for example), then the storage facility has to increase to make sure that sufficient fuel is available once all the machinery fuels up. In reality, the different farmers will most likely fill up their machinery in different moments. However, there is no data that can result in a fitting demand pattern, so the assumption was made to fill up all machinery once a day.

Figure 6-12. Resulting and initial LDC of fuel in scenario 2: base scenario.

6.2.4 Natural gas

Below, the NLS (figure 6-13) and resulting LDC (figure 6-14) of natural gas in scenario 2 are shown. What becomes clear from the NLS, is that there is no natural gas taken from the gas grid at all. Actually, there is actually a supply of green gas towards the gas grid. This is another indication that the amount of biogas produced is more than sufficient to fulfil the energy demand of the cooperation. As the previous investigation by Pierie et. al [2] indicated that only about half of the produced biogas was used internally, this was to be expected.

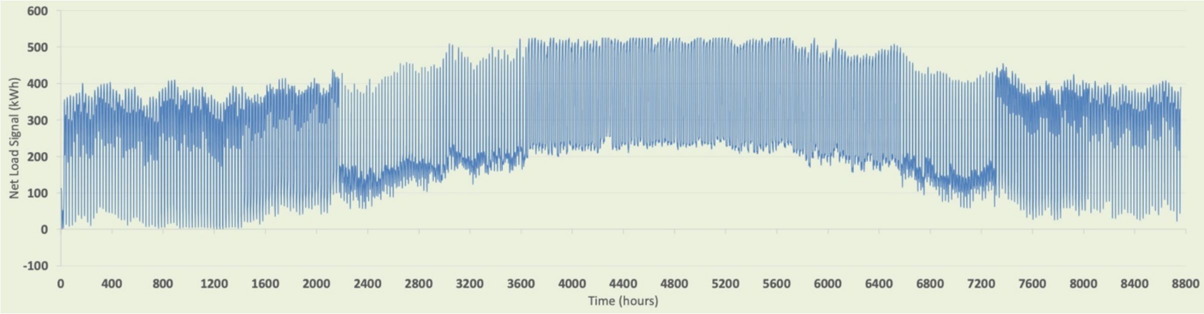


Figure 6-13. NLS of natural gas in scenario 2: base scenario.

However, the NLS shown in figure 6-13 indicates that the supply of green gas to the gas grid is extremely intermittent. First, it becomes clear from the general shape that the supply of natural gas is highest in the summer months, when the general demand for natural gas is lowest. Second, there are dark blue spots available in most of the months. These variations indicate that the daily spread in green gas supply to the national grid is substantial. What also stands out, is the fact that during the high fuel demand months (April/May and October, hours 2100 to 3600 and 6500 to 7300), the green gas availability is substantially lower. The LDC below in figure 6-14 shows that there is no natural gas taken from the gas grid. However, the national grid will get less than 100 kWh in roughly 1000 hours in the year, while it also has to be able to take in more than 500 kWh during 750-1000 hours of the year.

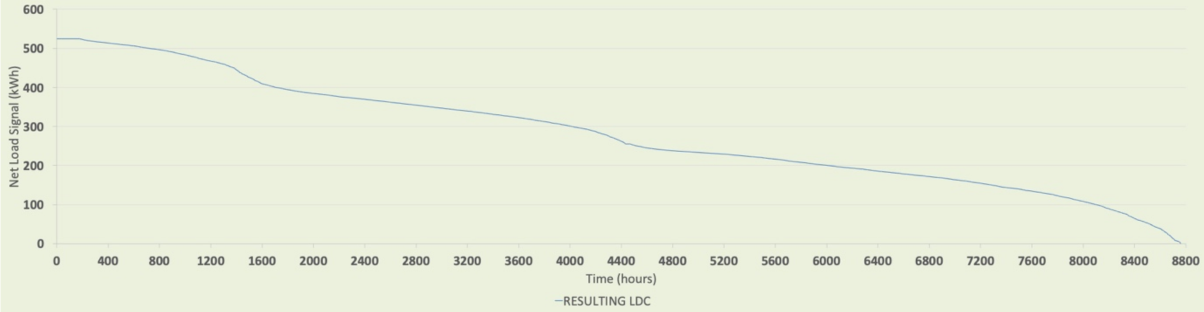


Figure 6-14. Resulting LDC of natural gas in scenario 2: base scenario.

6.3 Optimization scenario

From the previous results it can be concluded that the annual biogas production is more than sufficient to fulfil the hourly energy demands (electricity, heat and fuel) of the farming cooperation. The next question is whether the cooperation can become an energy provider (aside from the injected green gas). The results below are divided over three sections, corresponding to the three steps taken as described in the scenarios section. In this scenario, the focus lies on electricity. The heat and fuel demand are not affected by this scenario, the same counts for natural gas. Therefore, they are not displayed in the results below. An overview of the main and side results is provided below, in table 6-3, table 6-4 and table 6-5.

Table 6-3. Overview of main results and side results of scenario 3, step 1.

Scenario 3: Optimization scenario, step 1		
Main results:	Location	Figure
NLS electricity	Results	6-15
LDC electricity	Results	6-16
Side results:	Location	Figure
Wind turbine production pattern	Appendix	11-7
Solar PV production pattern	Appendix	11-8

Table 6-4. Overview of main results and side results of scenario 3, step 2.

Scenario 3: Optimization scenario, step 2		
Main results:	Location	Figure
NLS electricity (H_2 storage)	Results	6-17
LDC electricity (H_2 storage)	Results	6-18
NLS electricity (H_2 storage + battery storage)	Results	6-19
LDC electricity (H_2 storage + battery storage)	Results	6-20
Production pattern electrolysis technology	Results	6-21
Charge state H_2 storage	Results	6-22
Unavailability of H_2	Results	6-23
Side results:	Location	Figure
Charge state battery storage	Appendix	11-9

Table 6-5. Overview of main results and side results of scenario 3, step 3.

Scenario 3: Optimization scenario, step 3		
Main results:	Location	Figure
NLS electricity	Results	6-24
LDC electricity	Results	6-25
Production pattern electrolysis without peak shaver	Results	6-26
Production pattern electrolysis with peak shaver	Results	6-27
Charge state H_2 storage with peak shaver	Results	6-28
Unavailability of H_2 (with peak shaver)	Results	6-29
Side results:	Location	Figure
Incoming NLS peak shaver	Appendix	11-10
Outgoing NLS peak shaver	Appendix	11-11
Charge state H_2 storage without peak shaver	Appendix	11-12
Unavailability of H_2 (without peak shaver)	Appendix	11-13
H_2 surplus not taken into storage	Appendix	11-14

6.3.1 Step 1

Below, the NLS (figure 6-15) and resulting LDC (figure 6-16) of electricity in scenario 3, step 1 are shown. When comparing this NLS (figure 6-15) to the NLS from the base scenario (figure 6-7), it becomes clear that there is a lot of extra electricity production by the added production technologies (production peaks are now at over 1000 kWh instead of 90 kWh). What is also clearly shown, is that there is a lot of variety in the production. This will pose problems for a grid operator when electricity is fed to the grid, as there has to be a huge capacity available to take in all electricity at peak hours. What also becomes clear from the electricity NLS, is the fact that in winter months (hours 0 to 1500 and 7200 to 8760) the NLS is most dominantly influenced by the production of wind turbines. In the summer months, there is predominantly influence by the solar PV panels. This can be seen in the change of variation in the NLS.

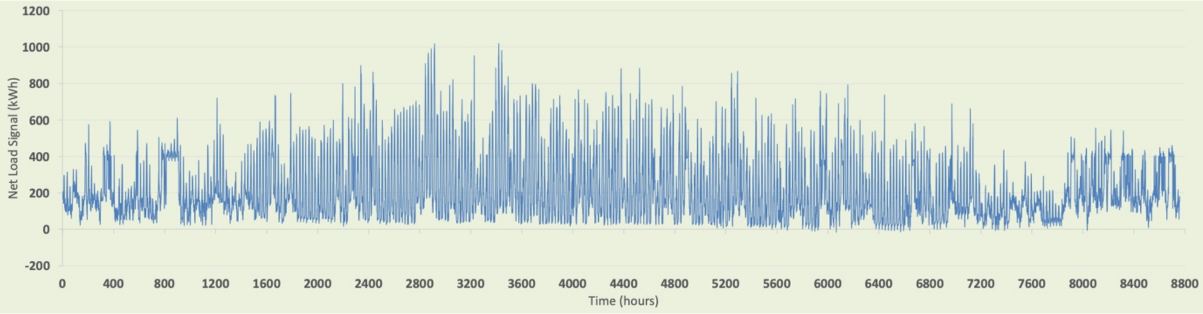


Figure 6-15. NLS of electricity in scenario 3, step 1.

Below, in figure 6-16, the resulting LDC of electricity is shown. When comparing this LDC with the one from the reference scenario, it becomes extra clear that the variety (huge peaks in the blue line in the left of the graph) in the electricity production will result in difficulties for a grid operator. It will be difficult to balance and expensive for a grid operator to take in such an unstable electricity surplus. When comparing the blue line of figure 6-16 to the blue line in figure 6-8, it becomes clear that the peaks in overproduction have increased substantially, and there are still a few hours in the year in which the electricity NLS is still negative, indicating a demand in these hours.

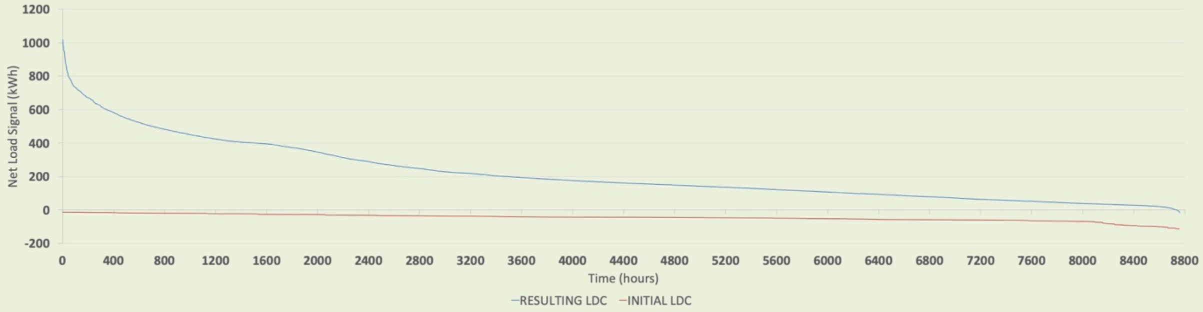


Figure 6-16. The resulting and initial LDC of electricity in scenario 3, step 1.

6.3.2 Step 2

Below, the NLS (figure 6-17), and resulting LDC (figure 6-18) of electricity without battery storage in scenario 3, step 2 are shown. From the NLS it becomes clear that the electrolysis technology and the H_2 storage are able to take up all the excess electricity. However, there are still some demands left in the electricity NLS. The graph of the LDC backs up this conclusion, it also indicates a small demand when looking at the right side in the LDC curve.

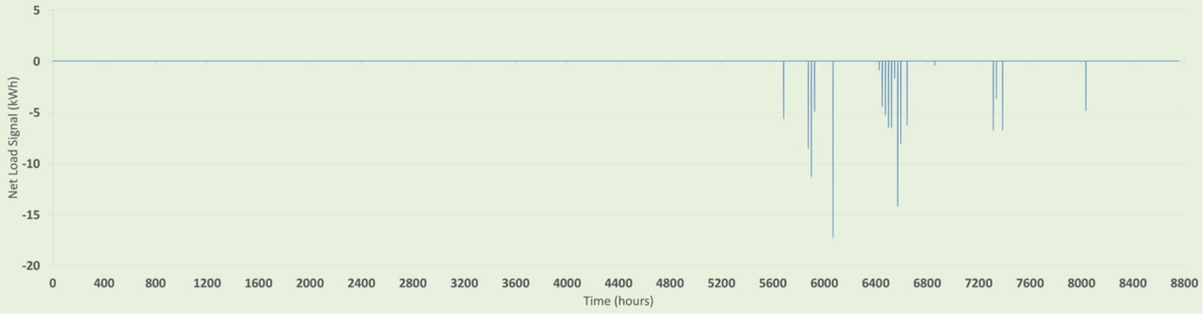


Figure 6-17. NLS of electricity without battery storage in scenario 3, step 2.

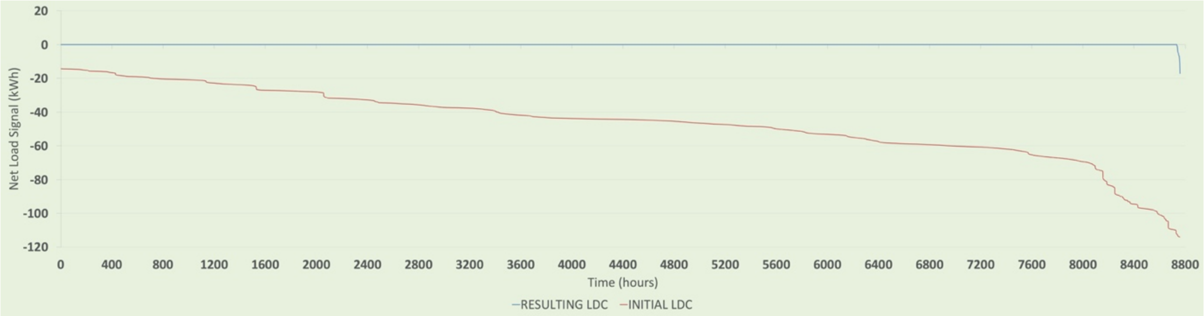


Figure 6-18. The resulting and initial LDC of electricity, without battery storage in scenario 3, step 2.

Below, the NLS (figure 6-19), and resulting LDC (figure 6-20) of electricity with battery storage in scenario 3, step 2 are shown. In this situation, the added battery shows that the electricity NLS can be brought completely to zero, which is backed up by the LDC curve shown below in figure 6-20. An additional graph that indicates the charge state of the used battery storage can be found in the appendix as figure 11-9.

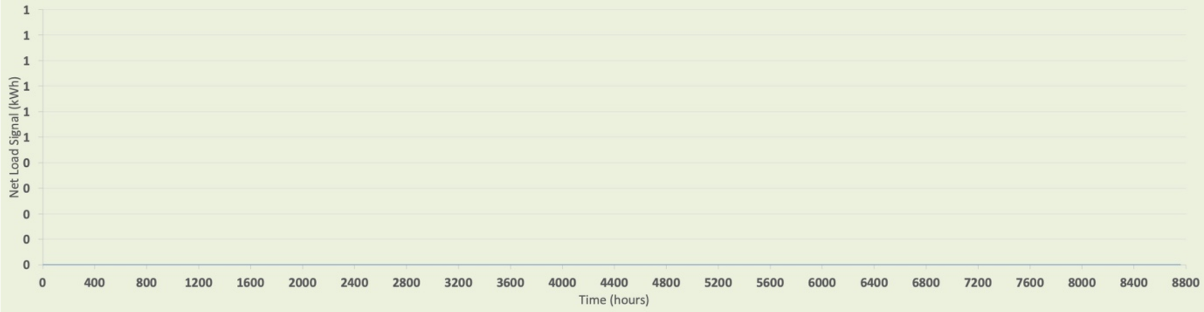


Figure 6-19. NLS of electricity with battery storage in scenario 3, step 2.

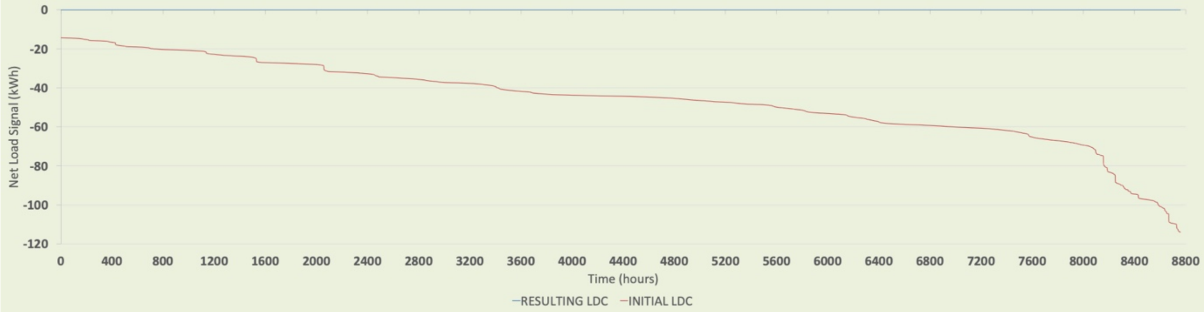


Figure 6-20. The resulting and initial LDC of electricity, with battery storage in scenario 3, step 2.

Below, the production pattern of electrolysis (figure 6-21), the charge state of the H_2 storage (figure 6-22) and the unavailability of H_2 (figure 6-23) are shown. What becomes clear from figure 6-21 is that the electrolysis technology has to be dimensioned to a capacity in which it is able to produce more than 700 kWh if needed, while there are also moments in which it only requires 50 kWh. This is not very efficient. Also, an electrolysis process is not a simple on-off process. It requires a stable input of electricity [21]. Therefore, the incoming NLS of electricity has to be a lot smoother before it can be used.

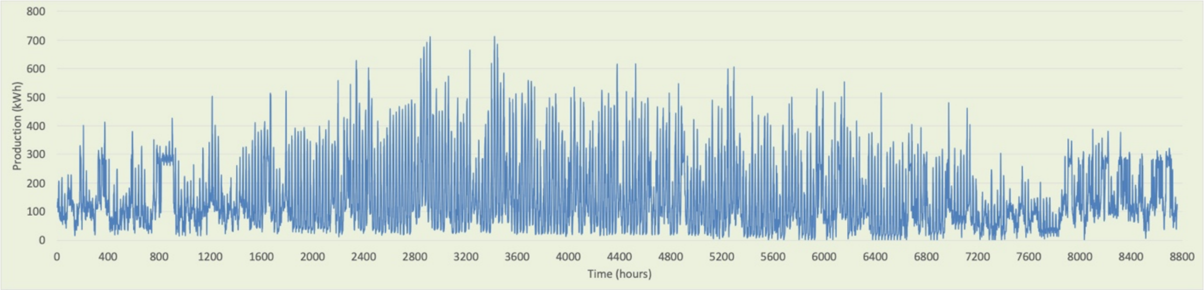


Figure 6-21. The production pattern of the electrolysis technology in scenario 3, step 2.

The charge state below in figure 6-22 indicates a H_2 storage with a capacity of 100000 kWh. With this capacity, and a fill of 20% in the beginning (20000 kWh), the storage is able to store almost all the H_2 that is produced with the excess electricity. In the end of the year, the charge state of the storage is roughly the same as in the beginning, indicating that this works for multiple years in a row. When an hourly outtake of 146 kW is taken, the hydrogen storage only draws empty at around hour 800, as can be seen below. A quick investigation shows that a 100000 kWh storage requires approximately 3000 26L hydrogen storage tanks that can be pressurized up to 700 bars [22].

Figure 6-22. The charge state of the hydrogen storage used in scenario 3, step 2.

The moment the storage is empty, is also visible in figure 6-23 below, which shows the moments in which the storage is not able to provide the wanted 146 kW of H_2, but it can only deliver around 20 kWh (125 kWh short).

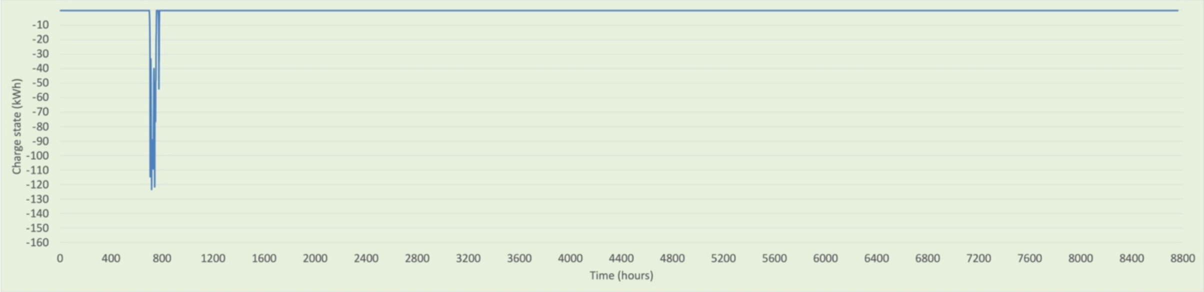


Figure 6-23. The unavailability of H_2 using an hourly outtake of 146 kW, in scenario 3, step 2.

6.3.3 Step 3

Below, the NLS (figure 6-24), and resulting LDC (figure 6-25) of electricity with battery peak shaver in scenario 3, step 3 are shown. The first thing that stands out while looking at the NLS is that the previous peaks that were solved in the demand are back. This is due to the fact that the regular battery storage was deleted and the peak shaver battery was installed. The LDC confirms this suspicion.

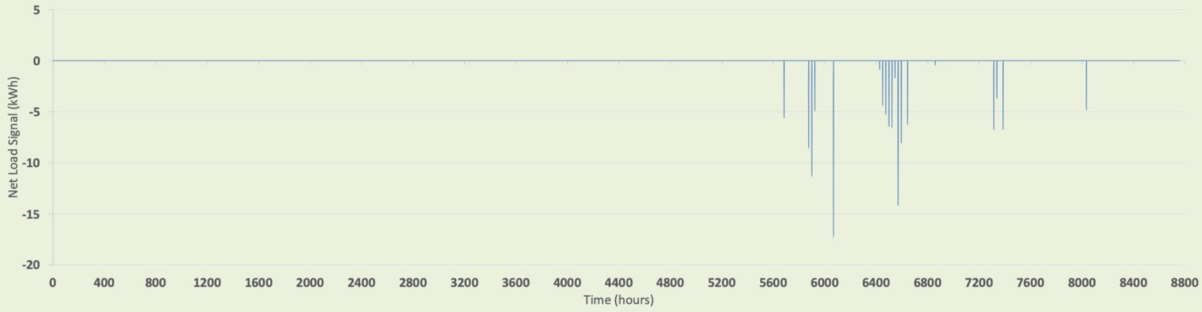


Figure 6-24. NLS of electricity with peak shaver (without regular battery storage) in scenario 3, step 3.

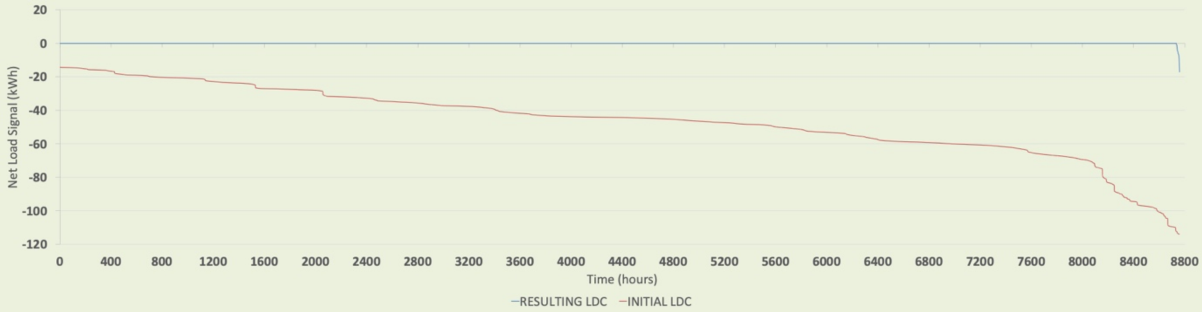


Figure 6-25. The resulting and initial LDC of electricity with peak shaver (without regular battery storage) in scenario 3, step 3.

Below, the production pattern of the electrolysis technology without (figure 6-26) and with (figure 6-27) peak shaver is shown. The electrolysis technology has peaks at around 700 kWh without using a peak shaver, but the peak shaving function can really help to reduce the capacity of the electrolysis technology. In figure 6-27 it is clear to see that the capacity of the electrolysis can be brought back to where it produces 450 kWh at max, rather than 700 kWh. Also, the ingoing electricity signal is a lot smoother, resulting in less stability problems. Two graphs in the appendix (figure 11-10 and 11-11) display the function of the peak shaver battery.

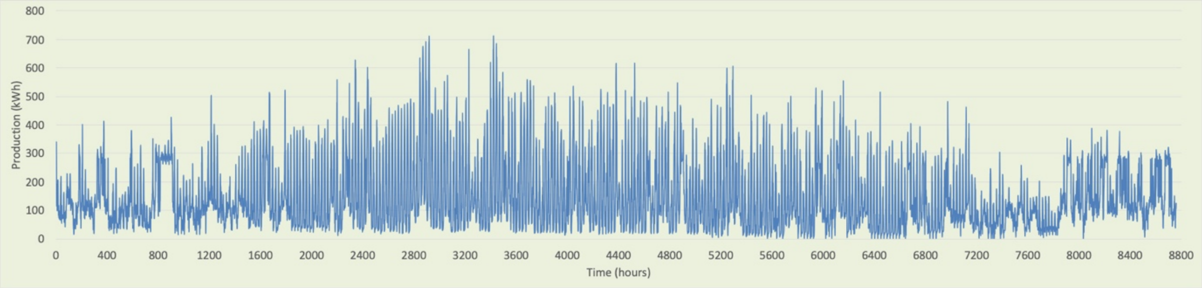


Figure 6-26. The production pattern of the electrolysis technology without a battery peak shaver in scenario 3, step 3.

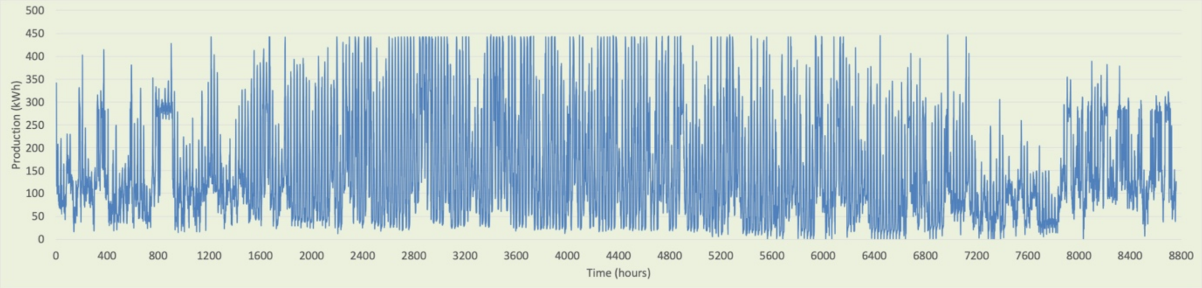


Figure 6-27. The production pattern of the electrolysis technology with a battery peak shaver in scenario 3, step 3.

Below, the charge state of H_2 storage (figure 6-28) and unavailability of H_2 (figure 6-29) are shown. With the battery peak shaver, the H_2 storage can still have the same 100000 kWh size, with only a brief moment around hour 800 in which it is not able to deliver the said 146 kW of H_2 to a user.

Figure 6-28. The charge state of H_2 storage with a battery peak shaver in scenario 3, step 3.

Figure 6-29 below shows that there is indeed again a moment around hour 800 in which the H_2 storage is not able to provide the full 146 kW of H_2. For extra clarification, two graphs of the charge state of H_2 storage and the unavailability of H_2, both without the use of a battery peak shaver, are added to the appendix (figure 11-12 and 11-13) for completeness. Additionally, an extra graph showing the H_2 surplus that is not taken up by the aforementioned H_2 storage is put there as well (figure 11-14). Due to the change from regular battery to a battery with a peak shaver function, a little more electricity is available. This results in the 100000 kWh storage capacity in being a little bit too small. The 100000 capacity was chosen to exactly fit the previous step 2 scenario. Implementing the battery peak shaver therefore calls for an increase in H_2 storage capacity of around 150 kWh, so around 0,15%.

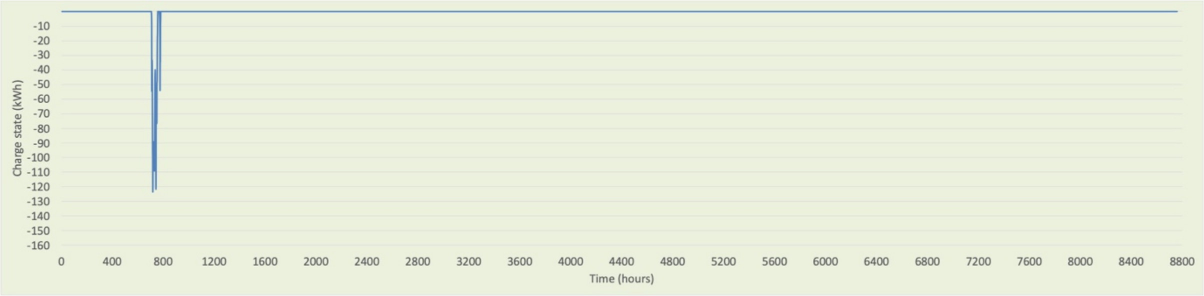


Figure 6-29. The unavailability of hydrogen with a battery peak shaver in scenario 3, step 3.

6.4 Sensitivity analysis

After the model was fully complete, a quick sensitivity analysis was performed to assess which variables in a node, or nodes as a whole, were sensitive to changes. First, it became clear that the demand patterns had a significant influence on the model outcomes. An increase of 10% in the electricity, heat, and fuel demand pattern peaks caused a 10% increase in the needed capacities of energy producing nodes. As a result of this increase, other nodes (storage, conversion) also required substantial increases in capacity. Therefore, it is extremely important that these demand patterns are as accurate as they can be. For the most credible results, it would be perfect if the energy demand patterns could be constructed on real measured hourly data (which is already the case when looking at the Liander household demand patterns).

Other significant variables are the used weather patterns in the wind and solar PV production nodes. A 10% increase of wind speed or solar irradiation (done in a couple of hours) caused a 5-10% increase in the production in those same hours, depending on the wind speed or irradiation. However, there is a maximum production available for a turbine or a solar panel, it will obviously not produce more than what is produced. The capacities of the wind and solar PV nodes are based on fulfilling the demand, and if the production per panel or turbine increases due to a changing weather pattern, the total capacity of the system of panels and turbines has to be increased or decreased. Therefore, a realistic and fitting weather pattern for both irradiation and wind speed is extremely important.

Currently, the AD production pattern is assumed to be constant. This resulted in an exclusion of biogas storage, as the constant supply of biogas was sufficient to fulfil all energy demands that had to be met by biogas. In reality, a production pattern in an AD system is not constant. Decreasing the constant production pattern with 5%, so 5% less available biogas each hour, resulted in a decrease of 5% in delivery of green gas to the national grid. Therefore, it is wise to use a production pattern based on real measurements, to make the results of an investigation like this more accurate. This will then also include the possible need for biogas storage.

In general, all variables in the nodes have an effect on the results of that node, and therefore indirectly a result on the model outcomes. All variables regarding efficiencies etc. have been selected based on available literature. However, not all variables were easy to find in literature, so some assumptions have been made. To further increase the validity of the model, more extensive literature research could result in better results.

7. RESULTS: VALIDATION AND VERIFICATION OF POWER NODES

As described in section 3.6.1, several validation techniques were used to validate the designed model, and as a result also the Power Nodes methodology. Below, all of these validation techniques are listed, together with outcomes that became clear when using the validation technique. Additionally, other important acknowledgements regarding the Power Nodes methodology that were discovered during the modelling process are described as well. Following from these results, a SWOT analysis is performed. This SWOT analysis is overviewed in figure 7-1.

7.1 Comparison to other Models

To validate specific nodes of this model, these nodes were compared to other models that exist, or outcomes of other models (if the model itself was not available for use). The biogas section of this model (AD unit, heat demand AD unit) was compared to the 'Biogas Simulator' model, which was designed by Frank Pierie as a part of the Flexigas project [2]. Additionally, other parts of the model (wind turbines, solar PV panels, battery storage, AD unit) were compared to the 'Clean Energy Design tool' which was also designed by Frank Pierie [23]. Other nodes in this model have not been validated through this validation method.

Remarks regarding Power Nodes methodology:
When comparing this Power Nodes structured model to other models, it immediately became clear that the Power Nodes methodology provides an extremely clear and understandable structure for a model user. It was more difficult to understand and go through the other models. However, this model was designed by the author, and the other models were not designed by the same author, which partly explains why they are difficult to follow. The conceptual model (as described in section 4.1) made the model a lot better understandable. The Clean Energy Design tool had a comparable conceptual model, but this conceptual model was visually more appealing for an end user. The Power Nodes methodology can therefore become more appealing in modelling structure and visualizations.

7.2 Face validity

Face validity of parts of the model has been conducted with multiple people that are all familiar with modelling. Primarily Frank Pierie has looked at the model multiple times, to look at the model's internal relations and the logic in the modelling structure. Additionally, the author has worked together a lot with Anne in 't Veld (who has used the same Power Nodes methodology) to compare and look at each other's models. Also, some nodes that were useful in both models were shared.

Remarks regarding Power Nodes methodology:
During the face validation, it became clear that it is really easy to share nodes with other models that can use the same node. Also, Anne in 't Veld created multiple versions of her model, and she stated that it was really easy to create variations in a model, without the need for starting over completely. Also, it was discovered that both researches struggled with the same issue of feedback loops, and a solution was created to circumvent this problem (as described in section 4.1).

7.3 Traces

When working on the model validation, traces were performed to have an indication of what a value change in one node would mean in other nodes and final results. For example, increasing the small wind turbine production with 5% for each hour, increased the electricity overproduction with around 2-3% in some hours, and roughly 1,5% in other hours. Another example, an increase of 5% in the annual total electricity demand had a significant influence on the final results: all capacities had to be increased by the same amount to still fulfil the electricity demand. This indicates that the demand patterns have a significant influence on the credibility of the results.

Remarks regarding Power Nodes methodology:
During this validation method, it became clear that a model of this size using this methodology structure is actually not suitable to be modelled in Excel. After changing a value, Excel required substantial time (minutes) to recalculate and visualize all the values and graphs. This is not user-friendly, and together with the problem of feedback loops it is credible to say that Excel is not suitable for this modelling structure when using larger models.

7.4 Extreme Conditions Tests

As a method to validate the outcomes of the model, extreme condition tests were performed on all of the sub-modules. In general, all extreme conditions that can occur in a sub-module, were created to see how the model and methodology held up. An example is shown in the table below, table 7-1. In this table, all extreme condition tests for the small wind turbine sub-module are displayed. A full list of all results from the extreme condition tests can be found in the appendix in section 11.4.

Table 7-1. Results of the extreme conditions tests for the small wind turbine sub-module.

Extreme Condition Test	Result/Taken action
Electricity demand is 0	Sub-module still produces energy
Electricity demand is between 0 and maximum capacity of wind turbine	Sub-module still produces energy
Electricity demand is above maximum capacity of wind turbine	Sub-module still produces energy
Wind speed is between 0 and cut-in speed	No production, which is ok. Mistake found in the used power curve, has been fixed.
Wind speed is at rated speed	Maximum production, does not exceed maximum capacity, when going over rated speed.
Wind speed is above maximum speed	Wind turbine cuts out, no production of energy.

Remarks regarding Power Nodes methodology:
Using the extreme conditions tests, a considerable number of mistakes were found. In this case, the choice was made to do the validation of all the sub-modules once the model was finished. However, due to the Power Nodes structure, all sub-modules can function on their own. Therefore, it is wise to validate a sub-module before implementation within the grand model. When validating the model using the extreme conditions test, some errors in the final results were found and it was quite difficult to redirect the cause of these errors as the entire model was put together already.

7.5 General remarks

When constructing and using the model, some other important things were found. First, it became clear that when modelling larger systems (national energy systems, etc.), it will become impossible to model everything specifically in nodes. Adding too many nodes makes the method less clear and less user-friendly. Also, it was discovered that when you want to model for example multiple solar parks using different irradiation patterns, you have to use separate nodes. Also, information streams have to be modelled in a clear way, this is still not as clear as it can be. Power Nodes requires a clear structure like MEFA to really function to its possibilities and clarity.

7.6 SWOT Analysis

Based on the results of using the validation techniques, but also based on the general remarks that occurred during the modelling and use of the model, the SWOT analysis below was created. It shows an overview of strengths and weaknesses of the Power Nodes methodology, as well as possible opportunities and threats.

SWOT ANALYSIS

STRENGHTS

- Strong conceptual model and visualization possibilities.
- Easy to use for unexperienced users.
- Possibility to share and re-use nodes.
- Easy to create several variations of one system.
- Easy to find mistakes due to separate sub-modules.

WEAKNESSES

- Excel: not suitable to use Excel in larger systems.
- NLS connections have to be made manually (easy to fail).
- Difficult to implement two weather patterns in one node.
- Information streams are not always clear.
- Difficult to keep focus in large systems (too many nodes).

OPPORTUNITIES

- Power Nodes can be extremely useful when a general crowd has to use it and understand it.
- There are possibilities to increase user-friendlyness by using a different program (Python, Matlab).
- An increased focus on RE and grid balancing will increase future demand in model structures like these.

THREATS

- If Excel is still used, there is a big chance of malfunctions, especially when models grow in size.
- Easy to lose overview when moving nodes around (connections have to be made manually).
- Other comparable modelling structures might arise when Power Nodes becomes clear for the public (competition).
- Power Nodes requires a clear structure like MEFA.

Figure 7-1. An overview of the SWOT analysis.

8. DISCUSSION

The discussion has been divided into three parts. First, the discussion about the model outcomes and other investigations regarding the first main reseach question is done. After that, the discussion regarding the Power Nodes methodology will follow. In the final section, possibilities for future research will be discussed.

8.1 Discussion regarding model and first research question

After running the reference scenario, it became clear that three demand patterns for the cooperation's energy demand emerged. However, it also became clear that these patterns are built in a monthly fashion: each day has the same hourly pattern during an entire month, only the months themselves differ. This is due to the fact that for the farming part of the energy consumption of the cooperation, no information or demand patterns were available. Therefore, a questionnaire was conducted among agricultural and dairy farmers, to construct demand patterns for the farming practices within the cooperation. To improve the validity of the results, it would be a good choice to use real measured data to construct demand patterns. In the base scenario, the production pattern for the AD unit was assumed to be constant. In reality, this is not the case. Unfortunately, there was no information or production pattern available, and therefore the decision was made to assume a stable production pattern. To improve the validity of the results, a real production pattern should be used. In the final optimization scenario, a 100000 kWh H_2 storage is installed. In reality, this would amount to 3000 26L storage tanks (700 bar). The question is whether this is practically feasible, also from an economic point of view. However, the storage currently outputs a steady 146 kWh of H_2 each hour. If the choice is made to vary this output a bit, so that it corresponds with the incoming produced H_2 (output more in the months when more H_2 is produced, output less in the months when less H_2 is produced), the storage itself can become substantially smaller. The battery with peak shaving function has positively influenced the incoming NLS signal for the electrolysis unit, by reducing the desired capacity from 700 kWh production to 450 kWh of production capacity. However, the variation in the incoming NLS signal is still to fluctuant for an electrolysis unit to run on. It will still be necessary to use some form of storage (battery) to output a stable electricity NLS that can be used by the electrolysis system. It could also be better to just send away the excess electricity, and use a more national scale H_2 system to store the excess energy.

Additionally, some practical limitations arise when thinking about implementing this theoretical case in practice. First, the case itself is based on the surroundings lands of Groningen. In this region, there is sufficient local biomass available to produce biogas. However, if this theoretical cooperation case would be moved somewhere else, it might be the case that there is no sufficient biomass available for the cooperation. Also, the model assumes one giant CHP plant for all 12 farms in the cooperation. In reality, each farm will most likely have their own CHP, which requires transport of biogas from the AD unit to the 12 farms. As a matter of fact, all transport of energy between farms is excluded from this research, but is of significant influence when implemented in practice. For example, the electricity produced by 200 solar panels and 2 wind turbines on each farm has to be transported to the location of the electrolysis and H_2 storage systems.

A key limitation for the practical implementation of this case, is the lack of economic analysis, as well as the environmental impacts of such an energy system. Before it is even possible to think about implementing such a theoretical case, an economic analysis should be done to find out whether this also makes sense from an economic point of view. Additionally, investigating the environmental impacts could show that a system design as in this case can actually be worse for the environment than expected.

8.2 Discussion regarding validation of Power Nodes and second research question

To validate and verify the constructed model, but also the Power Nodes methodology, several validation techniques were used. However, there are more validation techniques available than that were used in this validation. Therefore, to further improve validation of a Power Nodes model, additional validation techniques can be set up to further improve the methodology, but also to further improve the reliability of the results. The main charm of Power Nodes, namely the clarity and user-friendliness are easy to lose when models become too complicated, so a better investigation by using Power Nodes to model a large dynamic system (e.g. a national system), might show other deficiencies in the Power Nodes methodology.

8.3 Possibilities for future research

The conducted investigation shows that there are lots of possibilities for future research, both for the use of the Power Nodes methodology, but also to further investigate the farming cooperation case. In this investigation, a financial analysis has been left out. Also, the sustainable performance of such a farming cooperation setting has not been investigated. The most logical next step is to introduce both to the existing model. However, there are also other possibilities to further investigate the farming cooperation case. For instance, the cooperation case can become cheaper to install if a smaller AD unit is placed, that produces just enough biogas to fulfil the cooperation's own energy demand. Also, maybe the export of H_2 is not the most energy-efficient and easy way to distribute energy. A further analysis could be conducted to investigate what the best way is to distribute produced excess energy, to make the cooperation become an energy provider in the most effective way. Additionally, the individual nodes produced for this model, can be further developed. Some nodes are more sophisticated than others, and some are assembled in a basic fashion. This can definitely be developed further. Furthermore, there are also a lot of possibilities for the Power Nodes methodology itself. The best way to discover whether Power Nodes is a functional method, is to keep using it to model systems, especially systems that are completely different than this. Completely different systems will require a different approach and will therefore lead to different difficulties in modelling and implementation of the Power Nodes methodology. Another future research could investigate whether a theoretical farming case that suffices in Groningen, can also function in different parts of the Netherlands, with different farm sizes and compositions, and different biomass availabilities.

9. CONCLUSION

The conclusion has been divided into two main parts: conclusions regarding the model outcomes and answering the first main question, and conclusions regarding the Power Nodes validation and answering the second main question.

9.1 Conclusions regarding model and first research question

For clarity, the question answered in this section is displayed below, once more.

Research question 1: To what extent can a cooperation of farms become self-sufficient in terms of energy use, and provide balanced energy to the national grid by using biogas production, together with other kinds of renewable energy technologies?

From the results of scenario 1 the demand patterns for the cooperation of farms became clear. That, together with values for yearly demands provided a solid base for the investigation of the main question. The results from scenario 2 indicated that there is a possibility for the farming cooperation to fulfil their entire energy demand (electricity, heat, and fuel) by means of Anaerobic Digestion. There even is a surplus of biogas, which was converted to green gas and then injected into the national gas grid. In some hours, the cooperation was able to inject over 500 kWh's worth of green gas, with an hourly average of around 250 to 300 kWh of green gas, for the entire year. As expected, the green gas surplus was bigger in the summer months, where less gas is consumed to fulfil the heat demand of the cooperation itself. In that sense, the farming cooperation already became an energy provider.

Knowing that the farming cooperation was able to fulfil its own energy demand, it was interesting to find out whether the cooperation can become an energy provider as well, aside from the surplus in green gas. From the results of scenario 3, it became clear that, using 24 15kW wind turbines and a total of 2400 solar PV panels, together with a battery peak shaver, electrolysis technology and H_2 storage, the cooperation can deliver a steady hourly output of around 146 kWh of H_2. This can then be consumed in multiple ways, such as injection in the gas grid, use in the AD unit to increase biogas production, or conversion back into electricity by means of a H_2 powered gas turbine.

As discusses in the previous chapter, there are several practical limitations to implementing an energy system like this. However, if a system like this can utilize biomass waste to produce usable energy, a theoretical farming cooperation can become an important energy provider, on a local or national scale. Even if the decision is made to downscale the energy system so that only the demand of the cooperation is met, an energy system like this can still contribute to lowering fossil fuel consumption, as well as greenhouse gas emissions (partly coming from these fossil fuels).

9.2 Conclusions regarding validation of Power Nodes and second research question

For clarity, the question answered in this section is displayed below.

Research Question 2: Is the Power Nodes method a viable method to model a dynamic energy system that can calculate and display supply and demand on an hourly basis?

To answer this question, several validation and verification techniques were used. Additionally, the actual use of the Power Nodes methodology itself also provided a lot of insights. All insights have been summarized in the SWOT analysis, which in turn clearly displayed several strenghts, weaknesses, opportunities and threats for the Power nodes methodology. Among others, strenghts for the Power Nodes methodology lie in user-friendliness, clear conceptual model thinking, and the possibility to re-use and share nodes and create several variations of one system. Weaknesses lie in the modelling environment, the unclarity in information streams and practical implications, such as the use of multiple weather patterns in one node, and the manual connections of NLS’es between the nodes. There are opportunities in the future when more focus will lie on the integrating of fluctuating energy providers into a balanced grid, but there are also threats for Power Nodes. The ease with which you can move nodes around, also makes it easy to lose track and make mistakes in the connections between nodes. Also, a clear structure like MEFA is required.

10. REFERENCES

[1] J. F. F. P. Bos, J. De Haan, W. Sukkel, and R. L. M. Schils, “Energy use and greenhouse gas emissions in organic and conventional farming systems in the Netherlands,” *NJAS - Wageningen J. Life Sci.*, 2014.

[2] F. Pierie, A. Dsouza, C. E. J. van Someren, R. M. J. Benders, W. J. T. van Gemert, and H. C. Moll, “Improving the sustainability of farming practices through the use of a symbiotic approach for anaerobic digestion and digestate processing,” *Resources*, vol. 6, no. 4, 2017.

[3] Y. Li, S. Y. Park, and J. Zhu, “Solid-state anaerobic digestion for methane production from organic waste,” *Renew. Sustain. Energy Rev.*, vol. 15, no. 1, pp. 821–826, 2011.

[4] S. M. van der Maas, C.W.M.; Coenen, P.W.H.G.;Zijlema, P.J.; Brandes, L.J.; Baas, K.; van den Berghe, G.; van den Born, G.J.; Guis, B.; Geilenkirchen, G.; te Molder, R.; Nijdam, D.S.; Olivier, J.G.J.; Peek, C.J.; van Schijndel, M.W.; van der Sluis, “Greenhouse Gas Emissions in the Netherlands 1990-2007,” *Natl. Invent. Rep.*, vol. 2, no. 5, p. 128, 2009.

[5] SER, “Energy Agreement for Sustainable Growth,” no. september, pp. 1–146, 2013.

[6] S. A. Gebrezgabher, M. P. M. Meuwissen, and A. G. J. M. Oude Lansink, “Energy-neutral dairy chain in the Netherlands: An economic feasibility analysis,” *Biomass and Bioenergy*, vol. 36, pp. 60–68, 2012.

[7] Planbureau voor de Leefomgeving, “Balans van de Leefomgeving 2018,” p. 284, 2018.

[8] M. Berglund and P. Börjesson, “Assessment of energy performance in the life-cycle of biogas production,” *Biomass and Bioenergy*, vol. 30, no. 3, pp. 254–266, 2006.

[9] L. Sokka, S. Pakarinen, and M. Melanen, “Industrial symbiosis contributing to more sustainable energy use - An example from the forest industry in Kymenlaakso, Finland,” *J. Clean. Prod.*, vol. 19, no. 4, pp. 285–293, 2011.

[10] J. P. Barton and D. G. Infield, “Intermittent Renewable Energy,” vol. 19, no. 2, pp. 441–448, 2004.

[11] T. S. Uyar and D. Beşikci, “Integration of hydrogen energy systems into renewable energy systems for better design of 100% renewable energy communities,” *Int. J. Hydrogen Energy*, vol. 42, no. 4, pp. 2453–2456, 2017.

[12] R. U. Ayres, “Industrial Metabolism: Theory and Policy,” 1994.

[13] D. Bartley, C. Brugère, D. Soto, P. Gerber, and B. Harvey, “Comparative assessment of the environmental costs of aquaculture and other food production sectors: methods for meaningful comparisons,” *FAO/WFT Expert Work.*, no. April, pp. 24–28, 2006.

[14] Liander, “Average household demand patterns (electricity & gas).” 2016.

[15] F. Pierie, C. E. J. van Someren, G. A. H. Laugs, and R. M. J. Benders, “A new methodology for modeling local energy systems from a multi-perspective analysis: used for the modeling of an energy independent farming cooperation,” Groningen, 2020.

[16] Robert G. Sargent, “‘Verification and validation of simulation models,’ Simulation

Conference (WSC), Proceedings of the 2010 Winter Simulation Conference," no. January 2011, pp. 166, 183, 2010.

[17] Planbureau voor de Leefomgeving, "Conceptadvies SDE++ 2020 vergisting," 2020.

[18] M. F. Dobre, P., Nicolae F., "Main factors affecting biogas production - an overview:Letters, Romanian Biotechnological," *Rom. Biotechnol. Lett.*, vol. 19, no. 3, pp. 9283–9296, 2014.

[19] F. Pierie, "Personal communication." Groningen, 2020.

[20] M. Oolderink, "Questionnaires agricultural and dairy farms," 2019.

[21] M. Schalenbach, M. Carmo, D. L. Fritz, J. Mergel, and D. Stolten, "Pressurized PEM water electrolysis: Efficiency and gas crossover," *Int. J. Hydrogen Energy*, vol. 38, no. 35, pp. 14921–14933, 2013.

[22] H. C. Technologies, "700 bar Waterstof tank 26L verkoop," 2019. [Online]. Available: https://www.waterstof-centrum.nl/product/700-bar-waterstof-cylinder-26-l-verkoop. [Accessed: 25-Jun-2020].

[23] F. Pierie and A. D'Souza, "The clean energy design tool: design your own local renewable energy system as a community." Groningen, 2015.

[24] P. Ulbig and D. Hoburg, "Determination of the calorific value of natural gas by different methods," *Thermochim. Acta*, vol. 382, no. 1–2, pp. 27–35, 2002.

[25] Autoriteit Consument, "Besluit tot vaststelling van de maximumprijs en de berekening van de eenmalige aansluitbijdrage en het meettarief warmteverbruik per 1 januari 2019," pp. 1–18, 2019.

[26] H. Raheman and A. G. Phadatare, "Diesel engine emissions and performance from blends of karanja methyl ester and diesel," *Biomass and Bioenergy*, vol. 27, no. 4, pp. 393–397, 2004.

[27] Vestas, "2 MW platform," 2019. [Online]. Available: https://www.vestas.com/en/products/2-mw-platform. [Accessed: 14-Dec-2019].

[28] W. T. Models, "Hummer 10 kW," 2019. [Online]. Available: https://en.wind-turbine-models.com/turbines/1689-hummer-h8.16-10kw. [Accessed: 14-Dec-2020].

[29] EAZ Wind, "15 kW EAZ turbine," 2019. .

[30] Wind Turbine Models, "EAZ Wind 15 kW," 2019. [Online]. Available: https://en.wind-turbine-models.com/turbines/2044-eaz-wind-eaz-twelve. [Accessed: 14-Dec-2019].

[31] LG, "LG340n1c-V5," 2020. [Online]. Available: https://www.lg.com/us/business/solar-panels/lg-lg340n1c-v5. [Accessed: 03-Jan-2020].

[32] Tesla, "Tesla PowerPack," 2020. [Online]. Available: https://www.tesla.com/nl_NL/tesla-powerpack. [Accessed: 24-Jan-2020].

[33] MPower UK, "Battery performance characteristics," 2019. [Online]. Available: https://www.mpoweruk.com/performance.htm. [Accessed: 23-Jan-2020].

[34] F. Crotogino, S. Donadei, U. Bünger, and H. Landinger, "Large-Scale Hydrogen Underground Storage for Securing Future Energy Supplies," *18th World Hydrog. Energy Conf. 2010 - WHEC 2010 Parallel Sess. B. 4 Storage Syst. / Policy Perspect.*

Initiat. Co-operations, vol. 78, no. April, p. 10, 2010.

[35] G. Streckiene, V. Martinaitis, A. N. Andersen, and J. Katz, “Feasibility of CHP-plants with thermal stores in the German spot market,” *Appl. Energy*, vol. 86, no. 11, pp. 2308–2316, 2009.

[36] M. Qu, O. Abdelaziz, and H. Yin, “New configurations of a heat recovery absorption heat pump integrated with a natural gas boiler for boiler efficiency improvement,” *Energy Convers. Manag.*, vol. 87, pp. 175–184, 2014.

[37] C. A. Schug, “Operational characteristics of high-pressure, high-efficiency water-hydrogen-electrolysis,” *Int. J. Hydrogen Energy*, vol. 23, no. 12, pp. 1113–1120, 1998.

[38] J. Bekkering, A. A. Broekhuis, and W. J. T. van Gemert, “Optimisation of a green gas supply chain - A review,” *Bioresour. Technol.*, vol. 101, no. 2, pp. 450–456, 2010.

[39] J. D. Van de Ven and P. Y. Li, “Liquid piston gas compression,” *Appl. Energy*, vol. 86, no. 10, pp. 2183–2191, 2009.

11. APPENDICES

In this section, any relevant information that was not described in the main report is placed. First, the conducted questionnaires are shown, together with the results. Additionally, the used variables and values used in the modelling are listed. Furthermore, any side results that came out the scenarios and are not important enough to be in the main report are displayed here. Also, the results of some of the validation techniques are shown here.

11.1 Questionnaires

To produce demand patterns, questionnaires were conducted among local farmers. The questionnaires have been filled in by 2 dairy farmers and 3 agricultural farmers, and the results have been normalized (to convert farm sizes to farm sizes as used in the case by Pierie et. al). Afterwards, the average of the results was taken and these results are shown below in the two averaged questionnaires. Beware, the questionnaires are written in Dutch (to make it easier for the farmers to fill them in).

11.1.1 Averaged results agricultural farms

Verbruiksgegevens boerderijen

Inleiding

Voor mijn onderzoek ben ik bezig met het ontwikkelen van een methode om dynamische energiesystemen te modelleren. Vandaag de dag kunnen de meeste modellen op jaarbasis bepalen of er bijvoorbeeld voldoende energie geproduceerd wordt met zonnepanelen, windmolens of biomassa om aan de energievraag te voldoen. Zoals je misschien wel begrijpt, is de energievraag en de energieproductie niet in elk uur hetzelfde. Dat is ook gelijk het grootste probleem met de oude modellen. Dat er op jaarbasis genoeg energie beschikbaar is, wil niet zeggen dat het ieder uur past bij wat de energievraag is in dat uur.

Om mijn methode te testen, heb ik een dynamisch energiemodel gemaakt in Excel. Dit model is in staat om voor alle uren van het jaar (8760 uren) te bepalen of er op dat uur voldoende energie beschikbaar is om aan de vraag te voldoen. In dit model ga ik uit van een groep boerenbedrijven die samenwerken op het gebied van energieproductie. Deze coöperatie bestaat uit 5 melkveebedrijven en 7 akkerbouwers. De energievraag heb ik onderverdeeld in elektriciteit, aardgas en brandstof (diesel).

Zoals je misschien al kan begrijpen, is het erg belangrijk dat ik de energievraag per uur van de twee types boerderijen in kaart kan brengen. Tegenwoordig hebben veel huishoudens (en boerderijen) slimme meters, waarmee je per uur het verbruik kan zien. Mocht je deze hebben in je bedrijf, en kan je bij deze gegevens, dan hoor ik dat sowieso heel graag! Daarnaast zou ik je willen vragen om onderstaande tabellen in te vullen, dan ga ik proberen om het verbruikspatroon zo realistisch mogelijk samen te stellen. Voor elektriciteit en gas gebruik ik een huishoudens patroon (deze heb ik al) met daarbij opgeteld een bedrijfspatroon, deze hoop ik van jullie te krijgen. Mocht je maandelijkse waarden kunnen aflezen uit je slimme meter, dan zit hierbij natuurlijk het verbruik van het huis ook bij in. Dat maakt niet uit, zolang ik het maar weet.

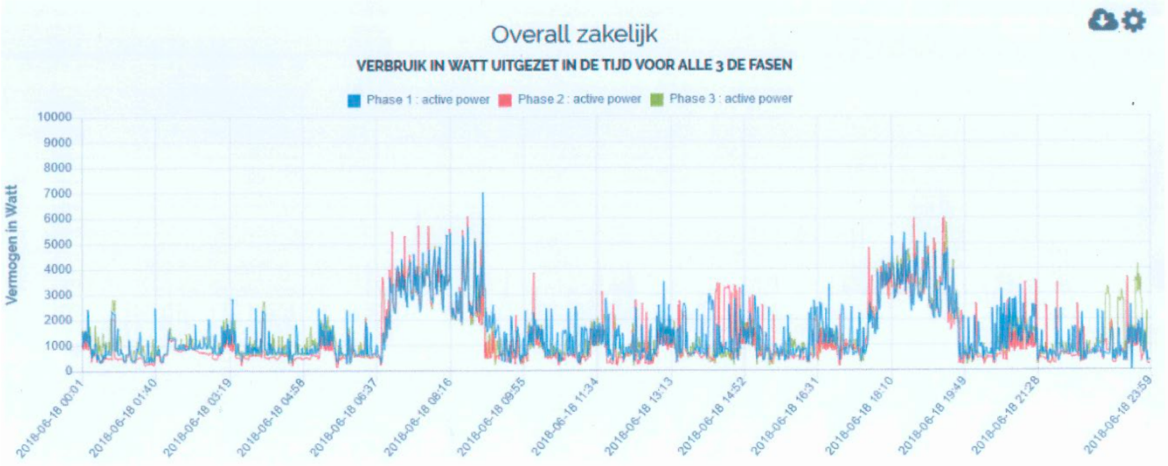
Brandstof

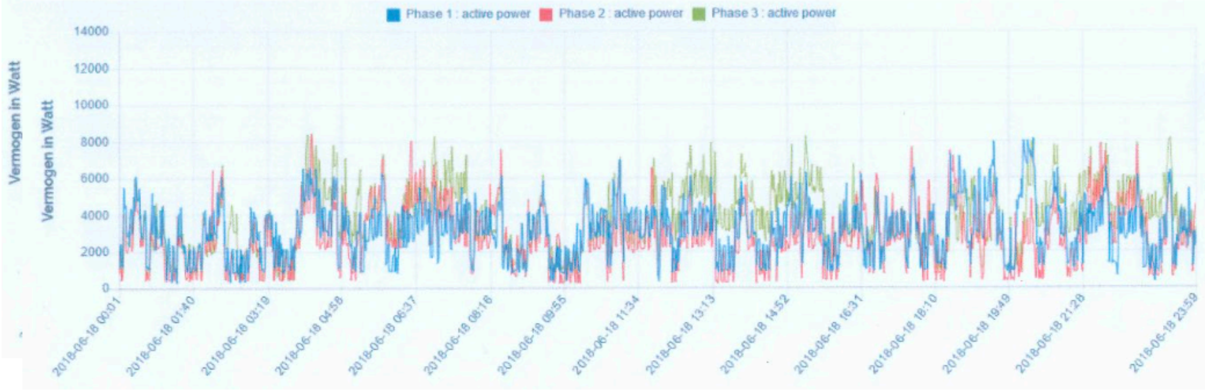
Voor brandstof ga ik uit van diesel. Deze diesel zou alle voertuigen op het boerenbedrijf voorzien. Voor deze brandstof is het belangrijk om te weten hoeveel diesel er op jaarbasis gebruikt wordt. Daarnaast is de verdeling van deze diesel over het jaar interessant. Ik kan me voorstellen dat er in sommige weken in het jaar nauwelijks brandstof wordt gebruikt, en sommige weken juist heel veel. Daarom hoop ik dat je bereid bent om naar je beste weten een inschatting te maken en onderstaande tabel in te vullen. Dit mag voor het afgelopen jaar (2019), aangezien dit het laatste volledige jaar is. Het dieselverbruik mag je invullen in liters, als je hier een inschatting voor kan maken. De 12 maanden bij elkaar opgeteld resulteren dan in het jaarlijkse verbruik. Hoe nauwkeuriger hoe beter, maar het hoeft niet op de liter nauwkeurig! Zolang het maar duidelijk is dat er bijvoorbeeld in september veel meer verbruikt wordt dan in januari.

Maand (2019)	Dieselverbruik
Januari	50
Februari	150
Maart	700
April	2200
Mei	1800
Juni	600
Juli	450
Augustus	650
September	900
Oktober	2200
November	500
December	100
Totaal (maanden opgeteld)	10400

Elektriciteit

Voor elektriciteit zijn meerdere dingen van belang. Ten eerste wat het elektriciteitsverbruik totaal per maand is (om de verschillen per maand weer te geven). In deze maanden ga ik dan uit van dezelfde verdeling van elektriciteit op een dag. Voor 1 dag ga ik bijvoorbeeld voor een melkveehouder uit van onderstaand dagelijks elektriciteitsverbruik. Deze grafiek stelt 24 uur voor, waarin de traditionele melkmomenten ’s morgens en ’s avonds duidelijk te zien zijn. Voor het gebruik van een melkrobot geldt het tweede plaatje (meerdere kleine pieken over de dag).





Ik hoop dan ook dat de akkerbouwers onder jullie voor mij een schetsje kunnen maken hoe het energieverbruik op een dag zou variëren zoals bovenstaand. Dit kan je doen door voor mij onderstaande tabel in te vullen, op de volgende manier: Zie alle uren samen als 100% van het dag verbruik. Voor ieder uur, hoeveel % zou dan in dat uur verbruikt worden? Voor de melkveehouders kan ik dit al doen op basis van de bovenstaande gegevens, helaas heb ik deze niet van akkerbouwbedrijven.

Tijdens koelen van de aardappels (meeste stroomverbruik). Koelmachines staan dag en nacht aan dus vrij stabiel verdeeld.

Uur	Verbruik in % voor akkerbouwers	% voor melkvee (gebaseerd op traditioneel melken plaatje hierboven
0:00	4	2%
1:00	4	2%
2:00	4	2%
3:00	4	2%
4:00	4	2%
5:00	4	2%
6:00	4	2%
7:00	4	10%
8:00	5	10%
9:00	5	3%
10:00	4	4%

11:00	4	3%
12:00	4	4%
13:00	5	3%
14:00	4	4%
15:00	4	3%
16:00	4	4%
17:00	5	3%
18:00	4	10%
19:00	4	10%
20:00	4	4%
21:00	4	4%
22:00	4	4%
23:00	4	3%
Totaal:	100%	100%

Daarnaast vraag ik de melkveehouders en akkerbouwers om onderstaande maandelijkse waarden in te vullen. Dit kan je vaak inzien via je energieleverancier. Alle 12 maanden opgeteld komen dan op je jaarverbruik.

Maand (2019)	Elektriciteitsverbruik
Januari	910
Februari	833
Maart	715
April	540
Mei	371
Juni	211
Juli	189
Augustus	561
September	881
Oktober	1012
November	914
December	981
Totaal (jaarverbruik)	8118

Gasverbruik

Voor gasverbruik werkt het eigenlijk hetzelfde als voor het energieverbruik. Helaas heb ik hier voor de melkveehouderijen ook geen voorbeelden voor, dus ik vraag zowel de melkveehouderijen als de akkerbouwers om onderstaande tabelletjes in te vullen, naar je beste weten. Zoals net, eerst een inschatting per uur, daarna een inschatting per maand.

Uur	Verbruik in % (deel van 100% totaal)
0:00	4
1:00	4
2:00	4
3:00	4

4:00	4
5:00	4
6:00	4
7:00	4
8:00	4
9:00	4
10:00	4
11:00	4
12:00	6
13:00	5
14:00	4
15:00	4
16:00	4
17:00	5
18:00	4
19:00	4
20:00	4
21:00	4
22:00	4
23:00	4
Totaal:	

Maand (2019)	Gasverbruik
Januari	580
Februari	513
Maart	412
April	331
Mei	168
Juni	41
Juli	36
Augustus	247
September	528
Oktober	610
November	596
December	610
Totaal (jaarverbruik)	4672

11.1.2 Averaged results dairy farms

Verbruiksgegevens boerderijen

Inleiding

Voor mijn onderzoek ben ik bezig met het ontwikkelen van een methode om dynamische energiesystemen te modelleren. Vandaag de dag kunnen de meeste modellen op jaarbasis bepalen of er bijvoorbeeld voldoende energie geproduceerd wordt met zonnepanelen, windmolens of biomassa om aan de energievraag te voldoen. Zoals je misschien wel begrijpt, is de energievraag en de energieproductie niet in elk uur hetzelfde. Dat is ook gelijk het grootste probleem met de oude modellen. Dat er op jaarbasis genoeg energie beschikbaar is, wil niet zeggen dat het ieder uur past bij wat de energievraag is in dat uur.

Om mijn methode te testen, heb ik een dynamisch energiemodel gemaakt in Excel. Dit model is in staat om voor alle uren van het jaar (8760 uren) te bepalen of er op dat uur voldoende energie beschikbaar is om aan de vraag te voldoen. In dit model ga ik uit van een groep boerenbedrijven die samenwerken op het gebied van energieproductie. Deze coöperatie bestaat uit 5 melkveebedrijven en 7 akkerbouwers. De energievraag heb ik onderverdeeld in elektriciteit, aardgas en brandstof (diesel).

Zoals je misschien al kan begrijpen, is het erg belangrijk dat ik de energievraag per uur van de twee types boerderijen in kaart kan brengen. Tegenwoordig hebben veel huishoudens (en boerderijen) slimme meters, waarmee je per uur het verbruik kan zien. Mocht je deze hebben in je bedrijf, en kan je bij deze gegevens, dan hoor ik dat sowieso heel graag! Daarnaast zou ik je willen vragen om onderstaande tabellen in te vullen, dan ga ik proberen om het verbruikspatroon zo realistisch mogelijk samen te stellen. Voor elektriciteit en gas gebruik ik een huishoudens patroon (deze heb ik al) met daarbij opgeteld een bedrijfspatroon, deze hoop ik van jullie te krijgen. Mocht je maandelijkse waarden kunnen aflezen uit je slimme meter, dan zit hierbij natuurlijk het verbruik van het huis ook bij in. Dat maakt niet uit, zolang ik het maar weet.

Brandstof

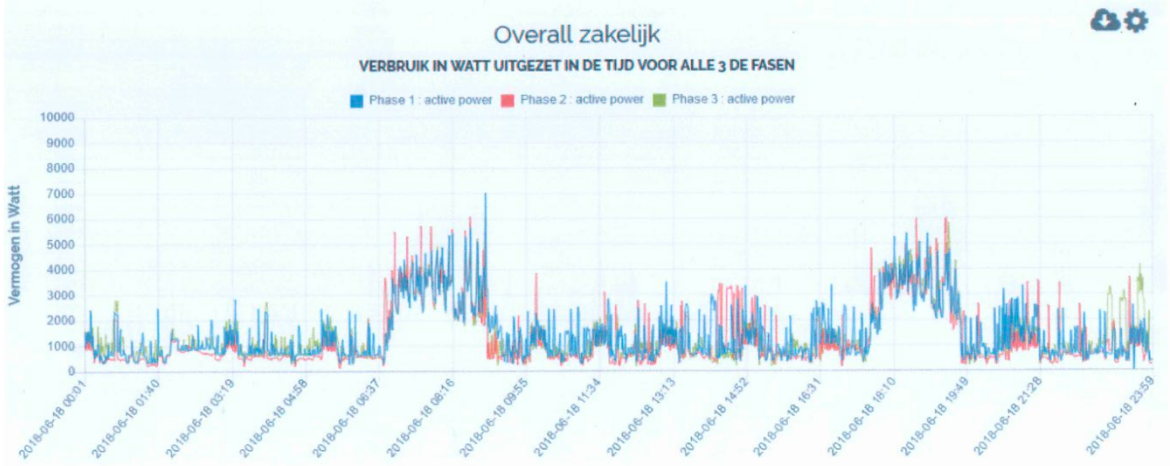
Voor brandstof ga ik uit van diesel. Deze diesel zou alle voertuigen op het boerenbedrijf voorzien. Voor deze brandstof is het belangrijk om te weten hoeveel diesel er op jaarbasis gebruikt wordt. Daarnaast is de verdeling van deze diesel over het jaar interessant. Ik kan me voorstellen dat er in sommige weken in het jaar nauwelijks brandstof wordt gebruikt, en sommige weken juist heel veel. Daarom hoop ik dat je bereid bent om naar je beste weten een inschatting te maken en onderstaande tabel in te vullen. Dit mag voor het afgelopen jaar (2019), aangezien dit het laatste volledige jaar is. Het dieselverbruik mag je invullen in liters, als je hier een inschatting voor kan maken. De 12 maanden bij elkaar opgeteld resulteren dan in het jaarlijkse verbruik. Hoe nauwkeuriger hoe beter, maar het hoeft niet op de liter nauwkeurig! Zolang het maar duidelijk is dat er bijvoorbeeld in september veel meer verbruikt wordt dan in januari.

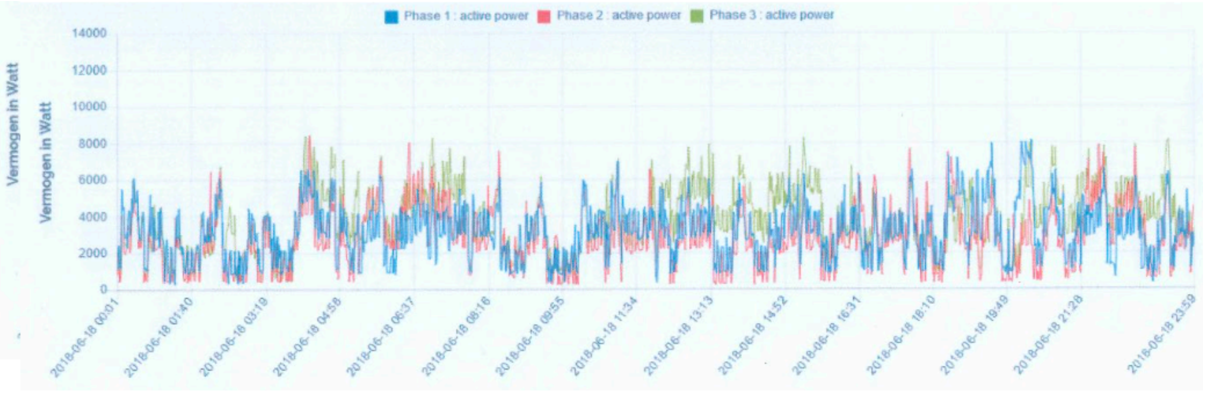
Maand (2019)	Dieselverbruik
Januari	200
Februari	300
Maart	450
April	600
Mei	900
Juni	1100
Juli	1300
Augustus	1100
September	800
Oktober	300

November	200
December	200
Totaal (maanden opgeteld)	7450

Elektriciteit

Voor elektriciteit zijn meerdere dingen van belang. Ten eerste wat het elektriciteitsverbruik totaal per maand is (om de verschillen per maand weer te geven). In deze maanden ga ik dan uit van dezelfde verdeling van elektriciteit op een dag. Voor 1 dag ga ik bijvoorbeeld voor een melkveehouder uit van onderstaand dagelijks elektriciteitsverbruik. Deze grafiek stelt 24 uur voor, waarin de traditionele melkmomenten 's morgens en 's avonds duidelijk te zien zijn. Voor het gebruik van een melkrobot geldt het tweede plaatje (meerdere kleine pieken over de dag).





Ik hoop dan ook dat de akkerbouwers onder jullie voor mij een schetsje kunnen maken hoe het energieverbruik op een dag zou variëren zoals bovenstaand. Dit kan je doen door voor mij onderstaande tabel in te vullen, op de volgende manier: Zie alle uren samen als 100% van het dag verbruik. Voor ieder uur, hoeveel % zou dan in dat uur verbruikt worden? Voor de melkveehouders kan ik dit al doen op basis van de bovenstaande gegevens, helaas heb ik deze niet van akkerbouwbedrijven.

Uur	Verbruik in % voor akkerbouwers	% voor melkvee (gebaseerd op traditioneel melken plaatje hierboven

0:00		2%
1:00		2%
2:00		2%
3:00		2%
4:00		2%
5:00		2%
6:00		2%
7:00		10%
8:00		10%
9:00		3%
10:00		4%
11:00		3%
12:00		4%
13:00		3%
14:00		4%
15:00		3%
16:00		4%
17:00		3%
18:00		10%
19:00		10%
20:00		4%
21:00		4%
22:00		4%
23:00		3%
Totaal:		100%

Daarnaast vraag ik de melkveehouders en akkerbouwers om onderstaande maandelijkse waarden in te vullen. Dit kan je vaak inzien via je energieleverancier. Alle 12 maanden opgeteld komen dan op je jaarverbruik.

Maand (2019)	Elektriciteitsverbruik
Januari	680
Februari	633
Maart	461
April	405
Mei	310
Juni	239
Juli	214
Augustus	363
September	380
Oktober	502
November	641
December	807
Totaal (jaarverbruik)	5635

Gasverbruik

Voor gasverbruik werkt het eigenlijk hetzelfde als voor het energieverbruik. Helaas heb ik hier voor de melkveehouderijen ook geen voorbeelden voor, dus ik vraag zowel de melkveehouderijen als de akkerbouwers om onderstaande tabelletjes in te vullen, naar je beste weten. Zoals net, eerst een inschatting per uur, daarna een inschatting per maand.

Uur	Verbruik in % (deel van 100% totaal)
0:00	3
1:00	3
2:00	2
3:00	2
4:00	2
5:00	2
6:00	5
7:00	10
8:00	15
9:00	3
10:00	2
11:00	2
12:00	2
13:00	2
14:00	2
15:00	2
16:00	2
17:00	2
18:00	5
19:00	10
20:00	15
21:00	3
22:00	2
23:00	2
Totaal:	100

Maand (2019)	Gasverbruik
Januari	377
Februari	339
Maart	210
April	173
Mei	55
Juni	40
Juli	29
Augustus	28
September	71
Oktober	111
November	236
December	312
Totaal (jaarverbruik)	1981

11.2 Variables modelling

In this section, all the variables and values used in the modelling are listed. They are sorted per type of node. First, the demand nodes are shown. After the demand nodes, the production, storage, conversion and upgrade nodes follow subsequently.

11.2.1 Demand nodes

11.2.1.1 Electricity demand

Table 11-1. Important values for the electricity demand node.

Variable	Value	Unit	Source
Demand dairy farm house	3500	kWh/a	[2]
Demand dairy farm farm	30000	kWh/a	[2]
Demand agricultural farm house	3500	kWh/a	[2]
Demand agricultural farm farm	30000	kWh/a	[2]
Number of dairy farms	5	farms	[2]
Number of agricultural farms	7	farms	[2]
Total	402000	kWh/a	-
Demand pattern	EXCEL	EXCEL	-

11.2.1.2 Heat demand

Table 11-2. Important values for the heat demand node.

Variable	Value	Unit	Source
Demand dairy farm house	2500	kWh/a	[2]
Demand dairy farm farm	1000	kWh/a	[2]
Demand agricultural farm house	2500	kWh/a	[2]
Demand agricultural farm farm	2000	kWh/a	[2]
Calorific value gas	35	MJ/Nm^3	[24]
Conversion factor	9,749	kWh/Nm^3	-
Common boiler efficiency for demand pattern	87,5	%	[25]
Total heat demand	417984	kWh/a	-
Demand pattern	EXCEL	EXCEL	-

11.2.1.3 Fuel demand

Table 11-3. Important values for the fuel demand node.

Variable	Value	Unit	Source
Diesel demand dairy farm	7450	L/a	[20]
Diesel demand agricultural farm	10400	L/a	[20]
Calorific value diesel	42	MJ/L	[26]
Conversion factor	10	kWh/L	-
Total fuel demand	1100500	kWh/a	-
Demand pattern	EXCEL	EXCEL	-

11.2.1.4 AD Heat demand

Table 11-4. Important values for the AD heat demand node.

Variable	Value	Unit	Source
Heat use per Nm_3	1,92	MJ/Nm_3	[17]
KNMI temp pattern 2011	EXCEL	-	[19]
Digester temperature	42	Degrees C.	[19]

11.2.2 Production nodes

11.2.2.1 Wind 2 MW

Power curve 2 mw wind turbine:

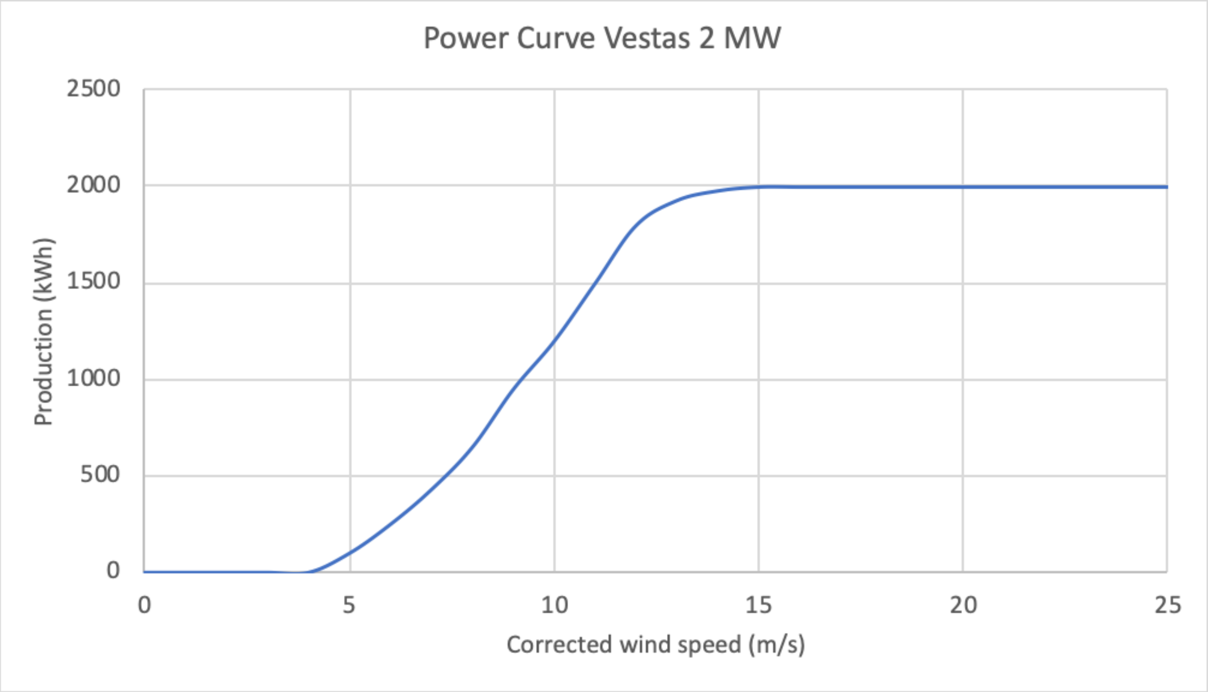


Figure 11-1. The used Power Curve for the 2 MW wind turbine[27].

Additional values wind turbine:

Table 11-5. Important values for the 2 MW wind turbine node.

Variable	Value	Unit	Source
Power output	2	MW	[27]
Turbine efficiency	100	%	(already in power curve)
Reformer efficiency	100	%	(not taken into account)
Cut-in speed	4	m/s	[27]
Cut-off speed	25	m/s	[27]
Rated speed	15	m/s	[27]
Hub height	80	m	[27]
Height measurement location	10	m	[19]
Roughness location	0,055	-	[19]
Wind pattern	EXCEL	EXCEL	[19]

11.2.2.2 Wind 15 kW

Power curve 15 kw wind turbine:

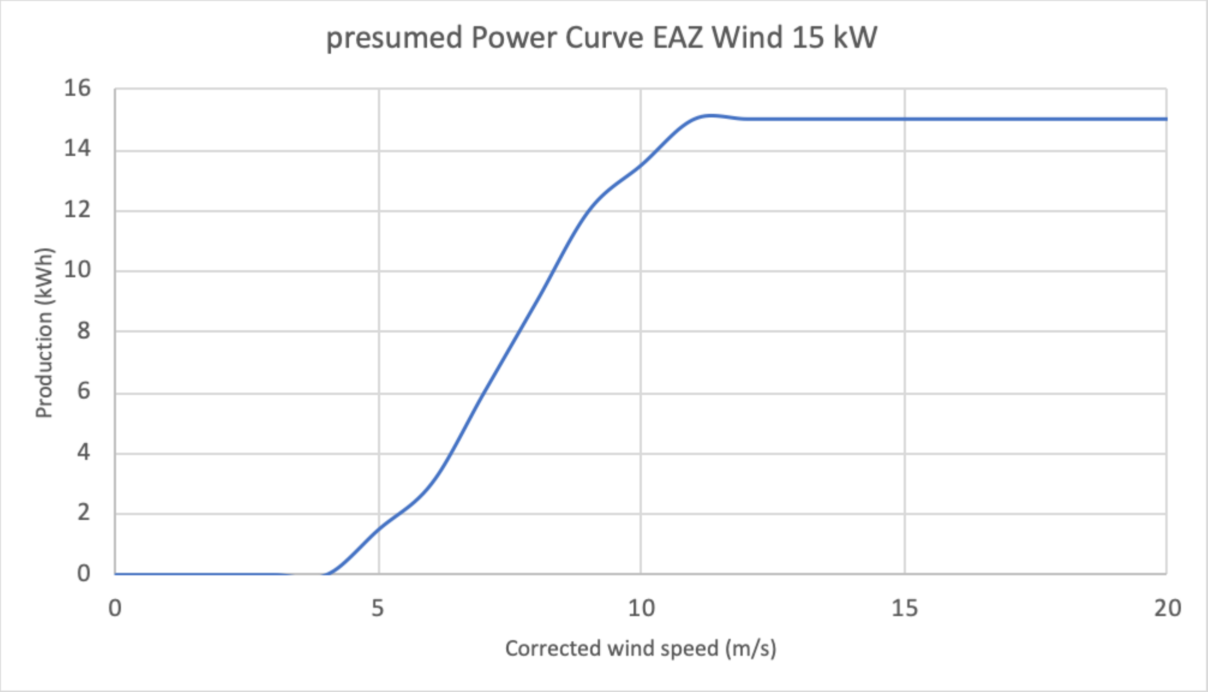


Figure 11-2. The used Power Curve for the 15 kW wind turbine[28].

Additional values wind turbine:

Table 11-6. Important values for the 15kW wind turbine node.

Variable	Value	Unit	Source
Power output	15	kW	[29]
Turbine efficiency	100	%	(already in power curve)
Reformer efficiency	100	%	(not taken into account)
Cut-in speed	2,5	m/s	[30]
Cut-off speed	20	m/s	[30]
Rated speed	8,5	m/s	[30]
Hub height	15	m	[29], [30]
Height measurement location	10	m	[19]
Roughness location	0,055	-	[19]
Wind pattern	EXCEL	EXCEL	[19]

11.2.2.3 Solar PV-panel

Table 11-7. Important values for the solar PV node.

Variable	Value	Unit	Source
Power output	340	Wp	[31]
Panel efficiency	19,8	%	[31]
Inverter efficiency	100	%	(not taken into account)
Surface area per panel	1,71	m^2/panel	[31]
Irradiation pattern	EXCEL	EXCEL	[19]

11.2.2.4 Anaerobic Digestion

Table 11-8. Important values for the AD production node.

Variable	Value	Unit	Source
Annual production	1203886,8	Nm^3/a	[2]
Methane content	56	%	[2]
Calorific value methane	35	MJ/Nm^3	[2]
Conversion factor	3,6	-	-
Production pattern	EXCEL	EXCEL	[19]

11.2.3 Storage nodes

11.2.3.1 Regular battery storage

Table 11-9. Important values for the regular battery storage node.

Variable	Value	Unit	Source
Capacity	25	kWh	-
Max charge power	600	kW/h	[32], [33]
Max discharge power	600	kW/h	[32], [33]
Max depth of discharge	99,99	%	[32]
Self-discharge efficiency	0,001	%/h	[33]
Charge efficiency	98	%	[32], [33]
Discharge efficiency	98	%	Assumed based on charge efficiency above
Start stage	0	kWh	-

11.2.3.2 Battery with peak shaving function

Table 11-10. Important values for the battery peak shaver node.

Variable	Value	Unit	Source
Capacity	2400	kWh	-
Max charge power	800	kW/h	Assumed possible, based on [32]
Max discharge power	300	kW/h	[32], [33]
Max depth of discharge	99,99	%	[32]
Self-discharge efficiency	0,001	%/h	[33]
Charge efficiency	95	%	Asssumed bit lower due to amount of charges
Discharge efficiency	95	%	Assumed equal to charge efficiency
Start stage	500	kWh	- (chosen to start up peak shaving function)
Charge threshold	600	kWh	-
Discharge threshold	250	kWh	-

11.2.3.3 H_2 storage

Table 11-11. Important values for the H_2 storage node.

Variable	Value	Unit	Source
Capacity	100000	kWh	-
Max charge power	700	kW/h	[34]
Max discharge power	600	kW/h	[34]
Max depth of discharge	99,99	%	[34]
Self-discharge efficiency	0,001	%/h	Assumed based on previous self-discharge eff.
Charge efficiency	98	%	[34]

Discharge efficiency	98	%	Assumed to be the same as charge efficiency
Start stage	23000	kWh	-
Hourly output hydrogen	146	kWh	-

11.2.3.4 *Biogas storage*

Table 11-12. Important values for the biogas storage node.

Variable	Value	Unit	Source
Capacity	0	kWh	Eventually not used in model
Max charge power	-	kW/h	Eventually not used in model
Max discharge power	-	kW/h	Eventually not used in model
Max depth of discharge	-	%	Eventually not used in model
Self-discharge efficiency	-	%/h	Eventually not used in model
Charge efficiency	-	%	Eventually not used in model
Discharge efficiency	-	%	Eventually not used in model
Start stage	-	kWh	Eventually not used in model

11.2.3.5 *Green fuel storage*

Table 11-13. Important values for the green fuel storage node.

Variable	Value	Unit	Source
Capacity	6500	kWh	-
Max charge power	1000	kW/h	Assumed possible based on filling speed at gas stations
Max discharge power	6500	kW/h	Assumed possible based on filling speed at gas stations
Max depth of discharge	99	%	Always some left in an empty tank (1 bar)
Self-discharge efficiency	1	%/h	Assumed 1%, could be less
Charge efficiency	100	%	Assumed no leaks
Discharge efficiency	100	%	Assumed no leaks
Start stage	250	kWh	-
Natural gas threshold	30	%	-

11.2.4 Conversion nodes

11.2.4.1 *CHP*

Table 11-14. Important values for the CHP node.

Variable	Value	Unit	Source
Capacity	255	kWh	-
Heat recovery efficiency	80	%	[35]
Electrical efficiency	35	%	[35]

11.2.4.2 *Gas boiler*

Table 11-15. Important values for the gas boiler node.

Variable	Value	Unit	Source
Capacity	0	kWh	-
Thermal efficiency	75	%	[36]

11.2.4.3 *Electrolysis technology*

Table 11-16. Important values for the electrolysis node.

Variable	Value	Unit	Source
Capacity	645	kWh	-
Conversion efficiency	70	%	[37], [21]

11.2.5 Upgrade nodes

11.2.5.1 *Green gas upgrader*

Table 11-17. Important values for the green gas upgrader node.

Variable	Value	Unit	Source
Capacity	600	kWh	-
Upgrading efficiency	95	%	[38]

11.2.5.2 *Green fuel upgrader*

Table 11-18. Important values for the green fuel upgrader node.

Variable	Value	Unit	Source
Capacity	300	kWh	-
Upgrading efficiency	85	%	[39]

11.3 Side results modelling

In this section, the side results of the modelled scenarios are listed. These side results are listed per scenario, as described in chapter 5.

11.3.1 Side results scenario 2

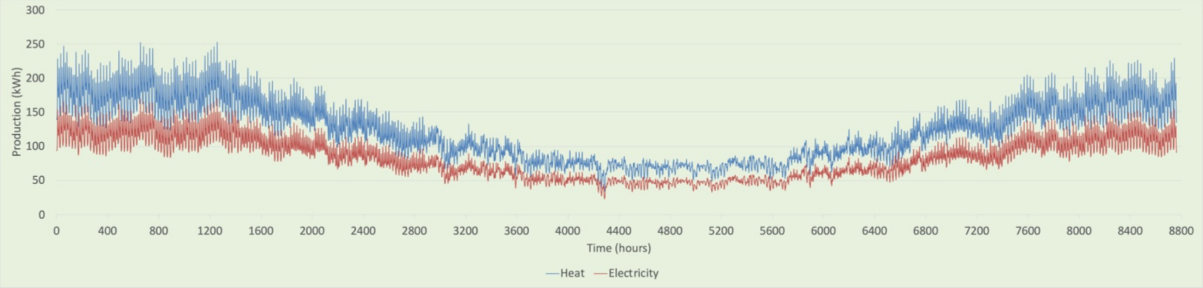


Figure 11-3. The CHP production pattern in scenario 2.

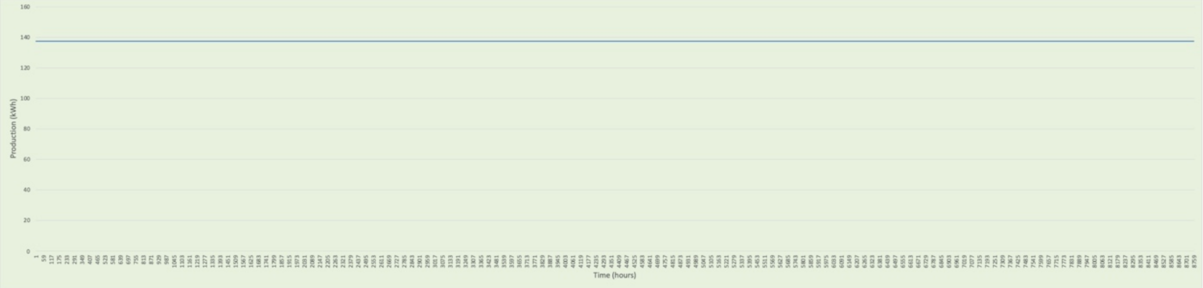


Figure 11-4. The AD production pattern in scenario 2.

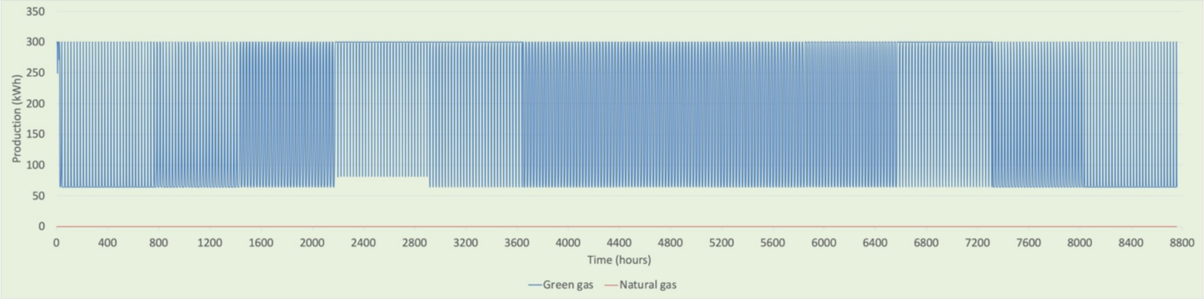


Figure 11-5. The green fuel upgrading production pattern in scenario 2.

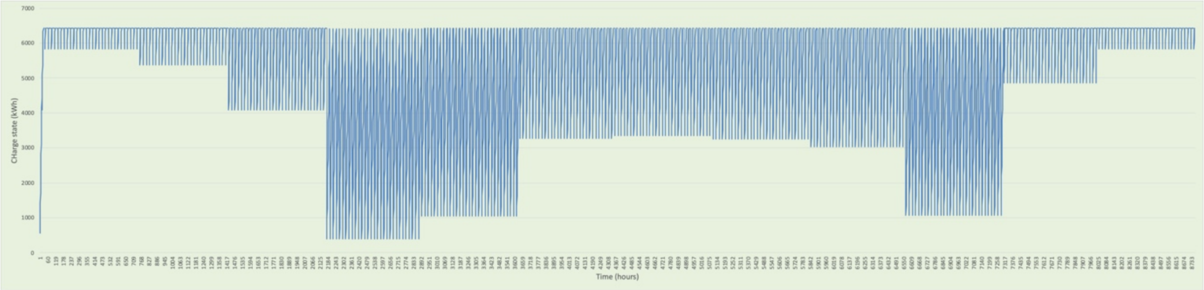


Figure 11-6. The charge state of the green fuel storage in scenario 2.

11.3.2 Side results scenario 3, step 1

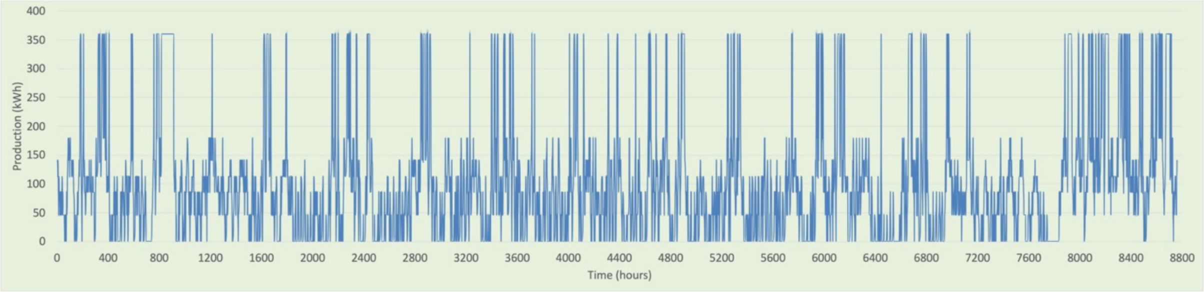


Figure 11-7. The production pattern of 24 installed 15 kW wind turbines in scenario 3, step 1.

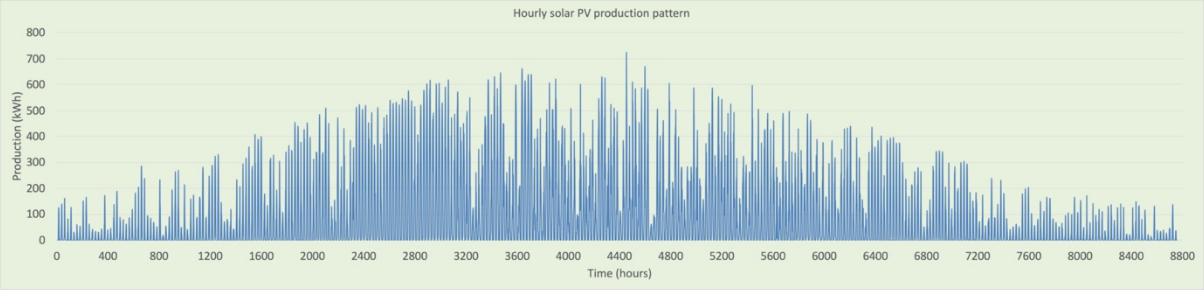


Figure 11-8. The production pattern of 2400 installed solar PV panels in scenario 3, step 1.

11.3.3 Side results scenario 3, step 2

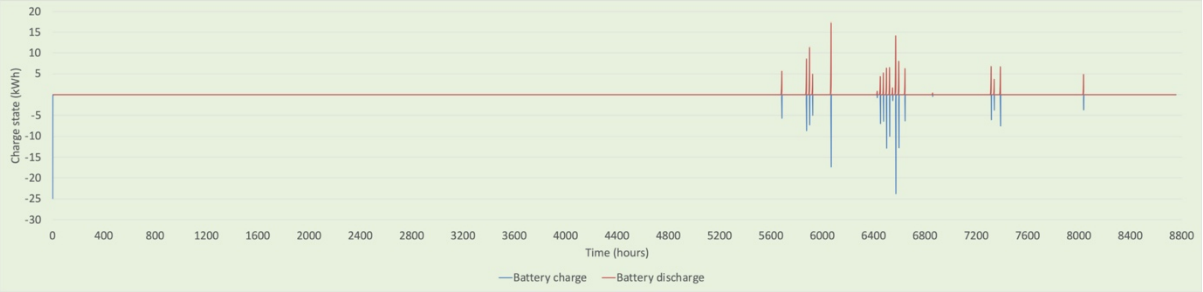


Figure 11-9. The charge state of the installed regular battery storage in scenario 3, step 2.

11.3.4 Side results scenario 3, step 3

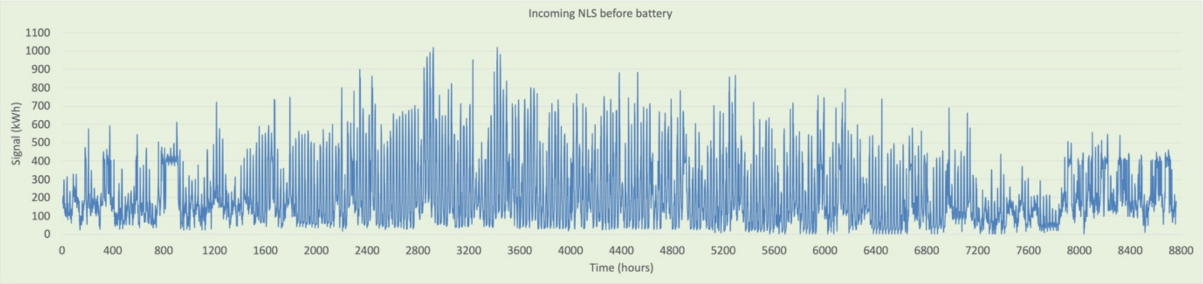


Figure 11-10. Incoming NLS before battery peak shaver in scenario 3, step 3.

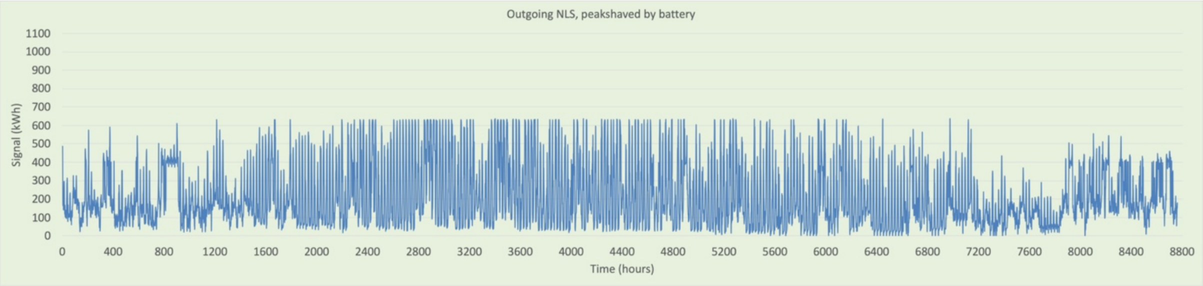


Figure 11-11. Outgoing NLS after battery peak shaver in scenario 3, step 3.

Figure 11-12. Charge state of H_2 storage without using a battery peak shaver in scenario 3, step 3.

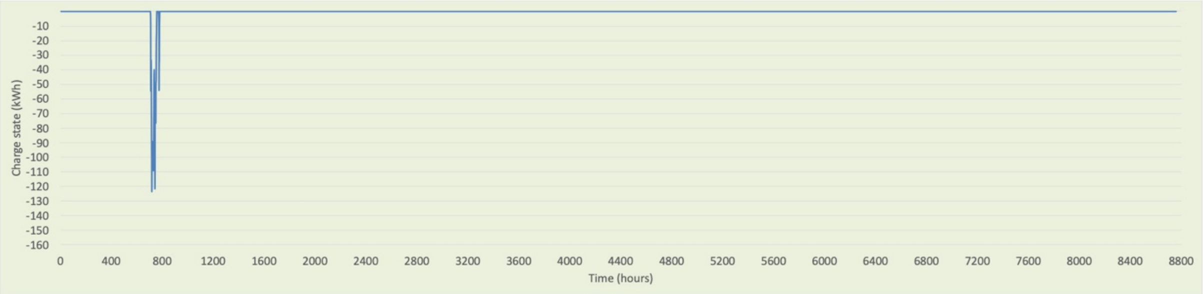


Figure 11-13. The unavailability of hydrogen without using a battery peak shaver in scenario 3, step 3.

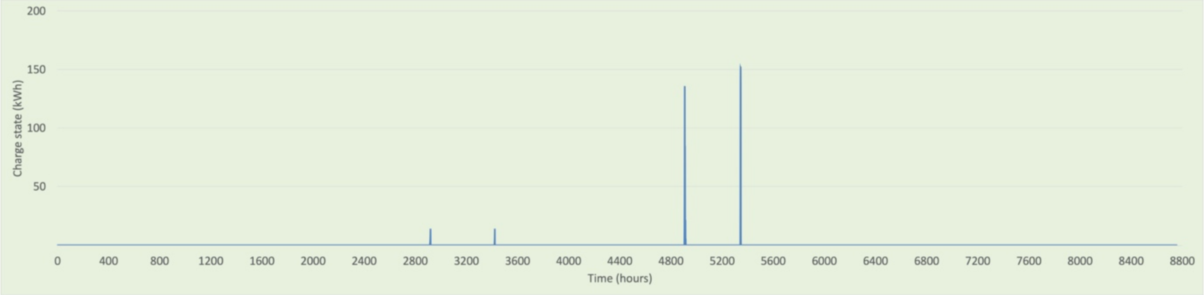


Figure 11-14. The remaining H2 that the storage is not able to take up in scenario 3, step 3.

11.4 Results Extreme Conditions Tests.

Table 11-19. Results of the extreme conditions tests of the large wind turbine sub-module.

Extreme Condition Test	Result/Taken action
Electricity demand is 0	Sub-module still produces energy.
Electricity demand is between 0 and maximum capacity of wind turbine	Sub-module still produces energy.
Electricity demand is above maximum capacity of wind turbine	Sub-module still produces energy.
Wind speed is between 0 and cut-in speed	No production.
Wind speed is at rated speed	Maximum production, does not exceed maximum capacity, when going over rated speed.
Wind speed is above maximum speed	Wind turbine cuts out, no production of energy.

Table 11-20. Results of the extreme conditions tests of the solar PV panels sub-module.

Extreme Condition Test	**Result/Taken action**
Electricity demand is 0	Sub-module still produces energy.
Electricity demand is between 0 and maximum capacity of solar panels	Sub-module still produces energy.
Electricity demand exceeds maximum capacity	Sub-module still produces energy.
Solar pattern is 0	No production of energy.
Solar pattern is between 0 and maximum capacity	Produces what is possible with available irradation.
Solar pattern exceeds max cap	Mistake found; maximum capacity was not taken into account. Now it does not produce more than maximum capacity.

Table 11-21. Results of the extreme conditions tests of the regular battery storage sub-module.

Extreme Condition Test	**Result/Taken action**
Electricity demand is 0	Nothing charged, nothing discharged.
Electricity demand is between 0 and maximum discharge of battery storage	Demand is discharged if available.
Electricity demand exceeds maximum discharge capacity of battery storage	Only maximum discharge is discharged.
Electricity demand is between 0 and available charge	Demand is discharged if available.
Electricity available is between 0 and maximum charge capacity of battery storage	Available charge is charged, unless full.

Electricity available is above maximum charge capacity of battery storage	Only maximum charge capacity is charged.
Electricity available is between 0 and available capacity	Available is stored until storage is full. Mistake found, fixed.

Table 11-21. Results of the extreme conditions tests of the battery with peak shaver function sub-module.

Extreme Condition Test	Result/Taken action
Electricity NLS is 0	Nothing charged, nothing discharged.
Electricity NLS is between 0 and charge threshold	Nothing is charged
Electricity NLS exceeds charge threshold	Everything above charge threshold is stored.
Electricity NLS is below discharge threshold	Electricity is discharged up to discharge threshold value, if available.
Electricity NLS asks for charge, but charge state is 100% full	Available charge is charged, unless full.
Electricity NLS asks for discharge, but charge state is completely empty	Available discharge is discharged, unless empty.

Table 11-22. Results of the extreme conditions tests of the CHP sub-module.

Extreme Condition Test	Result/Taken action
Heat demand is 0	No heat/elec production, no gas use. Mistake found in incoming NLS, fixed.
Heat demand is between 0 and max cap	Produces desired heat, unless no gas available
Heat demand is above max cap	Produces maximum capacity of heat, unless no gas available
Heat available (no demand)	No production of heat and electricity.

Table 11-23. Results of the extreme conditions tests of the gas boiler sub-module.

Extreme Condition Test	Result/Taken action
Heat demand is 0	No heat production, no gas use.
Heat demand is between 0 and max cap	Produces desired heat, unless no gas available
Heat demand is above max cap	Produces maximum capacity of heat, unless no gas available
Heat available (no demand)	No production. Mistake found, fixed.

Table 11-24. Results of the extreme conditions tests of the green gas upgrader sub-module.

Extreme Condition Test	Result/Taken action
Gas available is below max cap	All is upgraded
Gas available is above max cap	Only max cap is upgraded
Gas available is 0	No upgrading.

Table 11-25. Results of the extreme conditions tests of the biogas storage sub-module.

Extreme Condition Test	Result/Taken action
Biogas demand is 0	Nothing stored, nothing discharged
Biogas demand is between 0 and max discharge	Demand is discharged, unless empty
Biogas demand is above max discharge	Only max discharge is discharged
Biogas demand is between 0 and max charge	Available is charged, unless full
Biogas available is above max charge	Only max charge is charged
Biogas available is 0 and available cap.	Available is stored until full.

Table 11-26. Results of the extreme conditions tests of the green fuel storage sub-module.

Extreme Condition Test	Result/Taken action
Fuel demand is 0	No charge/discharge
Fuel demand is between 0 and max discharge	Demand is discharged, unless empty
Fuel demand is above max discharge	Only max discharge is discharged. Mistake found, fixed
Fuel demand is between 0 and available discharge	Available is discharged unless full
Fuel available is between 0 and max charge	Available is charged, unless full.
Fuel available is above max charge	Only max charge is charged, unless full
Fuel available is between 0 and available capacity	Available is charged, unless full

Table 11-27. Results of the extreme conditions tests of the green fuel upgrader sub-module.

Extreme Condition Test	Result/Taken action
Green fuel storage wants fuel	Upgrade amount that is wanted to fill storage
Green fuel storage is full	No upgrading
Green storage wants more than max cap	Only max cap is delivered
Green storage wants more than available in green gas	Only available is produced and stored. Mistake found in calculation, fixed.
Green fuel is below nat gas threshold	Nat gas is upgraded that hour
Green fuel is above nat gas threshold	Only green gas is upgraded that hour
Green fuel is nat gas threshold	Only green gas is upgraded that hour

Table 11-28. Results of the extreme conditions tests of the electrolysis sub-module.

Extreme Condition Test	Result/Taken action
If elec surplus between 0 and max cap	All surplus used in electrolysis. Mistake found, fixed by updating NLS.
If elec surplus above max cap	Only max cap used in electrolysis
If elec NLS is 0	No electrolysis
If elec NLS < 0	No electrolysis

Table 11-29. Results of the extreme conditions tests of the H_2 storage sub-module.

Extreme Condition Test	Result/Taken action
H_2 demand is 0	No charge/discharge
H_2 demand is between 0 and max discharge	Discharged if available
H_2 demand is above max discharge	Only max discharge is discharged
H_2 demand is between 0 and available charge	Charge until full
H_2 available is between 0 and max charge	Charge all available until full
H_2 available is above max charge	Charge only max charge
H_2 available is between 0 and available capacity	Charge until full. Mistake found, did not take max capacity into account. Fixed.