RES Groningen

Exploring different energy strategies for the RES region of Groningen to contribute to a CO2 neutral hourly electricity supply

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SUMMARY

In June of 2019, the Dutch government signed the Climate Agreement (Klimaat Akkoord) in which they laid out their plans on how to reduce Dutch greenhouse gas emissions by 49% compared to 1990 by 2030. One way of achieving this is to switch to renewable electricity production. In the Climate Agreement the goal of a total electricity production from renewables of 84 TWh in 2030 is formulated. A large share of this target, 49 TWh, will be met by installing capacity of wind at sea. The remaining 35 TWh will be realized by wind- and solar parks on land. This target does not include solar energy production on rooftops but is focused on large scale generation (>15kW). In order to achieve this target, 30 regions within the Netherlands have to state how much they are willing to contribute in a Regional Energy Strategy (RES). One of these regions is the province of Groningen.

The province of Groningen, consisting of 12 municipalities, has voiced its ambition on becoming a leader in the energy transition. The most densely populated municipality, the municipality of Groningen, already made plans on becoming CO_2 neutral by 2035. This will be done by decreasing the energy demand with 35%, producing 31% of the current energy demand within the municipality boundaries and importing 34% of the current demand. Among others, this import would entail the import of fossil free electricity from outside the municipality boundaries. On a yearly basis, this would not be a problem for the electricity system, since the technical potential of wind and solar PV could make the entire province self-supporting on a yearly basis. However, policy makers thus far did not look into the possibility of providing the municipality with an hourly balanced electricity system using different implementations of the RES

This research explores the possibility of providing an hourly balanced electricity supply to the municipality of Groningen using wind and solar PV installed in the rest of the RES region Groningen and different types of storage techniques. Using the Energy Transition Model (ETM) of Quintel, electricity demand patterns were created for the year 2035. These patterns were used as an input for the 'balancing model' created for this research. The ETM was also used to explore the electricity generation possibilities of the RES. The storage technologies hydrogen storage and batteries were modeled to see if they could -individually or combined- provide balance to the municipality on an hourly basis.

This research concludes that in combination with hydrogen storage, wind and solar PV installed in the RES region could provide the municipality of Groningen with a balanced electricity system. However, the technical potential of wind and solar PV is insufficient to provide the entire province of Groningen with a balanced electricity system on an hourly basis when using hydrogen for storage. In this case, batteries would provide a technical feasible option. However, when only using batteries to provide balance to the electricity system, the storage volume of the battery needed will be extremely large resulting in high costs.

Combining hydrogen storage and batteries to provide an hourly balanced electricity system for the province of Groningen when only using RES generation techniques reduces the costs of the battery needed. Results show that the more imbalance is resolved using hydrogen storage, the smaller the need of batteries will be. However, even the best-case scenario investigated in this research shows that the costs of this system and the area needed for its spatial implementation will be extremely high. These results indicate that without increasing the amount of electricity generated within the RES region of Groningen in order to facilitate more hydrogen storage or importing green electricity from outside of the provinces boundaries, balancing the provinces electricity network is not a realistic option.

SAMENVATTING

In Juni 2019 heeft de Nederlandse overheid haar nieuwe klimaatbeleid gepresenteerd middels het Klimaat Akkoord. In dit akkoord beschrijven zij de plannen om de Nederlandse emissies van broeikasgassen terug te dringen naar 49% van de uitstoot in 1990. Een van de maatregelen die genomen gaat worden is de transitie naar duurzaam opgewekte elektriciteit. Het Klimaat Akkoord stelt als doel om in 2030 84 TWh aan groene elektriciteit te produceren op Nederlands grondgebied. 49 TWh hiervan zal worden gerealiseerd door het plaatsen van windturbines op zee. De overige 35 TWh zal moeten worden opgewekt door grootschalige (>15 kW) wind- en zonneparken op land. Om dit doel te bereiken is Nederland verdeeld in 30 regio's. Deze regio's zullen een Regionale Energie Strategie (RES) moeten presenteren waarin zij hun plannen voor de installatie van zonne- en windparken kenbaar maken. Een van deze 30 regio's is de provincie Groningen.

De provincie Groningen heeft haar ambitie laten blijken een leider in de energie transitie te willen zijn. Om dit te bereiken zullen de 12 gemeentes nauw samen moeten werken bij het opstellen van de RES. De meest dichtbevolkte gemeente in de provincie Groningen is de gemeente Groningen. Voorafgaand aan het Klimaat Akkoord heeft de gemeente Groningen haar plannen richting een CO_2 neutrale gemeente in 2035 geformuleerd en gepubliceerd in 'De Routekaart Groningen CO_2 Neutraal 2035'. De gemeente heeft aangegeven deze plannen vast te houden bij het opstellen van de RES. Het realiseren van de gemeentelijke plannen zal leiden tot een importbehoefte van elektriciteit vanuit de RES-regio. Op jaarbasis zal dit, dankzij de grote technische potentie van zon en wind in de regio, geen probleem opleveren. Op uur basis daarentegen, zal door de grote variatie in productie over het jaar een probleem met het balanceren van het elektriciteitsnetwerk ontstaan waar tot op heden nog geen politieke aandacht aan is geschonken.

Dit onderzoek heeft de mogelijkheid om een gebalanceerde uurlijkse elektriciteitsvoorziening voor de gemeente Groningen te realiseren door RES-technologieën in te zetten in de regio in combinatie met verschillende opslag technieken. Het Energy Transition Model van Quintel is gebruikt om het vraag- en aanbodpatroon voor de RES-regio voor 2035 te modeleren. Om de mogelijkheid tot het balanceren van de elektriciteitsvraag van de gemeente Groningen te analyseren is een 'balans model' gecreëerd. In dit model zijn waterstof, batterijen en de combinatie van beide technologieën geïdentificeerd als mogelijke opslag technieken.

Naar aanleiding van dit onderzoek kan worden geconcludeerd dat energieopslag in de vorm van waterstof een haalbare optie is bij het balanceren van het elektriciteitssysteem van de gemeente Groningen wanneer de RES-regio wordt ingezet voor het produceren van groene elektriciteit. Om de hele provincie van een gebalanceerd elektriciteitssysteem te voorzien met behulp van waterstof is in de regio niet voldoende technisch potentieel voor wind en zon op land. Wel zou de gehele provincie gebalanceerd kunnen worden met behulp van batterijen. Dit zou leiden tot een grote vraag naar opslag volume wat de batterijen erg duur en daardoor geen geschikte optie zou maken.

Het combineren van waterstof opslag en batterijen zou een uitkomst kunnen bieden in het balanceren van het elektriciteitssysteem van de provincie bij het gebruik van elektriciteit opgewekt met RES-technologieën. De resultaten laten zien dat een toename in waterstof opslag zorgt voor een afname in het opslag volume dat nodig is aan batterijen. Wel zal, door een gebrek aan technisch potentieel, niet genoeg waterstof ingezet kunnen worden om een betaalbaar elektriciteitssysteem voor de provincie Groningen te creëren. Het genereren van groene elektriciteit door middel van andere (niet in de RES opgenomen) technologieën of het importeren van elektriciteit van buiten de provincie zouden meer realistische opties zijn.

LIST OF ABBREVIATIONS

RES – Regionale Energie Strategie / Regional Energy Strategy
ETM – Energy Transition Model

1. INTRODUCTION

Over the last decades, scientist have come to a consensus and conclude global warming as an effect of greenhouse gasses to be of anthropogenic cause (Cook et al., 2013). Therefore, in 2015, most countries have come together to sign the Paris Agreement. This agreement entails the ambition to prevent the global mean temperature from rising more than 2 degrees Celsius compared to pre-industrial levels, while perusing action to limit the increase to 1.5 degrees Celsius (UNFCCC, 2016). In order to achieve this goal, each country has to contribute and reduce the amount of greenhouse gasses they emit. In June of 2019, the Dutch government has signed the Klimaat Akkoord (Climate Agreement) in which they lay out their plans on how to reduce Dutch greenhouse gas emissions by 49% compared to 1990 by 2030 (Rijksoverheid, 2019). Their approach follows the Trias Energetica theory of Duijvenstein (Duijvestein, 1993), implying that the first steps taken are to reduce the energy demand. This is done in several ways, such as, insulating 7 million houses and 1 million buildings. Besides these energy reducing strategies, the energy that will still be needed will have to be generated as sustainable as possible. The Klimaat Akkoord states that this will, for example, be done by replacing all current mobility (e.g. cars) by emission free alternative. Only demand unmet by renewables will be produced using fossil fuels, which will have to be used as efficient as possible.

In the Klimaat Akkoord, the Dutch government has formulated the goal of a total electricity production from renewables of 84 TWh in 2030. A large share of this target, 49 TWh, will be met by installing capacity of wind at sea. The remaining 35 TWh will be realized by wind- and solar parks on land. This target does not include solar energy production on rooftops but is focused on large scale generation (>15kW). Unfortunately, when introducing wind and solar production facilities, a problem regarding social acceptance can occur (Wüstenhagen, Wolsink, & Bürer, 2007). The placement of production sites will impact multiple stakeholders and will thus have to be considered carefully. To be able to make more deliberated decisions on the placements of these production sites, the Dutch government has agreed to divide the Netherlands into 30 regions. These regions all have to deliver a so-called Regional Energy Strategy (RES). This RES will consist of a document containing their strategy on how to free houses and buildings from natural gas and on where, with which technology and how much capacity they plan to install from the renewable sources wind and solar PV by 2030. Six months after the signing of the Klimaat Akkoord each RES region has to hand in their concept version of the RES (Rijksoverheid, Interprovinciaal Overleg, & VNG, 2018). These strategies will be assessed on feasibility and ambitiousness. When all strategies are in, the Netherlands Environmental Assessment Agency (PBL) will add up the production of each RES region. When the total sum of the electricity produced in the 30 regions does not add up to the 35 TWh to be realized, the remaining production capacity will be divided over the regions by the national government. 12 months after the signing of the Klimaat Akkoord has taken place, a definite RES has to be presented by each region.

Within a RES region, multiple municipalities have to work together in order to deliver one RES. These municipalities, thus far, functioned as little islands being in charge of their own energy strategy and sustainability goals. However, now that they are responsible for the RES, they will depend on each other to meet the goals of the region. This interdependency between the municipalities does not only create challenges but can also create new opportunities in becoming a leader in the energy transition. This is something the RES region of Groningen strives to be ("Groningen zint op stevig plan voor windmolens en zonneparken: 'Wij willen af van aardgas en aardschokken' - Economie - DVHN.nl," n.d.). The region of Groningen consists of 12 municipalities of which the municipality of Groningen has the largest amount of inhabitants (Rijksoverheid et al., 2018). In 2018, the municipality of Groningen presented elaborate plans towards becoming a CO_2 neutral city in 2035 (*Routekaart Groningen CO2 neutraal*, 2018). Besides contributing to the plans of the RES, the municipality has stated to keep striving for this CO_2 neutral goal in which they will reduce the demand of energy by 35%, produce 31% of the current energy demand from renewables within the boundaries of the municipality and import 34% of the current energy demand (*Startdocument-Regionale-Energietransitie-Groningen*, n.d.). The ambition is to import as much of the energy demand not met by own production as possible from sources within the region. How much energy will be available and if the hourly production curve of the region will match the demand curve of the municipality of Groningen will depend on the plans made in the RES. While constructing the RES, the region could consider the consequences of their decisions on the energy supply of Groningen municipality in order to make the region as self-supporting and sustainable as possible.

While policy makers are focused on producing enough renewable electricity to meet the total electricity demand on a yearly basis, research has shown that integrating more renewables into the energy mix can cause hourly imbalances between supply and demand (Lund, 2003). Therefor it is important to look at hourly demand and supply curves when determining the best choice of technologies used. Much research is done on islands or regions with large shares of renewable electricity production and how they can be self-supporting using multiple forms of energy storage. For example, Sijm et al. (2017) determine the need of hourly flexibility of the Dutch national electricity grid, Fernandes and Ferreira (2014) look at storage strategies needed in Portugal under different percentages of renewable penetration and Centeno Brito et al. (2014) explorer the storage needs of a fossil free imaginary island whose electricity, heat and mobility demand are fulfilled with sustainable and renewable energies only. While most literature looks at energy systems with a high penetration of renewables and the impacts of those renewables on the hourly electricity balance, they all consider the regions of their research as isolated systems. This is in contrast with reality in which neighboring regions often have integrated energy systems.

An interesting example of literature studying the integration of the renewable energy system of two regions is the research of Thellufsen and Lund (2016). In this research, different regions of Denmark were modelled and their possible level of integration with the Danish energy system on hourly basis was determined. The research indicates when and how much electricity these regions will be able to import from within the Danish boundary and when a surplus of electricity is produced that can be exported to other Danish regions. As stated earlier, a lack of knowledge about the origin of the electricity to be imported by the municipality of Groningen in 2035 exists. Furthermore, policy makers have thus far failed to focus on the balancing of the electricity network in a way Thellufsen and Lund did for Denmark. Therefore, this research looks into the possibility of fulfilling the electricity demand of the municipality of Groningen by using the surpluses of electricity produced in the other municipalities of the RES region. In order to do this, multiple scenarios of the RES will be proposed and the hourly surpluses of electricity in these scenarios will be compared with the hourly import needs of the municipality of Groningen. The first part of the study will determine the surplus of electricity available from the RES region under different demand and supply scenarios. The second part of the study will look into the type of storage and its capacity needed to provide the municipality with electricity on an hourly basis under different scenarios.

1.1 Problem definition

Since the RES Groningen is in its early stages, many choices will still have to be made. Therefore, research should be done in order to help the policy makers of the region decide on the best way to go. The region of Groningen has expressed the ambition of becoming a leader in the energy transition. This implies that all action already taken and plans already made have to be maintained to keep up the willingness to contribute to the transition. One of these existing plans is the 'Routekaart Groningen CO_2 Neutraal 2035'. In this municipality leveled policy plan, a way towards a CO_2 neutral city of Groningen is laid out. This CO_2 neutral city will have a yearly electricity demand exceeding its own production capacity and will thus have to import electricity. Their goal is to import as much of this electricity as possible from other municipalities within the RES region Groningen. Balancing the yearly demand of the municipality using the RES region would not be a problem since enough space is available and current (fossil) power plants can provide plenty. However, with the implementation of the RES, the share of renewables into the region's electricity mix will increase. Both the municipality and the region will be producing most electricity using wind and solar technology. This might lead to a problem in providing the electricity import to the municipality needed on an hourly basis since shortages within the municipality will occur simultaneously with shortages within the RES region. The aim of this research is to determine the extent to which it is possible to import all electricity unmet by own production (on an hourly basis) of the municipality of Groningen from the RES region in different RES and storage scenarios excluding the fossil generation within the region.

1.2 Research question

In order to meet the research aim stated above the following question was answered:

To which extent will the hourly need of electricity import of Groningen municipality in 2035 be able to be met by the RES region of Groningen under different implementations of the Regional Energy Strategy and storage technologies?

The main research question can be divided in the following sub-questions:

1. What will be the future hourly import demand of Groningen municipality according to the 'Routekaart Groningen CO_2 Neutraal'?
2. What will be the future hourly electricity demand of the RES region Groningen?
3. What will be the future hourly electricity production of the RES region Groningen?
4. When/how much demand of Groningen municipality can be met by the RES region Groningen?
    a. How much storage capacity is needed?
5. Can the entire province of Groningen be self-supporting on an hourly basis?
    a. What type/how much storage capacity is needed?

1.3 Boundary settings

This research focusses on the RES region of Groningen (province of Groningen) and its ability to deliver electricity to the municipality of Groningen in 2035. To determine this, the research is focused on hourly electricity demand and supply curves. Within this research, the RES region of Groningen will be defined as the province of Groningen (excluding Groningen municipality) and the municipality of Groningen as the 'new' municipality, including Haren and Ten Boer. All electricity used and produced within the boundaries of these regions will be taken into account. However, electricity needed for the production of goods used within the boundaries but produced outside of the boundaries will not be taken into account. Furthermore, all other energy carriers are taken outside of the system boundary. Lastly, all costs associated with the energy system changed are taken as outside of the system boundaries, making this a technical analysis. Furthermore, international transport (for example aviation) is taken outside of the system boundary.

For the modeling of the future supply side of electricity within the RES region, only solar PV, inland wind turbines and coastal wind turbines are used. With this, other technologies such as wind on sea, geothermic energy and electricity from biomass are taken outside of the system boundaries.

1.4 Methods

As stated previously, the aim of the research proposed is to determine the possibility of importing all electricity unmet by own production, on an hourly basis, of the municipality of Groningen from the RES region in different RES scenarios. In order to meet this aim, multiple questions had to be answered. Each of these questions was answered using a different methodology. First, the future electricity import demand of Groningen municipality according to the 'Routekaart Groningen CO_2 Neutraal' has been determined. This was done using all information available in the 'Routekaart Groningen CO_2

Neutraal’ and the scenario of this built by the municipality of Groningen in the Energy Transition Model (ETM) of Quintel(“Energy Transition Model - Your free, independent, comprehensive, fact-based scenario builder.,” n.d.-a).

The demand pattern of the RES region Groningen was determined using the ETM. Literature research was conducted to make sound assumptions on the 2035 electricity demand of the region. A system analysis was performed in order to find the most important input parameters of the system. The technical potential of solar PV and wind in the region was determined and using the supply patterns of the ETM hourly generation was determined. Besides the hourly generation of the full technical potential, the hourly generation using wind and solar PV was determined when providing just enough to support the province on a yearly basis.

From the hourly demand and supply of both the municipality as well as the RES region, the hourly imbalance of the electricity system was determined. A storage model was designed to model the possible electricity exchange and the additional storage capacities needed in order to realize an hourly balance for the municipality of Groningen as well as entire province of Groningen (including the municipality) was determined.

2. THE GRONINGEN ELECTRICITY SYSTEM

This section will give an overview of the current energy system of both the RES region Groningen and the municipality of Groningen. Furthermore, planned developments of the system and policy plans are listed. Finally an outlook for 2035 will be provided for both the RES region Groningen and Groningen municipality.

2.1 Groningen current system

The province of Groningen is located in the northern part of the Netherlands. It had a population of 583,581 people in 2018 ("StatLine - Regionale kerncijfers Nederland," n.d.). The province has a total surface (land) of 232,390 hectares and is thus not densely populated. The most densely populated municipality within the province is the municipality of Groningen with a total population of 231,299 in 2019 ("StatLine - Regionale kerncijfers Nederland," n.d.). This section will provide an overview of the current energy system in the province of Groningen. After an overview of the whole province, a distinction between the municipality of Groningen and the rest of the province is made and both specific characteristics are described.

Currently, the Dutch national energy system is mostly centralized. Both a national electricity as a well-established natural gas network are present. These networks were legally separated in 1998 ("Voorwaarden gas & elektra - Netbeheer Nederland," n.d.). Since 1963, the NAM has produced natural gas from the gas field in Slochteren ("Gaswinning in Groningen - Raad van State," n.d.) making the province of Groningen a net-energy producing region. The electricity grid and the national gas network have always remained closely related since natural gas can be used in electricity production. In 2015, 60% of all electricity in the Netherlands was produced and transported through the centralized grid (CBS, 2015). Together with other fossil energy sources, which provide 94.1% of the total energy used in Groningen ("CO_2-monitor Groningen," n.d.), natural gas provided a relatively simple energy system in which the flexible energy source was used for centralized electricity production. In this system, less flexible electricity sources, such as coal, were used to generate the base load of electricity. Since the natural gas functions as dispatchable producer, the electricity grid could be balanced (Lee & Gushee, 2009). However, the amount of variable (renewable) energy sources has been growing over the last few years ("CO_2-monitor Groningen," n.d.). The growth of renewable energy sources changes the electricity demand patterns for fossil suppliers. Therefore, suppliers (such as coal-fired plants) will no longer be needed to supply a base load. Instead, more dispatchable production or storage facilities will be needed.

2.1.1 Groningen municipality

As stated previously, the municipality of Groningen is the area within the province of Groningen with the most habitants. The final energy demand of the municipality of Groningen was 18,597 TJ in 2015. Given the relatively large number of inhabitants it is not surprising that 28% of the municipality final energy demand comes from households("Energy Transition Model - Your free, independent, comprehensive, fact-based scenario builder - routekaart scenario," n.d.) which is high compared to the national average of 17% ("Energie in Nederland," 2018). Industry takes up 35% of the final energy demand while the transport sector and commerce and services sector take 20% and 17% respectively. As shown in figure 1, 24% (4,286 TJ) of the final energy demand is needed in the form of electricity. Within the municipality some electricity is already generated renewably. This contribution to the electricity system consists of approximately 3 TJ of wind and 140 TJ of solar (Veen, n.d.).

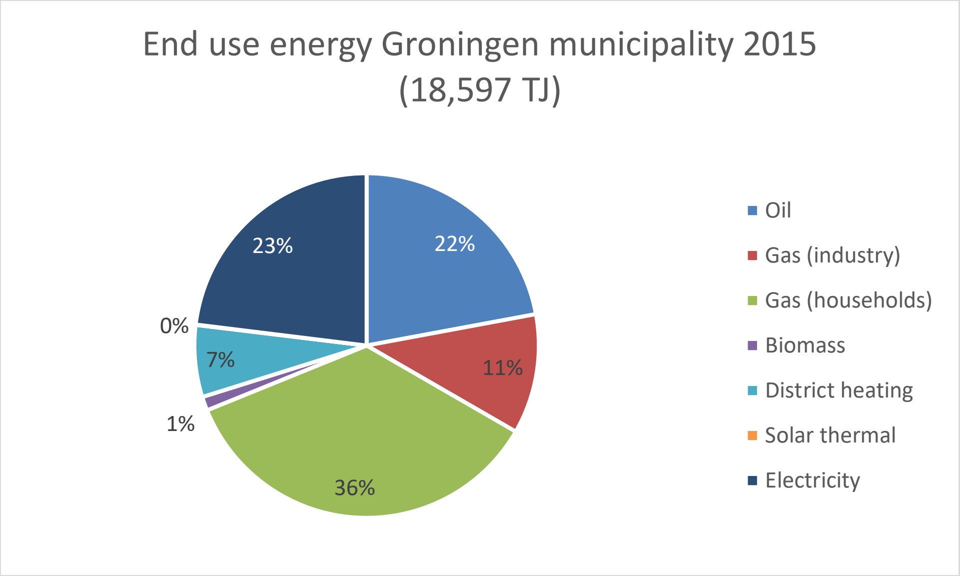

Figure 1. The end use of energy within the municipality of Groningen in 2016 according to the Energy Transition Model.

2.1.2 RES region Groningen

According to a start scenario of 2016 in the Energy Transition Model of Quintel ("Energy Transition Model - Your free, independent, comprehensive, fact-based scenario builder - RES regio startscenario," n.d.), the total end use of energy for the RES region Groningen (excluding Groningen municipality) was 100 PJ. 34 PJ of this demand was met by electricity, 45 PJ by natural gas and the remaining demand was met using other energy carriers such as diesel and biomass as is shown in figure 2. Within the province of Groningen, the largest energy using group is the industry. This sector uses one third of the total final energy demand of the province (*Energie monitor provincie Groningen*, n.d.) and is responsible for most of the provinces electricity use. The industry sector is located at the north-east coast of the province in Eemshaven and Delfzijl. The industry cluster provides 15% of the Dutch demand for the basic chemical industry (*Industrie agenda Eemsdelta*, n.d.).

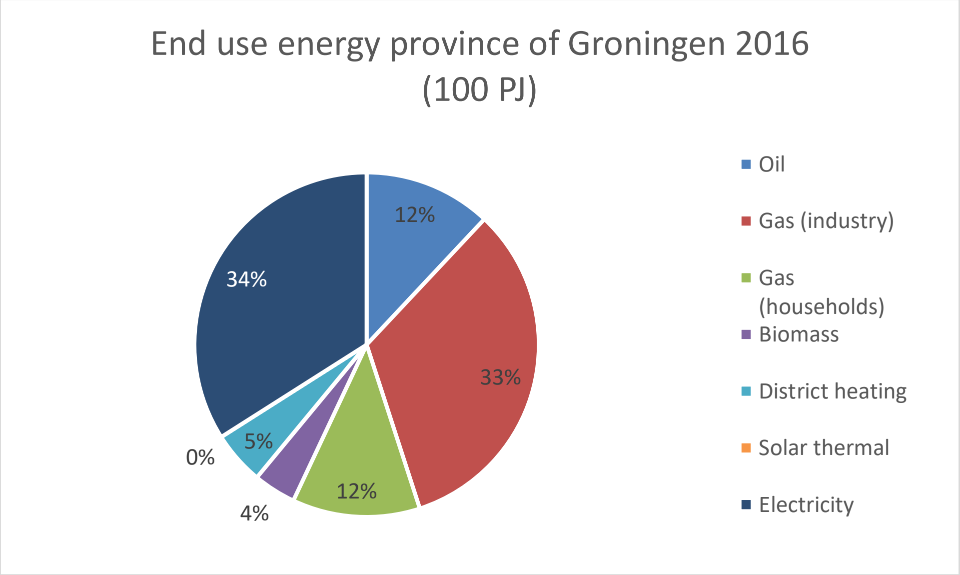

Figure 2. The end use of energy within the RES region of Groningen (excluding the municipality of Groningen) in 2016 according to the Energy Transition Model.

The RES region of Groningen is a contributor to the electricity production of the Netherlands. A large share of the production still uses fossil sources. In Eemshaven, RWE is the owner of a coal-fired plant with a capacity of 1560 MW(“Kolencentrale Eemshaven,” n.d.). Gas-fired power plants are also present in the region. These plants are the ENGIE plant in Eemshaven with a capacity of 1392 MW(“Eemscentrale - Wikipedia,” n.d.; “Engie sluit 4 gascentrales - Kennisplatform Energiesystemen,” n.d.), the Vattenfall plant in Eemshaven with a capacity of 1311 MW(“Nuon opent Magnum gascentrale in de Eemshaven - Vattenfall NL,” n.d.) and the Nouryon plant in Delfzijl with 530 MW capacity (“Nouryon Delesto,” n.d.). In 2017, the province of Groningen (including the municipality of Groningen) had 1050 TJ production from renewables (“CO_2-monitor Groningen,” n.d.).

2.2 Outlook 2035

The Netherlands presented their new climate policy ‘Het Klimaat Akkoord’ in June of 2019. One of the changes in the Dutch energy system that will happen according to this policy plan is shutting down all coal-fired power plants. Furthermore, energy reducing policies and policies to stimulate the grow of renewable energy sources are included in this policy(Rijksoverheid, 2019).

Within the province of Groningen, the drive to transfer from fossil to renewable energy production is enhanced by the earthquakes caused by gas production from the Groningen gas field. In the province of Groningen many different parties have contributed their vision on the energy transition of this region. They all have one thing in common: the province of Groningen will remain a leading party in the energy production and distribution of the Netherlands. In 2011, the province of Groningen and the municipality of Groningen presented their vision on the Groningen energy transition called ‘Het Groene Stopcontact’. This document states the ambition to produce 15.1% of the Dutch energy demand in Groningen (Quintel Intelligence, 2011). According to this offer, the energy will be produced from solar, wind, geothermal, biomass, waste and will also still include a small portion of fossil energy. In 2013, a commitment was made to realize an installed capacity of 885.5 MW of wind by 2020 (“IPO :: Wind op land,” n.d.). The province published a new vision on the energy transition in 2016 containing the short term goals for the years 2016-2019 (*Vol ambitie op weg naar transitie*, n.d.). These goals have been evaluated in May of 2018 (*Provincie Groningen*, 2018). The ambitions stated in these documents take, besides energy production, also energy reduction strategies into account and acknowledge that the energy system will have to change. The Province of Groningen keeps track of the changes in their energy system using the ‘Energie Monitor’ (*Energie monitor provincie Groningen*, n.d.). This year, the province of Groningen has been classified as a RES region. This means the province has to hand in a plan on how much renewable energy from wind on land and sun will be produced within the province by 2030 and where these technologies will be located (Rijksoverheid et al., 2018).

It can be concluded that the province of Groningen is making an effort in changing their energy system. However, besides the province of Groningen, many other parties are making plans and set visions on the Groningen energy system of the future. In the three northern provinces of the Netherlands 31 public and private parties from 6 European countries have set a vision on becoming an ‘hydrogen valley’ (“Hydrogen Valley - New Energy Coalition,” n.d.). This hydrogen valley will contain energy sources, storage, transport and applications in the different sectors in the Northern Netherlands. The project will be realized by 2025. Even sooner another project will be realized. The Nuon gas-fired electricity plant will start running on hydrogen by 2023 (“Eerste klimaatneutrale energiecentrale ter wereld komt in Eemshaven | De Volkskrant,” n.d.). These and other hydrogen projects will change the energy system of Groningen by adding a new energy carrier

Other parties working on the energy transition are the smaller governmental parties such as municipalities. For example, the municipality of Groningen is working on many projects. The ‘Routekaart Groningen CO_2 Neutraal’ shows a shift in the local energy goal from ‘energy neutral on a yearly basis’ towards ‘CO_2 neutral on a yearly basis’ (*Masterplan Groningen Energieneutraal*, n.d.;

Routekaart Groningen CO2 neutraal, 2018). With this shift, the importance of household heating systems comes in. Currently, most houses are heated by natural gas. When moving towards a CO_2 neutral city, new ways of heating have to be explored. These methods include, among others, heat pumps, geothermal heat, hydrogen or district heating (using excess heat from industry). The municipality has been working on neighborhood strategies in which the best suitable green heating technology is explored for each neighborhood in the municipality (*STAP VOOR STAP NAAR AARDGASVRIJE WIJKEN EN DORPEN Strategie en aanpak*, n.d.).

From al current works in progress mentioned above and new developments that will come up in the coming years up to 2035, the future energy system will get further remote from the centralized system it used to be. Hydrogen will be introduced as a new energy carrier in the system, houses will be heated using new (fossil free) technologies, industry increases its demand and more renewable capacity will be installed. In this new (decentralized) system, every small change influences the whole energy system. For example, the use of electric cooking instead of cooking on natural gas will reduce natural gas demand while increasing electricity demand. This will change the daily patterns of electricity demand which will already be difficult to manage due to the increase of renewable electricity sources. Therefore, more flexibility of the electricity system will be needed in order to cope with the fluctuating demand patterns, which could be provided using, for example, hydrogen. The energy system becoming more complex also increases the complexity of the models used in order to describe it. What the energy system will exactly look like in 2035 is very uncertain. However, this report will provide several outlooks on its possible characteristics. In the next section an outlook for both the municipality of Groningen and the RES region are provided.

2.2.1 Groningen municipality

Within the 'Routekaart Groningen CO_2 Neutraal 2035', the municipality of Groningen defines the concept as a CO_2 neutral city as follows: "*All energy used within the boundaries of the municipality of Groningen has to be produced in a CO_2 neutral way".* The ambition is to produce as much energy as possible within the city. However, due to a lack of space, energy will have to be imported. It is aimed to import this energy from the region. When following the Routekaart, the energy demand of the municipality will be decreased by 34% compared to 2018. 31% of the 2018 demand will be produced within the municipality boundaries and 35% will have to be imported. In order to reach these goals, multiple changes have to be made. These changes were defined by the municipality and divided in the sectors 'households', 'office buildings', 'industry', 'mobility' and 'renewable energy production'. The changes strived for in the 'Routekaart Groningen CO_2 Neutraal 2035' policy plan are stated below.

For households:

- 20% reduction of heat demand in households due to insulation
- Solar boilers on 50% of residences
- Access to heat network for 35% of the residences
- Heat pumps for 50% of the residences

For office buildings:

- 30% reduction of heat demand in company buildings due to insulation
- Thermal energy storage for 50% of the middle-small companies and access to the heat network for 35%

For industry:

- Office buildings have insulation level A++
- Food and paper sector have 50% electric heat production
- Other industries have 50% electric heat production and 25% biomass

- 1% efficiency improvement each year

For mobility:

- 90% of mobility can drive on a renewable source
- 100% of public bus transport is emission free
- 100% of freight traffic is CO_2 neutral. It is expected that 50% will use hydrogen, 40% bio-LNG and 10% will be electric

For renewable energy production:

- 500 MWp solar PV in solar parks
- 200 MWp of solar panels on houses
- 110 MWp of solar panels on company buildings
- 36 MWp wind on land
- All fuel produced within municipality boundaries is green fuel
- 67 MW of geothermal heat capacity

All of these and other developments expected by the municipality of Groningen were modeled using the Energy Transition Model of Quintel ("Energy Transition Model - Your free, independent, comprehensive, fact-based scenario builder.," n.d.-a). The inputs used for this scenario were based on an 2050 exploration of Quintel made for the 'Raad voor de Leefomgeving en Infrastructuur (RLI)' (*Beelden van een CO 2-arme Nederlandse samenleving in 2050*, n.d.). The assumptions from these scenarios were scaled and altered to fit the specifications of the municipality of Groningen and fitted to the year 2035 in a Quintel report (*Verhalen en scenario's over energiegebruik in 2035 in de stad en regio Groningen*, n.d.). Thereafter, the scenario described in this report was modeled in a new ETM scenario ("Energy Transition Model - Your free, independent, comprehensive, fact-based scenario builder.," n.d.-b) which has been evaluated during 4 expert sessions. All expert comments have been incorporated in the final ETM scenario of the 'Routekaart Groningen CO_2 Neutraal 2035'. By doing this, an outlook on the 2035 energy system of Groningen municipality was created. For this research all inputs determined by the municipality were used. The ETM scenario created can be found in Appendix A.

The ETM model created for the 'Routekaart Groningen CO_2 Neutraal 2035' policy plan results in the following implications for the electricity system of Groningen municipality in 2035. A CO_2 reduction of 94.3% will be realized when assuming that all imported energy will be of a green source. This includes biogas, green electricity and bio-LNG. While CO_2 emissions decrease, the total electricity consumption will increase from 4.443 PJ to 6.064 PJ. The electricity generated within the municipality will be 3.83 PJ. On a yearly basis, the municipality will have a shortage of 2.23 PJ electricity. However, due to the mismatch between demand and supply, 3.13 PJ of electricity will still have to be imported from outside the municipality boundaries. Balancing measures taken within the municipality reduce the total electricity import needed from the RES region on a yearly basis from 3.13 PJ to 2.57 PJ. The 'Routekaart Groningen CO_2 Neutraal 2035' achieves this reduction in import need by using 25% of the battery capacity of electric vehicles for balancing purposes. Figure 3 shows the residual electricity demand and supply patterns of the municipality with and without implementing balancing measures within the boundaries of the municipality. Calculations on the ETM output leading to these patterns can be found in Appendix A.

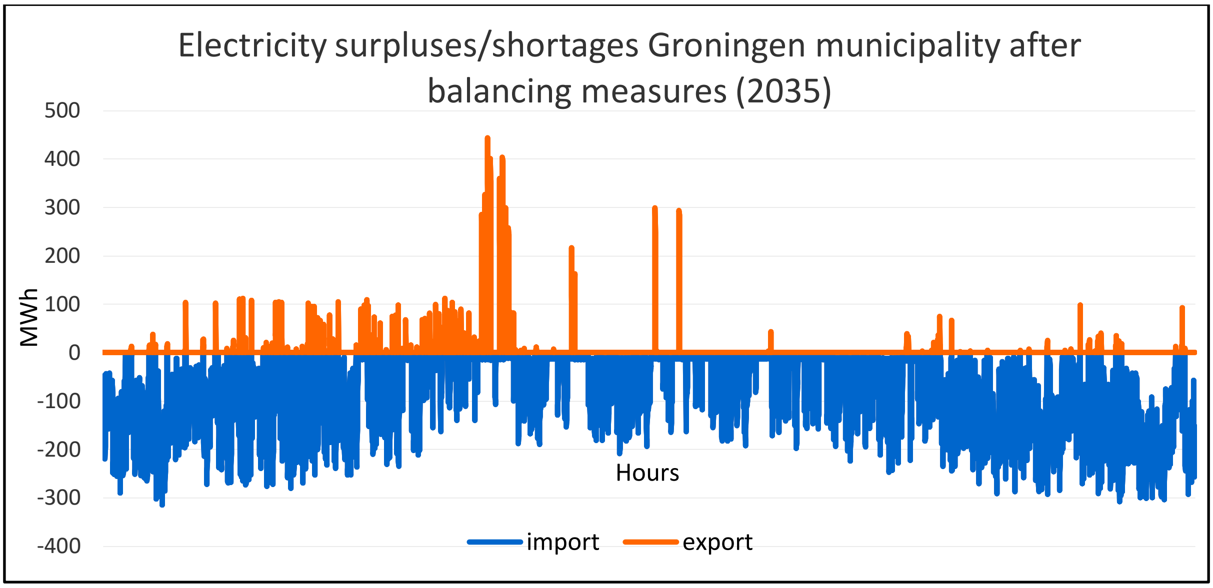

Figure 3. Electricity import and export of Groningen municipality when following the 'Routekaart Groningen CO_2 neutraal 2035' when implementing electric vehicle balancing measures.

2.2.2 RES region Groningen

The outlook of the 2035 energy system of the RES region Groningen provided here was mainly based on the outlook provided by the 'Routekaart Groningen CO_2 Neutraal 2035'. This section will give an overview of similarities and differences between the municipality of Groningen and the RES region on both the demand and supply side of the electricity system.

2.2.2.1 Demand outlook

Many assumptions made on future developments are beyond the local scale of the municipality. For the outlook on the 2035 RES region many assumptions are thus identical to those made by the municipality of Groningen while creating the ETM scenario of the municipality in 2035. These assumptions include amongst others: the expected efficiency improvements in all sectors, expected behavioral changes, expected growth of market share of technologies, increase in household's insulation, ways of passenger transport and outside temperature increase.

Due to the difference in current characteristics between the RES region and municipality of Groningen many 2035 characteristics of the energy system will differ as well. For example, the population of the RES region is, in contrary with the municipality, assumed to decrease in coming years. ("StatLine - Regionale prognose 2017-2040; bevolking, intervallen, regio-indeling 2015," n.d.)("StatLine - Regionale prognose 2017-2040; huishoudens, intervallen, regio-indeling 2015," n.d.).

As within the municipality, some characteristics of the RES region are assumed to (hardly) change in the coming years. These characteristics include the distribution of type of residences, domestic navigation technology for passenger transport, carbon capture and storage (CCS), international transportation and the absence of the steel industry.

On the contrary of the steel industry, other industries are assumed to grow. For example, the chemical industry is currently a major contributor to the energy use of the province of Groningen and is assumed to grow in the coming years. The analysis of the current energy system proved the size of the chemical industry an important variable, therefore, further research was done. In 2018, the Dutch national chemical industry used an amount of 289.6 PJ (“StatLine - Energiebalans; aanbod en verbruik, sector,” n.d.). According to VNCI, this amount will grow towards 450 PJ in 2050 (*Roadmap for the Dutch Chemical Industry towards 2050*, 2018). This entails a growth of 155.4% until 2050. The increase in size of the chemical industry in the RES region of Groningen is assumed equal to the Dutch growth. It is assumed that this growth will be linear over the years 2018-2050. This means that in 2035, a growth of 129.4% will be realized in the RES region of Groningen.

Many industry and technology developments are very uncertain but have a large impact on the energy use of the region. One of these industries is the aluminum industry. The aluminum industry in the RES region of Groningen consists of the company Aldel in Delfzijl. This company has had several unstable periods over the past years. Both in 2013 and 2017 the company (under different owners) has gone through bankruptcy (“Weer een nieuwe eigenaar voor failliet Aldel in Delfzijl | NOS,” n.d.). Therefore, the position of the aluminum industry can be classified as uncertain. Furthermore, both the ICT sector and the refinery sector have recently been in local news because of large growth in the sector indicating changes in these industry in the coming years(“Eerste Europese raffinaderij voor duurzame vliegtuigbrandstof komt in Nederland | Het Parool,” n.d.; “Google invests €1 billion in data centers in the Netherlands - NFIA,” n.d.). Another uncertainty towards 2035 is the evolvement of the train technology used within the region. There currently is a large difference in train technology used between the RES region and the municipality(“Energy Transition Model - Your free, independent, comprehensive, fact-based scenario builder - RES regio startscenario,” n.d.; “Energy Transition Model - Your free, independent, comprehensive, fact-based scenario builder - routekaart scenario,” n.d.). The municipality has an all-electric system while the region still depends on fossils for a large share. Electrification of this system could potentially lead to an increase in electricity demand within the region. Therefore, how this technology evolves will impact the energy system of 2035. Lastly, the agriculture sector in the province of Groningen has different characteristics then the sector has within the municipality of Groningen. Therefore, the energy use of this sector may evolve differently than that of the municipality and is thus uncertain. Lastly, developments in the amount of freight transport might influence the electricity demand substantially.

Demand side management

A form of demand side management that could be implemented in the 2035 electricity system of the RES region of Groningen is the smart charging of electric vehicles. This implies charging electric vehicles when demand is low and production from renewable sources is high. In the RES region of Groningen, a total of 342596 vehicles will be in use when following the growth rate of the last 6 years(“StatLine - Personenauto’s; voertuigkenmerken, regio’s, 1 januari,” n.d.). When assuming 90% of all vehicles will be electric (as assumed by the ‘Routekaart Groningen CO_2 Neutraal’), this indicates an amount of 308336 electric vehicles will be in use which could switch to a smart charging system in order to manage the electricity demand.

2.2.2.2 *Supply outlook*

Not only will the demand side of the electricity system change, the supply side will also change significantly. First of all, fossils used for electricity generation will disappear. The coal-fired power plant in Eemshaven will close since Dutch government prohibits the use of coal in electricity generation by 2030(“Eerste Kamer der Staten-Generaal - Wet verbod op kolen bij elektriciteitsproductie (35.167),” n.d.). Since the province of Groningen has expressed to be aiming to be a leader in the energy transition, the gas-fired power plants are assumed to be shut down by 2035. With the fossils disappearing, renewable electricity generation will grow rapidly. As mentioned before, the province of Groningen will have to present their Regional Energy Strategy (RES) in 2020. This strategy will contain the plans on solar and wind (on land) capacity to be installed by 2030. Since policy plans for the municipality of Groningen are already in place, this report assumes all additional RES plans on renewable production to be realized outside the boundaries of Groningen municipality. The National

Program Regional Energy Strategies has determined the technical potential of both solar and wind within the RES region. This technical potential adds up to a total of 13192 MW capacity consisting of 8552 MW solar panels, 3790 MW inland wind turbines and 850 MW coastal wind turbines. In this research it is assumed that the generation patterns of the different technologies will have the same generation patterns in 2035 as they did in 2015. When using these patterns, the technical potential of the RES generation technologies produce 64 PJ of electricity on a yearly basis, which is almost double the 2016 electricity demand of the province. Therefore, it can be concluded that the province of Groningen could be self-supporting on a yearly basis. Figure 4 shows the hourly generation patterns of week 1 and 26 of the year (representing a winter and a summer week respectively). It is clearly visible that the generation patterns of these technologies differ significantly. For the solar PV, a clear night and day cycle is visible. Furthermore, large differences in generation from solar PV can be seen between winter and summer.

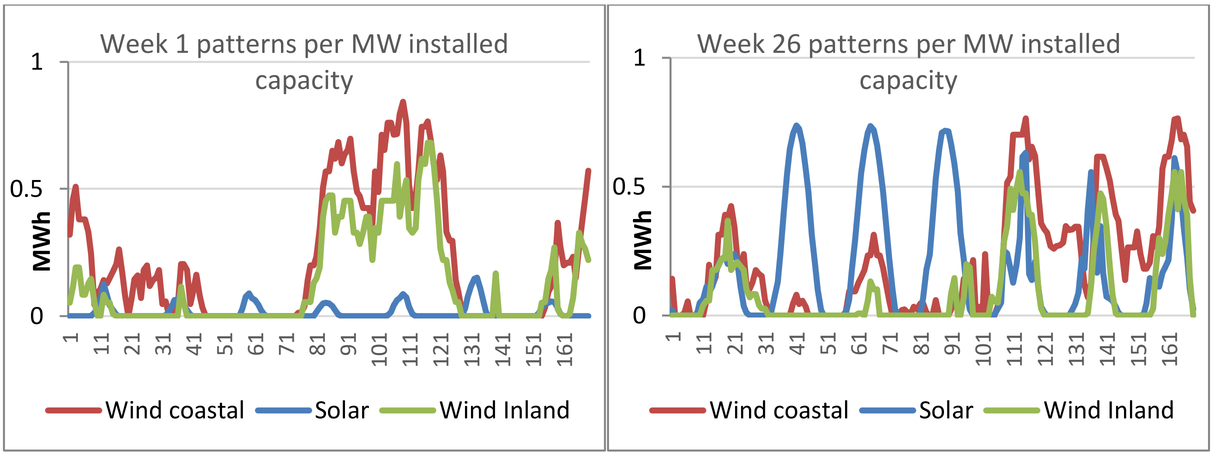

Figure 4. Hourly generation patterns of solar PV, inland wind turbines and coastal wind turbines in week 1 and 26.

Storage potentials

Since these renewable sources of electricity will be the main electricity supplier of the RES region by 2035, a volatile supply pattern is created. Therefore, the need of electricity storage will increase towards 2035. Several storage techniques could be used, including storing electricity in batteries or converting electricity to the energy carrier hydrogen to be stored as a gas.

When converted to hydrogen, the electricity produced by renewables can be stored as a gas. This hydrogen could be stored in salt domes. The province of Groningen has a total of 230 salt domes that, together, have a storage capacity of 24.8 TWh of hydrogen (*Ondergrondse Opslag in Nederland*, 2018a). However, the round-trip efficiency of using hydrogen is currently only 40.1% and is build up by a P2G efficiency of 70.85%, a storage efficiency of 95% and a G2P efficiency of 60% (Kooijinga, 2019b). Up to 2035, the efficiency of hydrogen storage and G2P conversion are expected to increase towards 98 and 67% respectively (Kooijinga, 2019b).

The round-trip efficiency of batteries is significantly higher than that of hydrogen storage. In this research, the round-trip efficiency of a battery is assumed to be 95% ("Lithium Ion – Lithium Ion Battery Test Centre," n.d.).

3. APPROACH AND SCENARIOS

3.1 System analysis

To perform an analysis of the Groningen electricity system, the Energy Transition Model (ETM) by Quintel was used. The ETM is a free to use, open source program. It was developed to improve people's understanding of the energy system and help energy policy makers in their decision process. It can model the entire energy system. However, not every sector, such as agriculture, is modeled in as much detail. This research requires data on future electricity use, for which the ETM is a useful tool. The model contains hourly patterns on electricity use per sector and supply. Furthermore, it is a model used by multiple RES regions and municipalities in order to model their proposed policies. It contains scenario baselines of all RES regions and all municipalities of the province of Groningen. In these baseline scenarios, users of the model can input the expected changes in the energy system up till the desired end year. The model will then calculate the influence these changes will have on the energy system.

The ETM provides an overview of the 2016 energy system of the province of Groningen ("Energy Transition Model - Your free, independent, comprehensive, fact-based scenario builder - Entire province of Groningen," n.d.). With this 2016 start scenario an analysis of the current energy system (of the province of Groningen including the municipality of Groningen) was made. The province of Groningen used 113 PJ of energy in 2016 of which 11% was used by households, 7% by the commerce and service sector, 11% for transportation, 69% by the industry and 1% for agriculture. The share of electricity in the energy mix was 37 PJ. Since this research focusses on the electricity use of Groningen and not on the total energy system, it was important to determine the major influences on electricity demand. Therefore, all variables used in calculating electricity demand in the ETM have been checked on their direct influence on the electricity demand of the province. This was done by increasing each input variable with 1%. The change in electricity demand caused by these changes are listed in Appendix B. All changes resulting in less than a 0.1 PJ change in demand were assumed not to be of great importance in determining the total electricity demand. This was done to determine which input variables should be used in different scenarios because of their high sensitivity.

The analysis of the current system showed that most sensitive variables concern efficiency improvements, demand growth and prosperity change. These variables are dependent on national trends and are therefore equal between both the municipality and the RES region. Besides these sensitive variables, the amount of passenger transport is also assumed to be a national trend and, therefore, the variable is assumed equal to that of the Groningen municipality. Freight transport, however, is expected to differ between the municipality and the RES region and is therefore seen as a variable input.

3.2 The balancing model

Since the technical potential of solar PV and wind can provide more than enough electricity to the province to be self-supporting (and thus provide for the municipality) on a yearly basis, the next challenge is to provide a balanced electricity system for the municipality on an hourly basis. In order to realize a balanced electricity system for the municipality of Groningen, the balancing model was designed for this research. A schematic overview of the model created can be found in figure 5. From the schematic overview it is clear that the hourly electricity surplus or shortage occurring in the municipality is taken as a non-variable input of the model. A description of this pattern can be found in section 2.2.1 Groningen municipality. In order to balance these given surpluses and shortages within the municipality the hourly surpluses of electricity of the RES region may be used. The surplus of electricity produced in the RES region is determined by the hourly demand and supply pattern of the region. These patterns are influenced by multiple variable factors as is shown in figure 5.

After determining the RES regions surplus of electricity, the model provides two options. The option chosen here determines the balancing region. The balancing region is the region for which a balanced electricity system will be realized with this model. When choosing option 1, the municipality of Groningen will be the balancing region and when choosing option 2, the balancing region will be the province of Groningen.

After choosing the balancing region, the storage technology used should be chosen. The model provides the option of using a single storage technology or a combination of hydrogen storage and batteries.

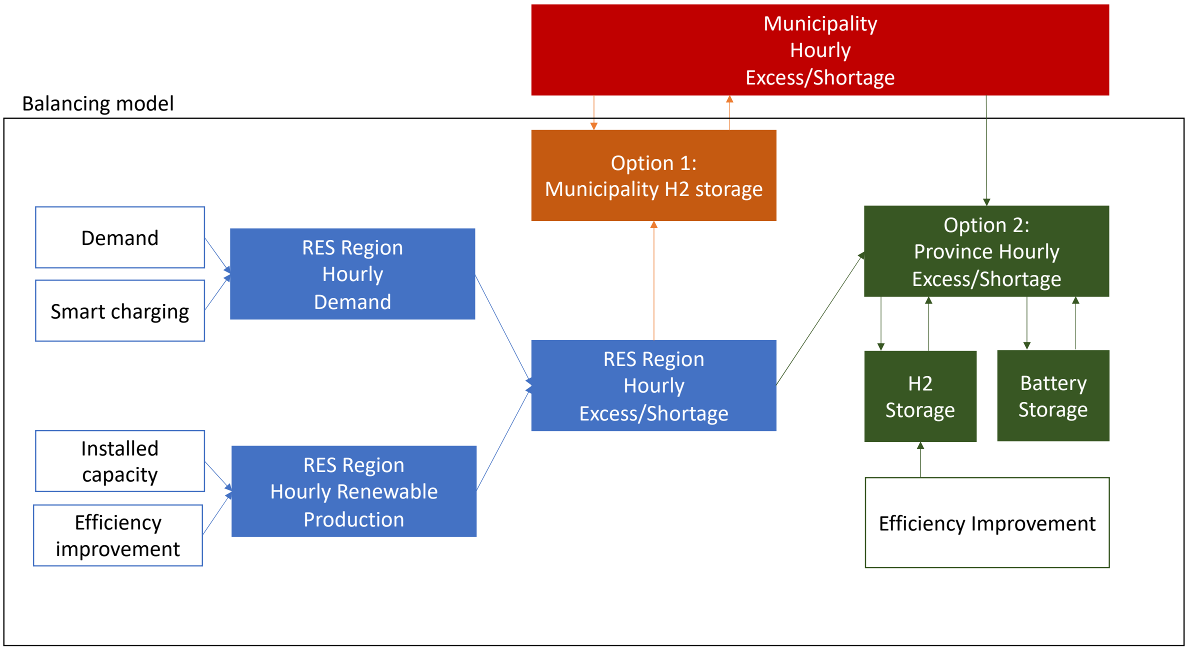

Figure 5. Schematic overview of the balancing model.

3.2.1 Hourly surplus RES region

In order to determine the surpluses that occur in the RES region, demand and supply patterns are combined. The hourly demand pattern is subtracted from the hourly supply pattern. This results in positive as well as negative hourly values. A negative hourly value can be seen as an electricity shortage in the region while a positive hourly value represents an electricity surplus which can be used to balance the balancing region.

(1) $RESSS(t) = Supply(t) - Demand(t)$

(2) $RESex(t) = RESSS(t)\ (if\ RESSS(t) > 0)$

With:
RESSS = RES region hourly electricity surplus/shortage
RESex = RES region hourly electricity surplus
t = hour (1 to 8760)

The following sections will discuss the determining of the demand and supply side patterns for the balancing region chosen.

3.2.1.1 Demand Patterns

In order to determine the demand for the RES region, this research used the Energy Transition Model. It contains scenario baselines of all RES regions and all municipalities of the province of Groningen. In these baseline scenarios, users of the model can input the expected changes in the energy system up till the desired end year. The model will then calculate the influence these changes will have on the energy system.

In order to calculate the electricity demand in 2035, the ETM uses different demand curves for each application. For household space heating, for example, hourly demand patterns are provided by TNO. An overview of all demand patterns used in the model can be found in the ETM documentation (“documentation/curves.md at master · quintel/documentation · GitHub,” n.d.).

The model is able to deliver multiple graphs and all hourly data can be extracted as a .csv file. The output of the ETM scenarios created in this research consists of an hourly pattern of electricity demand and supply of 2035. Using these patterns an hourly import and export need of the scenario region can be determined using Excel.

3.2.1.2 Supply Patterns

Within the ETM, generation patterns for solar PV, coastal wind turbines and inland wind turbines are given. These generation patterns are determined per country. Therefore, both for the RES region as for the municipality of Groningen, the same generation patterns are used. All production curves used in the ETM consist of measured data of the year 2016.

To determine the hourly electricity generation pattern of the RES region Groningen when using the regions full technical potential, the load curves of this supply scenario were extracted from the Energy Transition Model. In Excel, the following formula was used to calculate the hourly electricity generation pattern without the contribution of renewable technologies covered by the RES:

(3) $BaseLoadGeneration(t) = \sum Merit::MustRunProducer(t) + \mathrm{BS(t)} + \mathrm{EPW(t)} + \mathrm{HS(t)}$
With:
BaseLoadGeneration = hourly electricity generation from installed capacity excluding RES technologies (MW)
BS = buildings_solar_pv_solar_radiation (MW)
EPW = energy_power_supercritical_waste_mix (MW)
HS = households_solar_pv_solar_radiation (MW)

The Energy Transition Model provides the opportunity to include certain balancing mechanisms for the electricity system. However, since this research provides a model on storage technologies, the balancing options included in the ETM were not used. This indicated that no balancing efforts are included in the supply pattern created here. Furthermore, since this research focusses on balancing the electricity system when only using renewable generation techniques covered by the RES, all electricity generated from fossil sources is excluded from the generation pattern determined here.

In order to determine the hourly generation within the region, the normalized generation of the renewable technologies, from the ETM model, are multiplied by the installed capacities of the three technologies. Furthermore, the efficiency improvements expected towards 2035 are included. Hereafter, they are added to the stripped supply pattern resulting in the hourly generation within the RES region.

(4) $HourlyGeneration(t) = BaseLoadGeneration(t) + (A * NormalizedSolar(t) * IPS) + (B * NormalizedWindC(t) * IPWC) + (C * NormalizedWindI(t) * IPWI)$
With:

HourlyGeneration = The hourly generation including renewables within the RES region (MW)
NormalizedSolar = The normalized hourly generation for solar PV (MW)
NormalizedWindC = The normalized hourly generation for coastal wind turbines (MW)
NormalizedWindI = The normalized hourly generation for inland wind turbines (MW)
A = The expected efficiency of solar PV in 2035 compared to current efficiency
B = The expected efficiency of coastal wind turbines in 2035 compared to current efficiency
C = The expected efficiency of inland wind turbines in 2035 compared to current efficiency
IPS = Installed potential of solar PV (MW)
IPWC = Installed potential of coastal wind turbines (MW)
IPWI = Installed potential of inland wind turbined (MW)

3.2.2 Balancing region hourly surplus/shortage

After determining the RES regions hourly surpluses, the hourly surpluses and shortages of the balancing region chosen should be determined. This is done by adding the hourly surpluses and shortage of the municipality, the hourly shortages of the rest of the balancing region outside the municipality borders (if applicable) and the hourly surpluses of electricity produced in the RES region. This leads to the following formula:

(5) $SS(t) = Mun(t) + BALsh(t) + RESex(t)$
(6.1) $SS(t) = SSEx(t)\ (if\ SS(t) > 0)$
(6.2) $SS(t) = SSSh(t)(if\ SS(t) < 0)$
With:
Mun = the hourly shortage/surplus of electricity of the municipality (MW)
BALsh = the hourly shortage of electricity of the balancing region outside of the municipality (MW)
SSEx = the hourly surplus of electricity of the entire balancing area (MW)
SSSh = the hourly shortage of electricity of the entire balancing area (MW)

3.2.3 Single storage technology

When choosing for a single storage technology, this model provides two options of storage; hydrogen and batteries. The following section describes the method of determining the feasibility of the storage technology in terms of providing enough electricity to be self-supporting on a yearly basis.

(7.1) $ElecNOW(t) = Supply(t)\ (if\ SSSh)$
(7.2) $ElecNOW(t) = Demand(t)\ (if\ SSEx)$
(8) $ElecEff(t) = ElecNow(t) + \sum(\mathrm{RE} * SSEx(t))$
With:
ElecNOW = Amount of electricity used immediately within the hour of production (MW)
ElecEff = Amount of electricity that could be used efficiently after conversion losses (MW)
RE = The round-trip efficiency of the storage technology used

If the amount of electricity that could be used efficiently is larger than the total yearly electricity demand it can be concluded that hydrogen storage is a technically viable solution for the hourly imbalance. If not, more efficient electricity storage mechanisms should be used.

Storage facility needed

For the storage facility (as shown in figure 6) the total storage volume, the start level of the storage facility and the capacity needed are calculated.

Figure 6. The storage model with a given round-trip efficiency (R).

In order to determine these characteristics, the battery level was determined for each hourly datapoint. Using the following formulas:

(9) $P2S(t) = SSEx(t)\ (if\ SSEx)$

(10) $S2P(t) = -\frac{SSSh(t)}{\mathrm{R}}\ (if\ SSSh)$

With:

P2S = The amount of electricity stored in the storage facility (MW)
S2P = The amount of energy stored in the storage facility to be converted to electricity (MW)
R = Round-trip efficiency of the storage facility

With these outcomes, the level of hydrogen in storage could be determined using the following formulas:

(11.1) $LS(t = t) = LS(t = t - 1) + \mathrm{SSEx(t)}\ (if\ \mathrm{SSEx})$

(12.2) $LS(t = t) = \mathrm{LS}(t = t - 1) + S2P(t)\ (if\ \mathrm{SSSh})$

With:

LS = energy level in storage (MW)

The minimum capacity of the storage facility needed was determined by finding the hour with the largest shortage.

The energy level in storage needed at t=0 to prevent hydrogen shortages was found by determining the minimum value of LS found by using formula 19.

In order to determine the minimum storage volume needed, the Excel solver was used. The main objective being the last hours of the year to have a storage capacity equal to that of the first hour of the year by changing the total hydrogen storage capacity. Another constraint used in this calculation is that the total energy level in storage can never become negative.

3.2.4 Two storage technologies

When both the hydrogen storage and storage using batteries are used simultaneously, the hourly surplus/shortage of the balancing region was determined as described in section 3.2.2 ‘Balancing region hourly surplus/shortage’. In order to reduce the large differences between hours of surplus and hours of shortage the overproduction peaks are curtailed. The curtailment percentage in this research was set at 30% which is just below the point large electricity losses will occur caused by curtailment(Kooijinga, 2019a). With this curtailment percentage, the cut-off value of production could be determined following the following formula:

(13) $Cut - off\ value = maxProvEx * (1 - Curtailment\ percentage)$

With:

Cut-off value = the maximum amount of electricity used in the system per hour (MWh)
maxProvEx = the maximum electricity production per hour occurring in a year (MWh)
Curtailment percentage = the percentage of peak production that will not be used in the electricity system (MWh)

After determining the cut-off value, the unbalance in the system is calculated as followed:
(14.1) $Unbalance(t) = SS(t)\ (if\ SS(t) < cut - off\ value)$
(14.2) $Unbalance(t) = SS(t) - (SS(t) - cut - offvalue)\ (if\ SS(t) > cut - off\ value)$

From this adjusted hourly unbalance, a moving average (MA) is calculated. This is done by taking the average around every point of the unbalance using a certain time window. This time window can be adjusted. The moving average is calculated for each hour of the year, resulting in a smoother line than the initial unbalance.
(15) $MA(t) = \frac{\sum_{t+T}^{t-T} Unbalance(t)}{2T}$
With:
MA = The moving average at t=t
T = ½ of the time window used in calculating the moving average

To calculate the moving average of the first and last hours for which the time window is outside the yearly data, the data points are looped. Therefore, the moving average value of the first hour is partly calculated with the last hours of the year and for the last hour(s) of the year vice versa. The time window can vary between 1 (no change to data) and 8760 hours (full year averaged). This research used 5 different time windows varying from 2190 to 12 hours.

When the moving average of the unbalance is positive, electricity will be stored as hydrogen. A schematic overview of the hydrogen storage facility is in figure 8. When the moving average is negative, back-up production of electricity is needed in the system. To be self-supporting as a province, this back-up production is realized using the hydrogen stored when the moving average was positive.

(16) $P2G(t) = MA(t) * \mathrm{P2GC}\ (if\ MA > 0)$
(17) $G2P(t) = MA(t)/\mathrm{G2PC}\ (if\ MA < 0)$
With:
P2G = The amount of hydrogen added to storage (MW)
G2P = The amount of hydrogen removed from storage (MW)
P2GC = The efficiency of P2G conversion
G2PC = The efficiency of G2P conversion

Besides conversion losses, storage losses occur. The level of hydrogen in storage for each hour was calculated using the following formula:
(18) $H2(t = t) = ((H2(t-1) + P2G(t)) * \mathrm{S}) - G2P(t)$
With:
H2 = The amount of hydrogen in storage (MWh)
S = The efficiency of storing electricity in the battery

The production of hydrogen has to be at least equal to the use of hydrogen on a yearly basis to be self-supporting. In order to check this criterium for the different time windows the following method was used:
(19) $H2Pot = \sum MA\ (\mathrm{t}) * (\mathrm{P2GC} * \mathrm{S})\ (if\ MA(t) > 0)$
(20) $H2Use = \sum \frac{MA(t)}{\mathrm{G2PC}}\ (if\ MA(t) < 0)$
(21) $H2Pot \geq H2Use$
With:
H2Pot = The total amount of hydrogen on a yearly basis to be converted back to electricity (MWh)
H2Use= The total amount of hydrogen needed from storage on a yearly basis (MWh)

The following calculations were only done with the moving averages for which equation 29 is satisfied.

To resolve the short-term unbalance of the electricity system, batteries are used. The short-term unbalance is calculated as follows:
(22) $UnbalanceShort(t) = Unbalance(t) - MA(t)$
When the short-term unbalance is positive, the battery will charge while it will discharge in case of a negative unbalance.
(23.1) $UnbalanceShort(t) = Charge(t)\ (if\ UnbalanceShort(t) > 0)$
(23.2) $UnbalanceShort(t) = DisCharge(t)\ (if\ UnbalanceShort(t) < 0)$

In calculating this charge and discharge pattern, losses were not taking into account. However, losses are inevitable, and a battery has a certain roundtrip efficiency. Both when charging as when discharging losses occur. The charge and discharge efficiency are calculated as follows:
(24) $Charge/DisCharge\ Efficiency\ = \sqrt{R}$
With:
R = Round-trip efficiency

A conceptual representation of this battery is shown in figure 7.

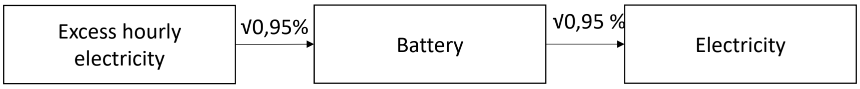

Figure 7. Schematic overview of a battery.

The battery level at any time can be calculated using the following formulas:
(25) $Battery(t = t) = Battery(t-1) + (Charge/DisCharge\ Efficiency * (Charge(t) + DisCharge(t)))$

The hydrogen storage and the battery level needed at t=0 to prevent shortages was found by determining the minimum value of Battery and H2 as described in formula 26 and 33 respectively.

In order to determine the minimum hydrogen storage needed, the Excel solver was used. The main objective being the last hours of the year to have a storage capacity equal to that of the first hour of the year by changing the total hydrogen storage capacity. Another constraint used in this calculation is that the total level of hydrogen in storage can never become negative. The same method was used to determine the minimum capacity of the battery.

3.2.5 Hydrogen storage improved efficiency

As shown in figure 5, when choosing for hydrogen storage, the variable 'efficiency improvement' can be implemented. Switching the efficiency improvements on leads to some minor alterations to the model. This is because, when assuming hydrogen storage to become more efficient, these improvement in round-trip efficiency is buildup of improvements in P2G conversion, storing efficiency and G2P conversion. A schematic overview of the hydrogen storage facility is shown in figure 8.

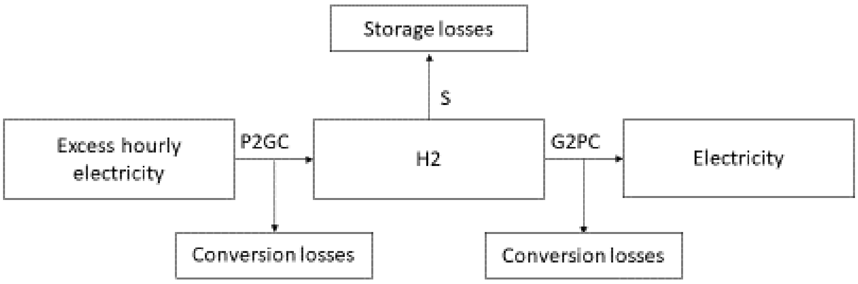

Figure 8. Schematic overview of a hydrogen storage facility.

Taking efficiency improvements into account, the new formula on determining the amount of electricity to be efficiently used becomes:

(26) $ElecEff(t) = ElecNow(t) + \sum((P2SC * S * S2PC) * ProvEx(t))$

With:

P2SC = The efficiency of P2S conversion
S2PC = The efficiency of S2P conversion
S = The efficiency of storage

3.3 Scenario studies RES region Groningen

For the RES region, multiple demand, supply and storage scenarios for the year 2035 have been developed in this study. Table 1 provides an overview of all scenarios created and their corresponding scenario name.

For the demand side of electricity system, four scenarios were created. First, a distinction between a relatively low and relatively high electricity demand was made for the year 2035. Furthermore, in both the low and high electricity demand, demand side management in the form of smart charging electric vehicles was introduced.

Two scenarios have been determined considering the supply side of the electricity system. Both scenarios only make use of the renewable energy sources sun and wind since these technologies are included in the RES. First, a supply scenario making use of the full technical potential of wind and solar PV was created. Second, a scenario containing just enough wind and solar capacity to make the province self-supporting was made. Besides the amount of electricity generation, the supply scenarios also differ in the region to which the generation is directed. When the generation pattern is directed to the municipality, this implies that all surplus electricity produced within the RES region during a certain hour will be directed to the municipality. When, after supplying the shortage of the municipality of that hour, there is still a surplus of electricity, this will be stored to supply the municipality in hours of shortage. When the generation pattern is directed to the entire province, the goal of the scenario is for the province of Groningen to be self-supporting on an hourly basis using different storage mechanisms.

The storage scenarios are built up by using different storage mechanisms (hydrogen, batteries or a combination of these technologies) and adding efficiency improvements in hydrogen storage or electricity generation. The efficiency improvement scenarios are only added when hydrogen is used as storage technology. The following sections will further describe the specifications of all scenarios described.

Table 1. Overview of different scenarios for the storing of electricity within the RES region of Groningen in order to provide the municipality of Groningen with electricity on an hourly basis.

Scenario name	Supply model used	Demand	Potential of renewables	Storage mechanism	Efficient hydrogen storage	Smart charging	Efficient generation
MLSH	Municipality	Low	Self-supporting	H2	-	-	-
MLFH			Full potential	H2	-	-	-
MHSH		High	Self-supporting	H2	-	-	-
MHFH			Full potential	H2	-	-	-
PLFH	Entire province	Low	Full potential	H2	-	-	-
PLFH+				H2	+	-	-
PLFH++				H2	+	+	-
PLFH+++				H2	+	+	+
PLFB				Batteries	-	-	-
				H2 and batteries			
PLF2190				MA2190	+	+	+
PLF730				MA730	+	+	+
PLF365					+	+	+
PHFH		High	Full potential	H2	-	-	-
PHFH+				H2	+	-	-
PHFH++				H2	+	+	-
PHFH+++				H2	+	+	+
PHFB				Batteries	-	-	-
				H2 and batteries			
PHF2190				MA2190	+	+	+
PHF730				MA730	+	+	+

3.3.1.1 Demand side scenarios

Two scenarios were created describing the electricity demand of the RES region. One of these scenario's being 'low electricity demand' and the other being 'high electricity demand'.

Scenario: low electricity demand

Aluminum industry

In the 'low electricity demand' scenario, it is assumed that Aldel will not be in business in 2035. Therefore, the production of aluminum within the RES region of Groningen will be assumed to be zero.

ICT sector

In the 'Routekaart Groningen CO_2 Neutraal 2035', a grow of this sector of 200% is assumed for the municipality of Groningen. For the low electricity demand scenario, the same growth rate will be assumed for the RES region.

Refineries

Within this sector, a new player is going to emerge in the near future ("Eerste Europese raffinaderij voor duurzame vliegtuigbrandstof komt in Nederland | Het Parool," n.d.). This refinery will produce biofuel for aviation. The capacity of the plant will be 100 000 ton of fuel per year. Literature research has shown a range of energy needed to produce bio-kerosene. An overview of literature can be found in Appendix E. For the low electricity scenario an energy use of 20.116 MJ/kg was assumed resulting in an energy use of 2.01 PJ for the refinery sector in 2035.

Passenger transport – train technology

Within the municipality of Groningen, all train technology is assumed to become electric by 2035(“Energy Transition Model - Your free, independent, comprehensive, fact-based scenario builder - routekaart scenario,” n.d.). However, the municipality of Groningen currently already has a way higher proportion of train transport electrified than the RES region(“Energy Transition Model - Your free, independent, comprehensive, fact-based scenario builder - RES regio startscenario,” n.d.). In the low electricity demand scenario, the electrification of passenger train transport in the region will go through the same growth as passenger train transport in the municipality of Groningen. This will result in a 72.5% electric system while the other 27.5% will still be powered by diesel.

Agriculture electricity use

For the agriculture sector in the municipality, the ‘Routekaart Groningen CO_2 Neutraal 2035’ predicts a decrease of electricity use by 1% per year. For the low energy demand scenario, the same yearly reduction of electricity use in this sector is assumed.

Freight transport

For the low electricity demand scenario, data from an exploration of future welfare of ‘Netherlands Environmental Assessment Agency (PBL)’ was used(CPB & PBL, n.d.). This report contains two reference scenarios of the Netherlands in 2030. The trends in freight transportation are expected to be equal for the region of Groningen as for the Netherlands as a whole. Since the exploration of the future in this report only goes until 2030, an annual trend was calculated and assumed to be equal until 2035. For the low electricity use scenario, an increase in freight transport of 0.4% per year has been assumed.

Scenario: high electricity demand

Aluminum industry

Starting in 2019, the Aldel aluminum production plant will start running at full capacity (“Restart total aluminium production Aldel Delfzijl - Groningen Seaports,” n.d.). At full capacity this production plant produces 110,000 tons of primary aluminum and 50,000 tons by remelting purchased aluminum (“Product | ALDEL - Damco Aluminum Delfzijl Coöperatie U.A.,” n.d.). For the ‘high electricity demand’ scenario it is assumed that, in 2035, this aluminum production facility will still be the only producer within the province of Groningen and be running at full capacity. Literature research has shown that primary aluminum production takes 14.318 kWh per kg(Haraldsson & Johansson, 2019). For secondary aluminum the energy use is about 5% of the energy use of primary aluminum production(Giorgio, n.d.). This leads to a total of 5.8 PJ on a yearly basis.

ICT sector

Many projects developing the ICT sector of the region have already been started. With these projects and the possibility of even more projects in the future, the ICT sector in the RES region is assumed to grow with more than 200% by 2035. Outside of the borders of Groningen municipality, the RES region of Groningen currently has three large data centers owned by Google, Datacenter Groningen and QTS (“Map - Dutch Data Center Association,” n.d.). The Google datacenter is currently powered by 130MW renewable energy and employs 350 employees. Google is currently working on expanding this datacenter which will lead to a 125 additional job opportunities once the facility is in operation (“Google invests €1 billion in data centers in the Netherlands - NFIA,” n.d.). Since no data on the exact capacity is available, it is assumed that the number of employees has direct relation to the capacity of the facility. This would mean a total capacity of 182MW (1.34 PJ) will be running at this site by 2035. This expansion of capacity is just an example of the rapid increase of this sector. For the Dutch ICT sector, the total capacity has increased from 1256MW in 2017 to 1391MW in 2019(“‘Totaal vermogen

Nederlandse datacenters stijgt naar 1391MW' - IT Pro - Nieuws - Tweakers," n.d.). This is an average growth rate of 1.052 each year. In this scenario, it is assumed that this growth rate will remain stable until 2035 leading to a total increase of 262% in the ICT sector.

Refineries

Previously, it was stated that a new bio refinery will be opened in Groningen in the near future. An overview of literature on the energy needed to produce bio-kerosene can be found in Appendix E. For the high electricity demand scenario, an energy demand of 31.8 MJ/kg is assumed lead to an increase in total demand of 3.18 PJ for the refinery sector.

Passenger transport – train technology

For 2035, it is quite likely that the region will (just like the municipality) strive for an all-electric system. Therefore, in the high electricity demand scenario, all passenger trains will be electrified.

Agriculture electricity use

Contrary to the low electricity demand scenario, the high electricity scenario predicts a grow in electricity use in the agriculture sector. Between 2011 and 2016, the electricity use of this sector in the entire nation has grown with a factor 1.005 ("Energieverbruik per sector, 2011-2016 | Compendium voor de Leefomgeving," n.d.). This scenario assumes this growth to be equal for the RES region and that it will remain constant until 2035. This would lead to an input of the yearly growth of 0.15% per year. Since the ETM only uses inputs with one decimal, an input of 0.2 was used.

Freight transport

For the low electricity demand scenario, data from an exploration of future welfare of 'Netherlands Environmental Assessment Agency (PBL)' was used(CPB & PBL, n.d.). This report contains two reference scenarios of the Netherlands in 2030. The trends in freight transportation are expected to be equal for the region of Groningen as for the Netherlands as a whole. Since the exploration of the future in this report only goes until 2030, an annual trend was calculated and assumed to be equal until 2035. For the low electricity use scenario, an increase in freight transport of 1% per year has been assumed.

Smart charging of electric vehicles

Both the 'low electricity demand' and the 'high electricity demand' scenario do not include any demand side management strategies such as smart charging electric vehicles or storing buffers in heat pumps. However, since smart charging of electric vehicles can reduce the unbalance of demand and supply in the electricity system, a 'low electricity demand- smart charging' and a 'high electricity demand – smart charging' were created. In these scenarios, the 'low electricity demand' and 'high electricity demand' scenarios were altered by changing the way of charging. The differences between these scenario's and the smart charging scenarios can be found in the table below.

ETM input

Quintel provided a start scenario of the RES region of Groningen (excluding Groningen municipality) in 2016. This start scenario can be found in Appendix C.

The changes in the energy system of the municipality assumed in the 'Routekaart Groningen CO_2 Neutraal 2035' were used to determine the electricity demand of Groningen municipality in 2035. To determine the electricity demand of the RES region in 2035 it was assumed that the trends within the RES region will be equal to those in the municipality of Groningen. This results in equal shifts in, for example, technology improvements, insulation levels and consumer behavior. Appendix D provides an overview of all inputs that differ to the inputs of Groningen municipality.

The table below provides an overview of the differences in input used between these scenarios. A total overview of all inputs used in the ETM can be found in Appendix C.

The Energy Transition Model provides the opportunity to model the costs of the energy system. However, since this research only contains a technical analysis, this function is not used. All inputs of this section remain unchanged from the start scenario available.

Table 2. Differences in ETM inputs between the municipality and both 'low' and 'high' electricity demand scenarios for the RES region Groningen.

	Municipality 2035 demand	RES region 2035 demand - Low electricity demand	RES Region 2035 demand - High electricity demand
Demand · Transport · Passenger Transport · Train Technology · Electric	100%*	72,5%	100%
Demand · Transport · Passenger Transport · Train Technology · Diesel	0%%	27,5%	0%
Demand · Transport · Freight Transport · Applications · Freight Transport	2%	0,4%	1%
Demand · Industry · Aluminum · Aluminum	100%*	0%	1236%
Demand · Industry · Refineries · Size	100%*	143%	152%
Demand · Industry · Central ICT · Size	200%	200%	262%
Demand · Agriculture · Demand Growth · Electricity	-1%	-1%	0,2%

* A value of 100% in the ETM indicates the assumption that this part of the energy system does not change compared to 2016.

The changes in ETM input made in order to obtain the smart charging scenarios are shown in the table below.

Table 3. Differences in ETM inputs between smart charging and normal charging scenarios.

	RES region 2035 demand - Low electricity demand	RES Region 2035 demand - High electricity demand	RES region 2035 demand - Low electricity demand – Smart charging	RES Region 2035 demand - High electricity demand – Smart charging
Flexibility · Net Load · Demand response – Electric vehicles · Charging everywhere	100%	100%	0%	0%
Flexibility · Net Load · Demand response – Electric vehicles · Charging smart	0%	0%	100%	100%

3.3.1.2 Supply side scenarios

Multiple scenarios describing the 2035 production within the RES region were created. The first scenario describes the supply available when the full technical potential will be used. These technical potentials were determined by the NPRES, who are responsible for the national organization of the RES regions(Veen, n.d.). In the second supply scenario, the RES region will only produce enough electricity to be self-supporting on a yearly basis. These supply patterns were created using the total demand of the region and the normalized patterns for solar PV, inland wind turbines and coastal wind turbines. An optimization of the installed capacity of these technologies was made in order to minimize the number of hours in which a shortage of electricity occurs. The technical potential of the generation technologies was never exceeded while searching for the optimal installed capacity of each technology.

Table 4 shows all installed capacity described by the different scenarios. All other supply inputs possible in the ETM were set to zero. The input used for these supply scenarios was based on the ETM output of the different demand scenarios. A detailed description on how these inputs were calculated can be found in section 3.1.2.1 Supply patterns.

Table 4. Input ETM for different supply scenarios.

	Full potential (MW)	Self-supporting low electricity demand (MW)	Self-supporting high electricity demand (MW)
Renewable electricity · Wind turbines · Onshore inland	3790	3419	3291
Renewable electricity · Wind turbines · Onshore coast	850	561	619
Renewable electricity · Solar power	8552	5724	8208
Renewable electricity · Waste power · Waste incinerator	40	40	40

As can be seen in figure 5, for the full potential supply patterns, some scenarios assume an increase in generation efficiency. In this case, it is assumed that solar PV, wind (inland) and wind (coastal) will become 2.3% (Malinowski, Leon, & Abu-Rub, 2017), 1.1% and 1.14%(Energy For Complete Set of Factsheets visit Wind Energy Wind Resource and Potential, n.d.) more efficient by 2035. This leads to the input values of A = 1.023 B =1.011 and C = 1.0114 for formula 4 in the storage model. When no efficiency improvements are expected, these input values remain 1.

3.3.1.3 *Storage Scenarios*

As shown in table 1, for the storage scenario a choice can be made between storing electricity in the form of hydrogen, in a battery or using a combination of both technologies.

4. RESULTS

This section will discuss the results generated in this research. First, an overview of the different demand and supply patterns created for the RES region is given. Second, the feasibility of the different storage scenarios will be discussed.

4.1 Demand and supply patterns

Section 3.3 Scenario studies RES region Groningen describes different demand and supply scenarios for the RES region of Groningen. Table 5 contains an overview of the yearly electricity demand or generation for these scenarios in 2035.

Table 5. Electricity demand and generation for the year 2035 when applying different demand and supply scenarios.

Demand/Supply scenario	Demand (PJ)	Generation (PJ)
Province demand 2016	34.4	
Low electricity demand 2035	50.0	
Low electricity demand – Smart charging 2035	50.0	
Low electricity demand – Self-supporting 2035		50.3
High electricity demand 2035	57.7	
High electricity demand – Smart charging 2035	57.7	
High electricity demand – Self-supporting 2035		58.3
Full potential 2035		64.3
Full potential – Increased efficiency 2035		65.5

As could be seen in table 5, the effects of smart charging electric vehicles on the electricity demand of the RES region on a yearly basis are not visible. However, this form of demand side management does have an effect on an hourly basis. Figure 9 shows the demand pattern of the RES region with and without implementing smart charging as demand side management. It is clearly visible that the smart charging of electric vehicles smoothens the demand pattern.

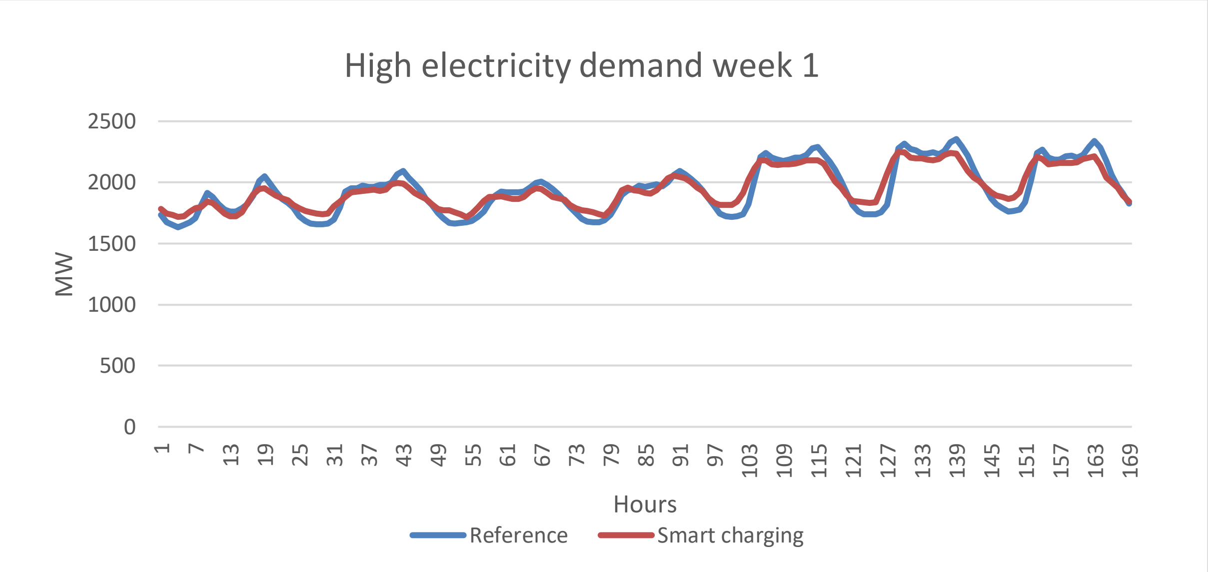

Figure 9. The demand patterns of the RES region in week 1 of the year 2035 with and without implementing smart charging.

When installing the full technical potential of RES technologies in the RES region Groningen, almost half (15.17 TWh) of the national target of 35 TWh is realized.

4.2 Storage scenarios

As described in section 3.3 Scenario studies RES region Groningen, the different demand and supply scenarios were combined. To these combinations, storage scenarios were applied. Figure 10 shows the electricity demand, production and storage for the scenarios in which a single storage technique was used. For the scenarios with the municipality of Groningen as the balancing region, the demand was determined by adding the electricity immediately used within the RES region to the hourly municipality demand.

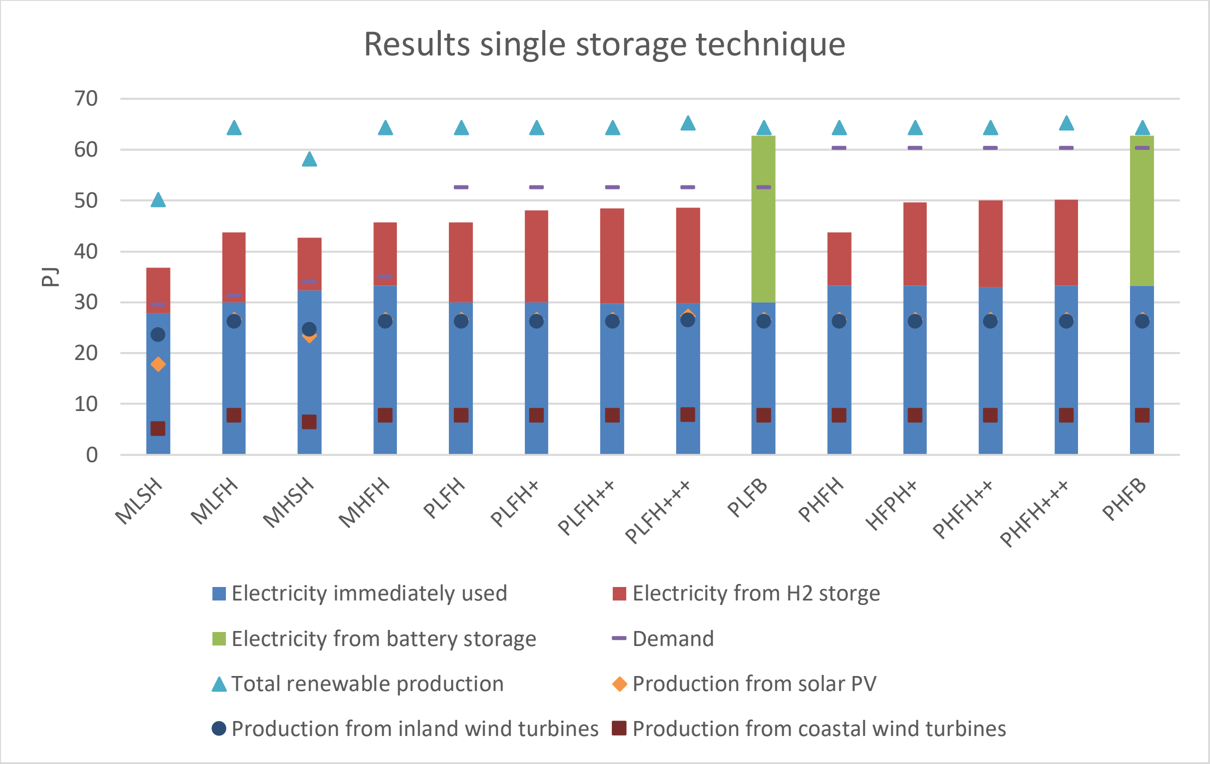

Figure 10. Electricity demand, generation and storage in scenarios in which a single storage technique was used.

From figure 10 it can be concluded that only in the scenarios that set the balancing region as the municipality and the scenarios that use batteries as the chosen storage technique, the electricity system can provide enough electricity to cover the demand. In the other scenarios, too much energy gets lost during the conversion and/or storage of the electricity. For example, for both the PLFH and the PLFH+++ scenario not enough electricity from H2 is available to cover demand. However, between these scenarios an increase in available electricity is observed. This indicates a decrease in hours of shortage. Figure 11 and 12 show the load duration curves of the PLFH and PLFH+++ scenario. When comparing these graphs, it can indeed be concluded that the measurements extra taken in the PLFH+++ compared to the PLFH scenario decrease the number of hours a shortage of electricity occurs in the system.

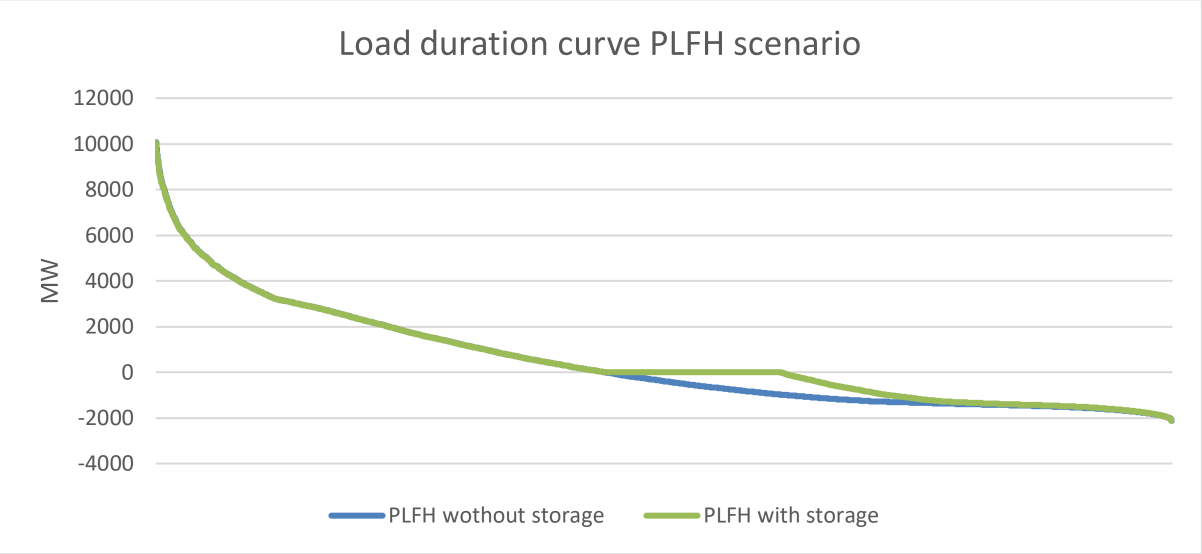

Figure 11. Load duration curve PLFH scenario.

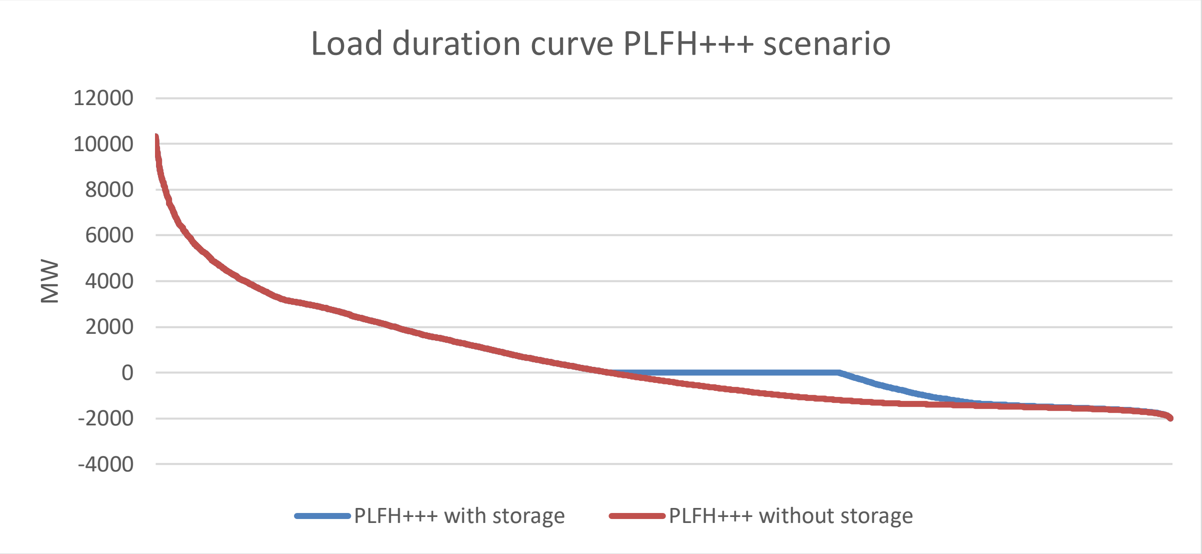

Figure 12. Load duration curve PLFH+++ scenario.

For the scenarios using a combination of storing techniques, results are displayed in figure 13. The graph shows the demand created for electricity from hydrogen and the amount of hydrogen available when using the moving average method. For scenario PLF2190, no the demand for hydrogen is zero since the moving average in this case is positive throughout the year. Besides the hydrogen demand and supply, the electricity demand from batteries (which is increased because of the production of hydrogen during hours of shortage) and the amount of electricity available from batteries in each scenario are shown. It can be observed that each scenario provides plenty of hydrogen while the scenarios are all lacking electricity from batteries. This is due to the fact that, when using the moving average method, the input of the battery and the demanded outputs of the battery are equal on a yearly basis. The lack of electricity is therefore due to the electricity loss when using battery storage. This shortage in the battery part of the energy system can be covered by using the surpluses of hydrogen available in the system. The last bar of the graph shows that in each of the scenarios explored in this research, enough hydrogen is available to ensure full coverage of the demand.

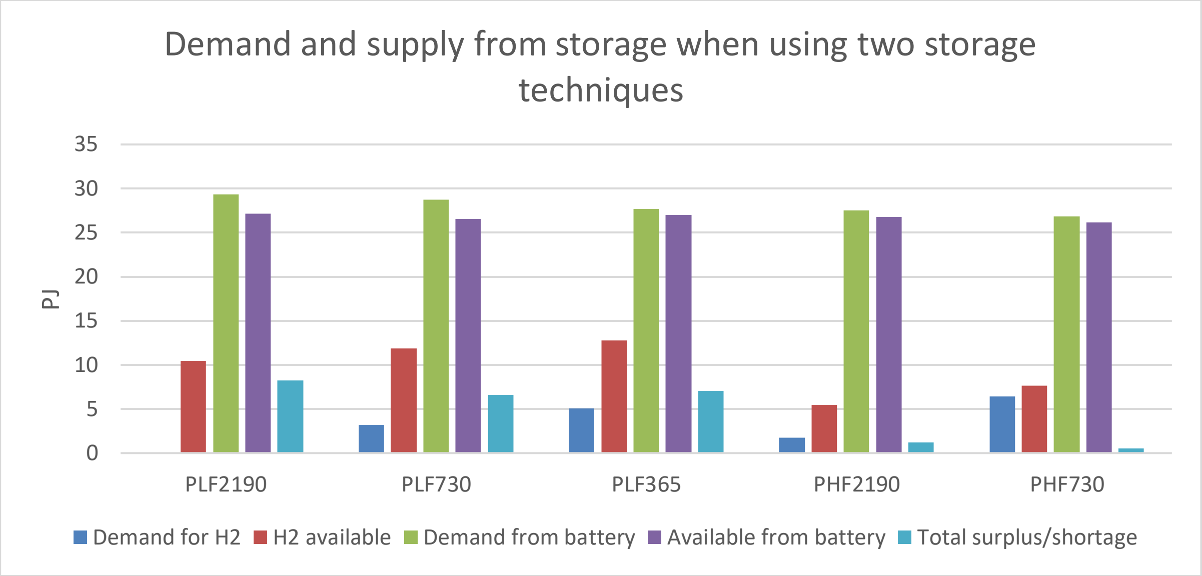

Figure 13. Demand on electricity from different storage techniques and the availability of electricity from these storage techniques in scenarios using a combination of storage techniques.

Figure 14 shows an overview of the electricity system when using the moving average method in the PHF730 scenario. From this it can be seen that indeed more electricity is demanded from the battery than the electricity demand when the moving average is positive and thus hydrogen is produced. Furthermore, it is shown that hydrogen can be produced even when production is lower than the demand at a certain moment. This is due to the fact that this depends on the moving average which is calculated over multiple (in this case 730) hours. Lastly, it is visible that electricity is used immediately as much as possible and that the surpluses of electricity production are stored in the battery.

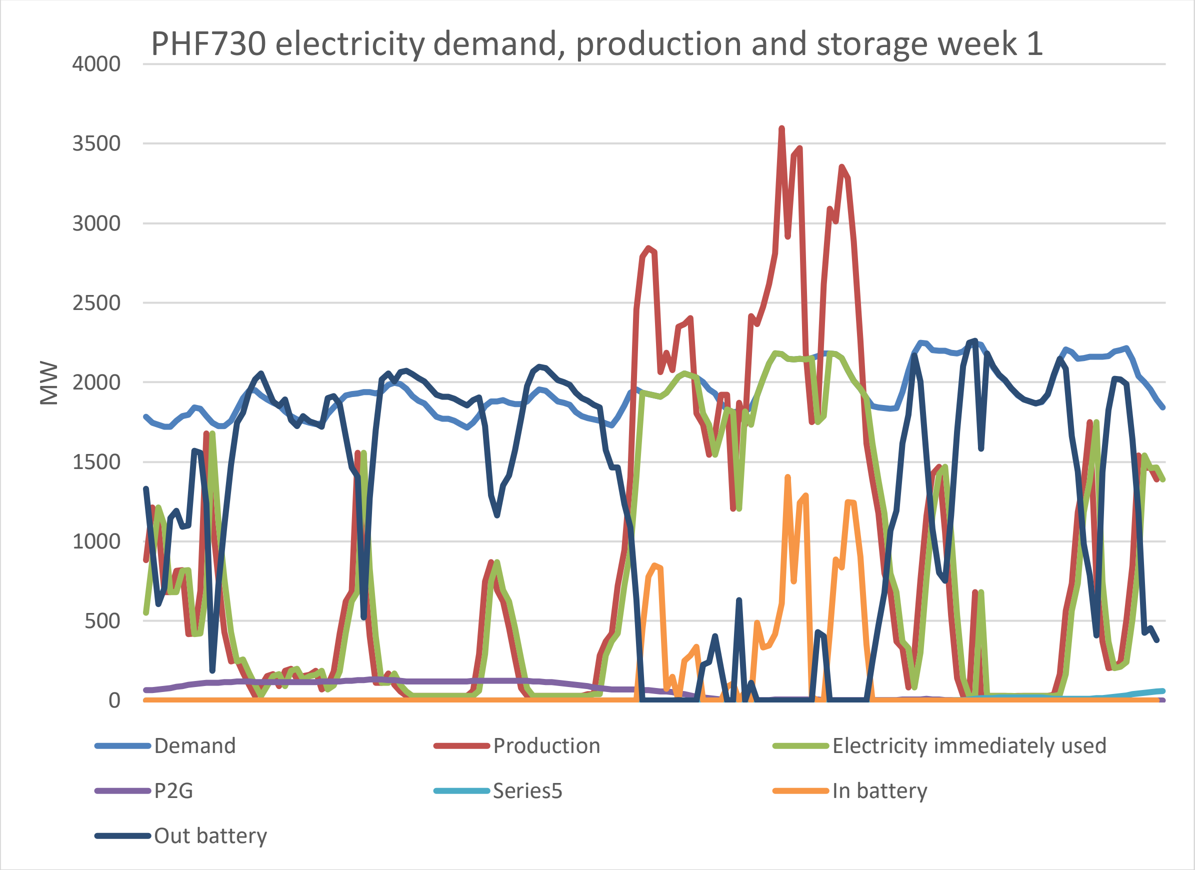

Figure 14. Electricity demand, production and storage for week 1 of the PHF730 scenario.

For the technical viable scenarios, the storage facilities were modeled using the models described in section 3.2 ‘The balancing model’. The amount of energy required in the storage facility at the start of the year, the total storage volume needed and the charge and discharge capacity of the storage units required are shown in table 6.

Table 6. The amount of energy required in the storage facility at the start of the year, the total storage volume needed and the capacity of the storage units required for the technically viable scenarios.

Scenario	Start level storage (GWh)		Storage volume (GWh)		Storage charge - discharge capacity (GW)	
	H2	Battery	H2	Battery	H2	Battery
MLSH	12		68		1.8 - 0.3	
MLFH	8.5		44		1.9 - 0.3	
MHSH	13		65		2.1 - 0.3	
MHFH	10		55		2.1 - 0.3	
PLFB		391		797		10 - 2.1
PLF2190	0	1058	0	1130	0.7 – 0	6.6 - 2.7
PLF730	127	693	666	727	1.1 – 1.0	6.8 - 3.1
PLF365	298	565	921	607	1.3 - 1.2	6.7 - 3.5
PHFB		1060		1678		9.8 - 2.4
PHF2190	228	1057	491	1106	0.5 - 0.2	5.8 - 2.6

4.3 Results interpretation

4.3.1 Municipality H2 storage

When using the surplus electricity produced in the RES region only to balance the electricity system of the municipality a total hydrogen storage between 44 and 68 GWh is needed. It seems counter intuitive that, with limited installed capacity, the need for storage is higher in a low electricity demand scenario than in a high electricity demand scenario. However, when only installing enough capacity to be self-supporting on a yearly basis, the installed capacity will be lower for the low electricity demand while demand peaks remain approximately the same. This results in more periods of shortage and therefore a higher need for storage. The hydrogen produced can be stored in salt domes within the province of Groningen. The total efficient storage volume available in Groningen is 31 TWh divided over 230 salt domes (*Ondergrondse Opslag in Nederland*, 2018b). Therefore, it can be concluded that balancing the electricity system of the municipality of Groningen using hydrogen is technically possible.

However, all scenarios on balancing solely the municipality proposed in this research require a huge amount of extra capacity of renewables to be installed in the RES region. While the RES region itself does use the electricity produced in real-time, large imbalances in the RES region electricity system remain.

4.3.2 Province storage

In contrary to the system in which balance to the municipality is given by the RES region, providing balance to the entire province is not possible using only hydrogen storage. Therefore, the possibility of using batteries to provide flexibility to the province was examined. Technically, this storage technology proved to be viable. However, social acceptance might become problematic since the residents of the RES region will not share in the benefit of having a balanced electricity system, while a lot of their surroundings will be formed by the generation capacity installed. In order to generate enough electricity, the full technical potential of wind turbines and solar PV have to be installed, which would result in a total area of 128 km^2 of solar panels (which accounts for 4.3% of the total surface area of the province) and 1547 wind turbines of 3 MW each. A Tesla Powerwall, for example, has a maximum charge/discharge capacity of 5.0 kW and can store up to 13.5 kWh and sells at a price of 7,500 euros ("Tesla Powerwall Home Battery Complete Review | EnergySage," n.d.)("Powerwall | The Tesla Home Battery," n.d.). In the best-case scenario, when using these power walls, the province would need over 59 million power walls in order to provide the required balancing. This would be an unrealistic amount of 100 power walls per household. Leading to a total investment cost of 442.5 billion euros or little over 7.5 million euros per household.

When combing the large-scale battery storage with hydrogen storage, a large amount of hydrogen storage is needed. When choosing the scenario with the highest need of hydrogen storage (921 GWh) this would still only be around 3% of the Groningen storage capacity in salt domes (31 TWh). From this it could be concluded that the storage of hydrogen would not be a problem in Groningen.

As expected, the combination of technologies reduces the storage volume in batteries needed. In the best-case scenario (PLF365) the need for Tesla Power Walls reduces to 44.9 million or 78 Power Walls per household. This results in a decrease in costs of 105.4 billion euros compared to the scenario in need of the largest battery storage volume. However, additional costs will have to be made in order to facilitate the hydrogen storage needed in this scenario. The costs of storing hydrogen in salt caverns amounts to 2.97 euro/MWh (Kooijinga, 2019b). With a total of 3.5 TWh of hydrogen produced in the best-case scenario, the costs of storing hydrogen in salt caverns will be 10.4 million euros per year, which lead to a total cost of 315 million euros for 30 years. The conversion of this amount electricity to hydrogen has a total cost of 2.4 billion euros when using a PEM electrolyser for its entire lifetime of 30 years (Kooijinga, 2019b). Using a combination of hydrogen and batteries is thus way cheaper than only using batteries.

5. DISCUSSION

This research provides an insight on the effect of certain choices made when constructing the Regional Energy Strategy of the region Groningen with the goal of providing balance to the electricity system of Groningen municipality. It is important to notice that only the electricity system of Groningen has been taken into account. These results are thus not applicable for the entire energy system. In order to develop a system in which the entire hourly energy demand of the municipality of Groningen is provided by the RES region, further research should be conducted.

First of all, within this research, the Energy Transition Model by Quintel was used to generate demand and supply patterns for RES region in the year 2035. As explained in the model description of the ETM, the supply of wind and solar electricity is determined by national supply curves. Inland and coastal patterns are separated but are still based on national instead of regional measurements. This might influence the results since Groningen patterns may differ from the national average due to weather conditions (number of sunny hours). To calculate the hourly generation from renewables, the ETM uses generation patterns of the year 2016. With an average wind speed of 3.9 m/s (KNMI, 2016), the year 2016 had a generation from wind turbines below the average as determined by Pierie et al (to be published). The solar irradiance, however, was above average with 117.16 W/m^2(KNMI, 2016; Pierie et al., n.d.). These deviations from the average wind speed and generation influenced the generation and therefor the storage facilities needed determined in this research.

The start scenario for both the RES region and the entire province of Groningen were provided by Quintel. However, Quintel has mentioned the possibilities of inaccuracies within these data sets. This inaccuracy is caused by the fact that both data sets are built up from information of single municipalities (the RES region was determined by adding up all partitioning municipalities). Since industry of a specific sector is often owned by one company per municipality, the exact demand of these sectors may not be disclosed. Therefore, an estimation was made for each municipality. Summing up the demand of the municipalities leads to a higher total energy demand in the start scenario than actually measured in 2016. This automatically leads to a relatively high electricity demand projection for 2035. Improving the quality of the start scenarios might change the outcomes of this research.

Besides inaccurate start values, the Energy Transition Model start scenario for the RES region of Groningen provided by Quintel does not contain data on the current size of the steel, other metals and fertilizer industry. Since, in the ETM, it is only possible to give percentual growth, these sectors cannot be modeled for the future of Groningen. When these sectors are expected to emerge, the model can thus not give a representative outlook on the future energy system.

In order to model the demand pattern of the RES region in the ETM, many forecasts of the 2035 situation were based upon the government document ‘Routekaart Groningen CO_2 Neutraal 2035’. This document refers to ‘work sessions with experts’ for their input used. Since no further references are used, the scientific quality of these input values may be questioned. Furthermore, despite the ambition of the municipality to implement their plans on the ‘Routekaart Groningen CO_2 Neutraal 2035’, the electricity system of the municipality of Groningen might evolve in a different manner than the RES region of Groningen, creating a change in its residual electricity demand in 2035.

In all demand scenarios, the opening of a new bio refinery plant is described. The total energy it will consume is approximated based on the bio kerosene produced. However, for the energy sources used for heat production, no changes have been made. It could be that bio refinery will need a different approach of heating and therefor a different distribution of resources used.

Besides the smart charging of electric vehicles, the demand side scenarios do not take any form of demand side management into account. Motivating habitants of Groningen to use electricity when electricity is produced instead of during periods of low generation could smoothen the unbalance between demand and supply. With a smoother unbalance pattern, less storage will be needed. This could change the results in terms of suitable storage mechanisms or storage capacities needed.

Since the aim of this research was to determine the extent to which it is possible to import all electricity unmet by own production (on an hourly basis) of the municipality of Groningen from the RES region Groningen in different RES and storage scenarios, the only technologies used within these research are RES generation technologies. This implies that only large scale (>15kW) solar PV, inland wind turbines and coastal wind turbines were used. However, geothermal energy, electricity from biomass and other forms of energy generation might also be implemented within the RES region of Groningen. Some of these technologies, such as electricity from biomass, may contribute to the flexibility of the electricity system. This could reduce the need for solar PV and wind turbines and might reduce the storage capacities needed for the region. Besides the denying presence of other technologies, this research, suggest installing the full technical potential of wind turbines and solar PV. However, technical potential and actual potential often differ quite a bit. This indicates that the installed might be lower resulting in a smaller amount of electricity generated on a yearly basis. Furthermore, installing the maximum potential of solar PV and wind turbines will change the landscape significantly which might result in public resistance. Putting the technical potential into national perspective also shows that this would be quite unrealistic. Looking at the goal of the National Program Regional Energy Strategies to generate 35 TWh of electricity from wind and solar PV Groningen would contribute almost half (15.17 TWh) which would be disproportional to both its energy use and its population.

Within this research, the battery proposed is assumed to have a round trip efficiency of 95%. However, some literature shows that the typical lithium battery only reaches a round trip efficiency of 90% (Lamboo, n.d.). Furthermore, this research does not include the self-discharge of the lithium batteries. Since, on a yearly basis, the discharging of the battery will already be more than charging of the battery, an extra amount of backup hydrogen is needed to recharge the battery.

The results in this study show a minimum capacity needed of certain storage technologies in order to be self-supporting. However, these results were based on the data of one year of generation. The generation patterns of solar PV and wind turbines differ each year. Some storage scenarios that seem suitable in this research may not be feasible in a year with less renewable generation.

Lastly, all costs for the battery storage option have been calculated using the Tesla Power Wall as a reference battery. Different type of batteries may result in different costs.

6. CONCLUSION

The aim of this research was to determine the extent to which it is possible to import all electricity unmet by own production (on an hourly basis) of the municipality of Groningen from the RES region Groningen in different RES and storage scenarios. Within the RES Groningen, only large wind and solar generation are included. This research showed that with the technical potential of these technologies, the entire province of Groningen could be self-supporting for electricity on a yearly basis. Furthermore, providing the municipality with electricity from the RES region Groningen in order to create a balanced electricity system for the municipality on an hourly basis was proved to be possible. In this case, hydrogen storage between 44 and 68 GWh would be needed with a charge capacity between 1.8 and 2.1 GW and a discharge capacity of 0.3 GW. The hydrogen produced to realize the balancing of the electricity system could be stored in salt domes within the province of Groningen. When using the RES region Groningen to provide balance only for the municipality of Groningen, a problem with social acceptance may occur since people living outside of the municipality of Groningen would not get the profit of a balanced electricity system while carrying the burden of the renewable generation technologies installed. Therefore, the possibility of balancing the electricity of the entire province was investigated. On a yearly basis, the technical potential of wind and solar PV in the province of Groningen provide more than enough to be self-supporting. On an hourly basis, however, the renewable electricity generation technologies cause an imbalance in the electricity system that has to be balanced using storage technologies. This research showed that when using the technical potential of renewables (which would result in 1547 wind turbines and 128 km^2 of solar PV), due to conversion losses, hydrogen alone is not suitable to provide enough flexibility to balance the electricity system of the entire province of Groningen. Even with efficiency improvements in both the generation of electricity from renewables and hydrogen storage and demand side management in the form of smart charging electric vehicles, the conversion losses for hydrogen storage proved to be too high. In order to make hydrogen a suitable option, more renewable production capacity is needed. Within the RES, these options are limited. However, the Klimaat Akkoord also announces that a large capacity of wind on sea to be installed. Part of this capacity might be allocated to the province of Groningen. In order to conclude on the possibility of hydrogen storage to provide enough balance when wind on sea capacity may be used in Groningen further research is needed.

Due to their high round-trip efficiency, batteries did prove to be technically suitable for balancing the electricity system of the entire province of Groningen when only using RES generation technologies. Without taking the self-discharge of the battery into account, this would result in a battery with a storage volume between 797 GWh and 1.7 TWh, a charge capacity between 10 and 9.8 GW and a discharge capacity between 2.1 and 2.4 GW for low and high electricity demand respectively. This would resemble the amount of one hundred power walls with the investment costs of over 7.5 million per household in the low electricity demand scenario and even more in the high electricity demand scenario. This indicates that, while using only battery storage is technically possible, it would not be economically feasible.

The optimum combination of hydrogen storage and batteries to provide flexibility to the provinces electricity system, as proposed in this research, proved to reduce the storage volume of batteries needed to 607 GWh with a charge capacity of 1.3 GW and a discharge capacity of 1.2 GW in a low demand scenario. The amount of hydrogen storage needed, in this case, would be 921 GWh with a charge capacity of 1.3 GW and a discharge capacity of 1.2 GW. A cost reduction of 105.4 billion euros on investment costs could be realized on battery storage when comparing the hybrid system with a battery only system. The additional costs of converting electricity to hydrogen and storing it in salt caverns would, in this case, amount to 2.7 billion euros (excluding the costs of generating the electricity lost during conversion) which is indeed much cheaper than using batteries. These results show that, when using hydrogen in combination with batteries, the province of Groningen can be self-supporting on an hourly basis even when only using RES generation technologies for its electricity production. This means that, even without the contribution of offshore wind (of which The Netherlands will install 49 TWh by 2030) and other renewable electricity sources, the province of Groningen would be able to support their own future electricity demand. When other electricity generation technologies would be installed, this would increase the possibility of using hydrogen and decrease the amount of battery storage needed, decreasing the total investment costs of the system. Furthermore, this might provide the opportunity of installing less of the RES technologies than their technically potential which would be more realistic. This research shows that balancing the Groningen electricity system proves to be possible but would require expensive storage facilities. Since this system is only part of the entire energy system, balancing the entire energy system will prove to be even more difficult.

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8. APPENDIX A – ETM INPUT ROUTEKAART GRONINGEN CO_2 NEUTRAAL

For the output of the municipality of Groningen, the scenario by the makers of the 'Routekaart Groningen CO_2 Neutraal 2035' was used. The scenario created by the municipality and used in this research can be found here:

https://pro.energytransitionmodel.com/scenarios/355118

8.1 Calculating municipality residual demand

Using Excel, the residual electricity demand on an hourly basis was determined. In order to do this, the municipality demand side pattern as well as the supply pattern were determined using the following formulas:

(1) $$Demand = \sum Merit :: User::TotalConsumption$$

(2) $$Supply = \sum Merit::MustRunProducer + \sum Merit::DispatchableProducer + \sum Merit::VolatileProducer + \sum Merit::Flex::Base + Merit::Flex::Storage$$

From formula (2) it can be derived that storage facilities within the municipality are assumed to be used. The residual electricity demand (RED) of the municipality was determined using the following formula:

(3) $$RED = DemandMu - SupplyMu$$

When RED is negative, a surplus of electricity is produced while when RED is positive, a shortage of electricity occurs within the municipality of Groningen.

9. APPENDIX B – IMPORTANT OUTCOME SYSTEM ANALYSIS

Table 7. Change in electricity demand for sensitive variables whit a 1% input increase.

Input Variable	Change in electricity demand with a 1% increase (PJ)
Demand · Households · Residences	0.12316
Demand · Households · Space Heating & Hot Water · Condensing combi boiler	-0.11284
Demand · Households · Space Heating & Hot Water · District heating	-0.11762
Demand · Households · Prosperity · Hot water	0.47322
Demand · Households · Prosperity · Electric appliances	0.33848
Demand · Households · Prosperity · Heating demand	2.36082
Demand · Buildings · Insulation	-0.11817
Demand · Buildings · Appliances · Appliances efficiency	-0.44632
Demand · Buildings · Demand growth · Number of buildings	2.25907
Demand · Buildings · Demand growth · Electricity per building	0.97374
Demand · Buildings · Demand growth · Heat per building	1.10291
Demand · Buildings · Demand growth · Cooling per building	0.18065
Demand · Transport · Efficiency improvement · Combustion engine vehicles	-2.43763
Demand · Transport · Passenger transport · Applications · Passenger transport	1.80647
Demand · Transport · Freight transport · Applications · Freight transport	1.43842
Demand · Industry · Chemicals · Size	0.17491
Demand · Industry · Chemicals · Efficiency improvement electricity	-3.04061
Demand · Industry · Chemicals · Electric boiler	0.25045
Demand · Industry · Central ICT · Efficiency improvement	-0.60238
Demand · Industry · Food · Efficiency improvement	-1.31198
Demand · Industry · Paper · Efficiency improvement	-0.3611
Demand · Agriculture · Demand growth · Electricity	0.14397

10. APPENDIX C – ETM SCENARIOS RES REGION AND PROVINCE

Quintel provided a start scenario in which the municipality of Groningen is excluded from the province of Groningen. This start scenario can be found here:

RES Start scenario: https://pro.energytransitionmodel.com/saved_scenarios/8370

From this start scenario, the demand scenarios were constructed which can be found here:

RES Low demand: https://pro.energytransitionmodel.com/saved_scenarios/8371
RES High demand: https://pro.energytransitionmodel.com/saved_scenarios/8372

Quintel also provided a start scenario for the entire province of Groningen which can be found here:

Province start scenario: https://pro.energytransitionmodel.com/saved_scenarios/8860

11. APPENDIX D – OVERVIEW INPUTS ETM RES REGION WHEN FOLLOWING MUNICIPALITY TRENDS

Table 8. The differences between the 2035 outlook of the municipality and the RES region.

	Municipality demand 2035	RES region demand 2035
Households · Population & Housing Stock · Population	245,000	335,100
Households · Population & Housing Stock · Residences	135,171	135,171
Households · Population & Housing Stock · Residences · Apartment	35.3%	16.4%
Households · Population & Housing Stock · Residences · Cornerhouse	12.9%	11.7%
Households · Population & Housing Stock · Residences · Detatched House	13.4%	35.8%
Households · Population & Housing Stock · Residences · Semi-detatched House	8.8%	17.5%
Households · Population & Housing Stock · Residences · Terraced House	29.6%	18.9%
Households · Insulation · Apartment	27.7%	29.3%
Households · Insulation · Cornerhouse	24.4%	20.8%
Households · Insulation · Detatched House	26%	16.8%
Households · Insulation · Semi-detatched House	27.7%	20.9%
Households · Insulation · Terraced House	27.7%	23.9%
Households · Solar Panels · PV Panels	31%	48.7%
Households · Solar Panels · Solar Thermal Collectors	39.4%	31.7%
Buildings · Insulation	57.7%	56.2%
Buildings · Solar Panels · PV Panels	29%	74.4%
Transport · Passenger Transport · Applications · Cars	60%	70.3%
Transport · Passenger Transport · Applications · Trains	15%	6.0%
Transport · Passenger Transport · Applications · Busses	0%	8.8%
Transport · Passenger Transport · Applications · Motorcycles	10%	6.1%
Transport · Passenger Transport · Applications · Bicycles	5%	8.9%
Transport · Freight Transport · Applications · Trucks	10%	74.1%
Transport · Freight Transport · Applications · Trains	0%	4.9%
Transport · Freight Transport · Applications · Domestic Navigation	7.1%	21.0%
Industry · Chemicals · Size	111%	130%

12. APPENDIX E – OVERVIEW OF LITERATURE ON BIO-REFINERY

A bio kerosene production facility will be running in Groningen by 2035. Literature has shown a variety of energy needed in order to produce this bio kerosene. The table below contains an overview of literature found. When energy use was given per MJ of produced product, the minimum energy content for kerosene of 42.8 MJ/kg (*Sustainable Way for Alternative Fuels and Energy in Aviation Final Report*, 2011) was used to calculate the energy need per kg produced product.

Table 9. Overview literature production bio kerosene.

Energy needed	Raw material	Product	Source
13.46 MJ/kg produced	Waste cooking oil	Bio-diesel	(Intarapong, Papong, & Malakul, 2016)
0.47 MJ/MJ produced = 20.116 MJ/kg produced	Used cooking oil	Bio-diesel	(Ou, Zhang, Chang, & Guo, 2009)
631-744 MJ/GJ produced = 27.0-31.8 MJ/kg produced	Used cooking oil	Bio-diesel	(Thamsiriroj & Murphy, 2011)

Since all literature found is on bio-diesel instead of bio-kerosene and the energy content of bio-diesel is lower than that of bio-kerosene, the first finding (13.46 MJ/kg) is expected to be too low. Therefore, for the low electricity demand scenario, the second finding (20.116 MJ/kg) is used and for the high electricity demand scenario the last finding (31.8 MJ/kg) is used.