An explorative scenario study into a 100% renewable energy system in the Netherlands in 2050

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Table of contents

Abstract

The Paris Agreement and Dutch Climate Agreement have accelerated scenario studies into the energy system of 2050. Most scenarios focus on reaching a zero CO_2-emissions scenario or focus on 100% renewability but then have large energy demand reductions. The NVDE wanted to explore the possibility of a 100% renewable energy system without limiting economic structural growth for energy demand reduction purposes. This explorative scenario study models a 100% renewable scenario using the Energy Transition Model (ETM), a bottom-up modelling approach, with two assumptions regarding Dutch economic structure: 0% (2050a) and 1% (2050b) growth per year for the industrial sector. An adapted Trias Energetica is used for scenario building based on three pillars: (i) electrification and efficiency improvements, (ii) implementation of renewable sources, and (iii) balancing the system using storage and conversion techniques. This resulted in a decrease in final energy demand to 1330 PJ (-35%) for 2050a and 1494 PJ (-27%) for 2050b. Both scenarios lead to a secure, 97% renewable energy system. It was concluded that not a pre-set constraint in economic structure, but resulting electrification and efficiency improvements lead to the decrease in demand. The main technologies deployed are large-scale wind and solar PV, green hydrogen, large-scale batteries, and power-to-heat/hydrogen installations. Innovation opportunities in a highly renewable energy system were determined for flexibility options. For better insights into the flexibility requirements, more research is needed on the system implications of innovations in current technologies, future industry, an increased interconnection capacity and an international approach to the energy transition.

Executive summary

This scenario study has explored the possibility of a 100% renewable energy system in the Netherlands in 2050 in which industrial demand is not limited ex ante. The modelled scenario is not the only outlook for the future, but should be seen as a vision that shows that such a fully renewable energy system is technologically possible and that indicates the most important elements of it.

Building the scenario

Two main conditions were determined as starting point:

1. Full renewability of the energy system.
2. No limitation in industrial growth for energy demand reduction purposes.

Based on these conditions and the potentials found in previous scenario studies, the scenario was built. An adjusted version of the Trias Energetica was used, in which the third pillar about balancing supply and demand was changed from 'addition of fossil fuels in the most efficient way' to 'efficient use of storage and conversion'. The scenario is modelled for 0% (2050a) and 1% (2050b) industrial growth per year using the bottom-up approach Energy Transition Model (ETM).

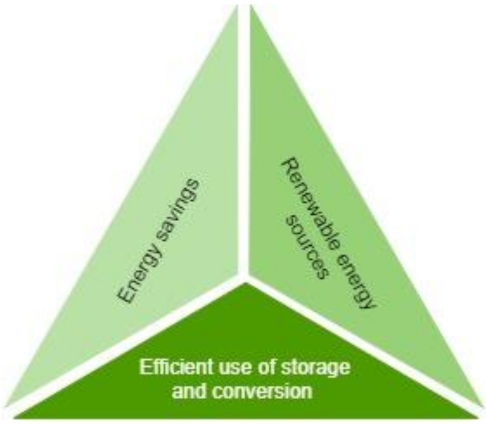


Figure 1. Adjusted Trias Energetica used in this study.

Energy demand

The final energy demand decreases to 1330 PJ (-35%) for 2050a and 1494 PJ (-27%) for 2050b compared to 2015. Industry remains the largest contributor to the total demand, and its share increases from 37% in 2015 to 49% (2050a) and even 54% (2050b), while demand in the built environment is roughly halved and demand in the transport sector decreases by more than a third compared to 2015.

The reduction in final demand is caused by strong electrification of the built environment and transport sector. Electric heat pumps and a heat network play an important role in the built environment. In the transport sector, most road transport will be electric in 2050. In both sectors, hydrogen is used for end-uses that are not easy to electrify. The fuels for international transport are not included in the scenario. It is estimated that a refinery sector with renewable feedstock can accommodate for the required fuels, because the exported fossil fuels are roughly triple the amount of required renewable fuels. In the industrial sector, electricity, hydrogen, and a heat network are equally as important. Due to efficiency improvements, the final energy demand decreases in 2050a. The 1% growth per year leads to a net increase in industrial energy demand in 2050b. The fossil feedstock could not be replaced by renewables in the ETM, so it is recommended to improve the industrial sector in the ETM.

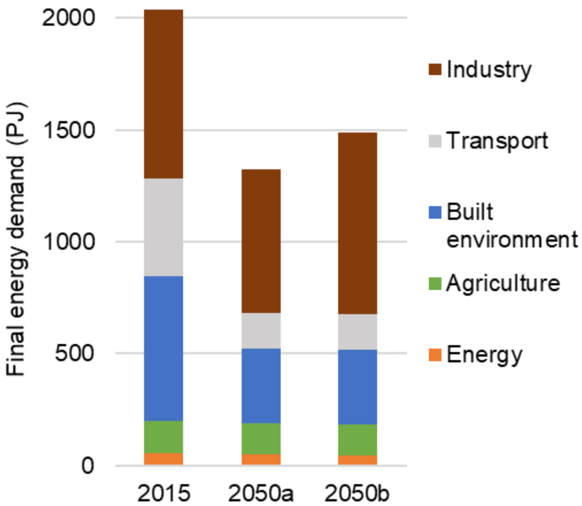


Figure 2. Final energy demand in 2050a/b compared to 2015 (PJ).

The reduction in final energy demand is comparable to previous scenario studies that focused on an energy system with high shares of renewable energy. Because the energy system can accommodate both 0% and 1% industrial growth per year, it is concluded that a renewable energy system in feasible without limiting the growth of the industrial sector.

Energy supply

The demand is met by a 97% renewable energetic energy supply. The remaining 3% fossil energy sources are residual streams that cannot be changed in the ETM. Because the individual streams are negligible, the scenario is considered to be 100% renewable.

Electricity plays an important role in the energy supply. Most electricity is generated by the 65 GW wind and 93 GW solar sources installed. A small amount of electricity is generated by dispatchable hydrogen plants during peak demand. All green hydrogen in the scenario is produced from electricity surpluses and electricity generated in 25 GW offshore wind parks designated for hydrogen production. The hydrogen is mainly used for supplying heat for industry. To a smaller extent, the hydrogen is used as transport fuel and for electricity generation. In 2050a, a significant share of the produced hydrogen is also exported.

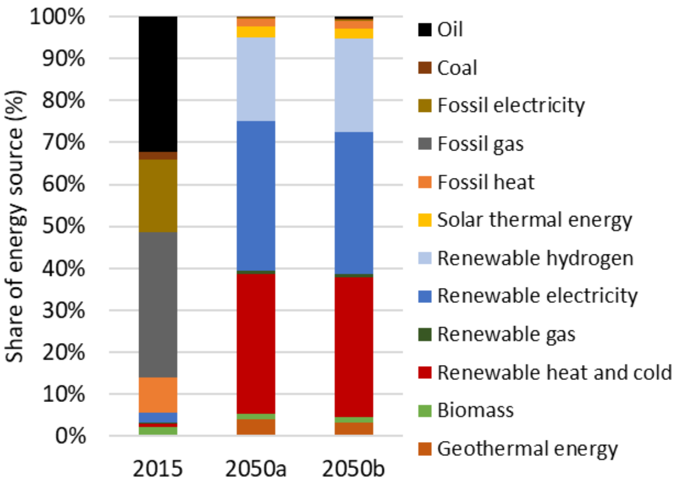


Figure 3. Renewability of final energy demand in 2050a/b compared to 2015 (PJ).

Renewable heat also plays a considerable role in the energy supply. Due to electrification efforts in the built environment, heat pumps make use of ambient air, which reduces the required heat supply. In addition, a heat network is implemented in the built environment, agriculture, and industry. The heat for the heat network is supplied by geothermal energy sources, power-to-heat heat pumps and residual heat from industry.

Flexibility

Because of the high share of variable electricity sources, the electricity generation, and thus energy supply, is highly weather dependent. Without flexibility options, the energy system shows a yearly surplus of electricity, a shortage of hydrogen, and heat surpluses in summer and shortages in winter. For ensuring a secure system without black-outs, system flexibility options are deployed. For hydrogen and heat, long-term storage is deployed.

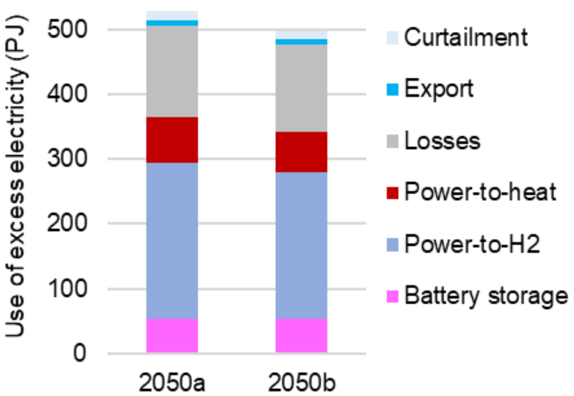


Figure 4. The use of excess electricity in 2050a/b (PJ).

The excess electricity that is generated throughout the year is mostly converted to hydrogen and heat. This results in corresponding conversion losses. In addition, the surplus is stored in batteries of electric cars, in home batteries, and in large-scale storage, and to a small extent some electricity is exported. This reduces the need for curtailment.

Innovations in storage and conversion technologies, and in the demand-response of industry at peak energy demand and low supply improve flexibility options.

Another flexibility option that balances the system is import and export. This does not play an important role in the modelled scenario, because of the cost-based modelling approach of import in the ETM. However, a more international or at least north-west European energy system promises to be more cost-effective than the country-based approaches to the energy transition. Therefore, it is recommended that further analysis is conducted on the potential of import in our future energy system.

Preface

I would like to attribute this page of my thesis to say thank you to those who have helped me during my master thesis. First of all, I would like to thank Marc, who has been a great source of support and guidance through my thesis. Marc is a source of inspiration with, as it seems, unlimited knowledge on the Dutch energy system and who always knows how to lighten up the mood by making a joke. I would also like to thank Joyce and Taina, for their guidance and trust. You have given me your full support during the thesis, and it was a pleasure working with you. One more thing: thank you for marathon reading my thesis in the last weeks before my defense! I would also like to thank Floris for making time to go through my thesis and examine the academic quality. Furthermore, I would like to thank Irene and Bart for helping out with the webinars. Without Irene's help with the presentation and the interactive questions, I would not have been able to have so much interaction with the members. Bart, thank you for helping out with the introduction and structuring the feedback afterwards, and thank you for introducing me into the wonderful world of the ETM. Lastly, I would like to thank the NVDE for making the research possible, and my other NVDE colleagues for giving me such a warm welcome and pleasant work environment even in these challenging COVID times.

Introduction

1.1. Host organization

This research project is proposed by the NVDE – the Netherlands association for renewable energy (Nederlandse Vereniging voor Duurzame Energie). NVDE is an organization that represents the interests of companies in the field of renewable energy. Currently, over 6000 companies are affiliated with the NVDE[1]. Examples of these organizations are energy companies (Eneco and Essent), renewable energy sector organizations (Holland Solar, NWEA and Platform Geothermie), grid operators (Tennet and Alliander), consultancies (CE Delft and TNO), and banks (ABN AMRO and ASN bank). The main goal of the NVDE is enhancing the energy transition and aiming for a fully renewable energy economy in the Netherlands in 2050. Some activities of the NVDE are gathering information, connecting organizations in the renewable economy, and communicating information about renewable energy to the public and political parties. The NVDE does not have departments since it is a small organization. During this study, I have worked closely with Marc Londo who works on strategic development.

1.2. Background information

Since the NVDE strives for a fully renewable energy system in the Netherlands in 2050, the NVDE is interested in a design for this future energy system. A scenario study can model and thereby test energy system designs. Most energy system studies focus on challenges arising from global climate change due to anthropogenic emissions.

Climate change has been extensively studied and this research has been summarized by the Intergovernmental Panel on Climate Change (IPCC). An increase in global temperature is observed since the start of the industrial revolution[2]. This increase is caused by the enhanced greenhouse effect of the atmosphere due to an increase in atmospheric greenhouse gas levels (mainly CO_2). This occurred multiple times during the history of the earth because of e.g., volcanic activity, but currently the global warming is mainly caused by the burning of large amounts of fossil fuel[3]. In the projected 'business as usual' scenario from IPCC, the amount of global greenhouse gas emissions is expected to rise even further. This is mainly caused by increased energy demand due to further development of underdeveloped countries and a growing world population over the next century. Depending on the amount and rate of change in the world's energy system and economy, different prospective scenarios are possible. The IPCC has divided them into four pathways (Representative Concentration Pathways). The pathway that leads to the lowest global temperature increase is also the lowest emission scenario[2]. The increase in global temperature is proportional to the number of adverse effects on human society and environment. Some examples of the impacts of climate change are coastal flooding due to sea level rise, heat waves due to more extreme weather events, inland flooding due to extreme precipitation and reduced crop yields due to droughts[4].

In order to prevent disastrous anthropogenic influence on the climate, leaders of the countries that have endorsed the United Nations Framework Convention of Climate Change (UNFCCC) meet every year during the Convention of Parties (COP)[5]. In 2015 the COP21 took place in Paris. During this assembly, all countries acknowledged the Paris Agreement, stating that the countries would try to limit the aforementioned global warming to 2°C above pre-industrial levels, and preferably reduce it to below 1.5°C[6]. In 2016, the European Union agreed that their GHG emission should be reduced by at least 40% compared to 1990 levels by 2030[7]. The Netherlands determined their national contribution in the Climate Law with a 49% GHG emission reduction target by 2030 compared to 1990 and a 95% GHG emission reduction target by 2050[7,8]. To reach the target for 2030, the climate agreement was ratified by the government, companies, and other involved parties in the main energy sectors: built environment, transport, industry, agriculture and land use, and electricity[8]. PBL has studied the climate agreement and concluded that the mentioned technological solutions could lead to a 49% GHG emission reduction in 2030[9].

The potentials for renewable energy in the Netherlands are high for wind and solar energy sources. Within the climate agreement, there is a large focus on wind and solar for our future energy supply. However, in 2019 the share of wind (11.5 GWh) and solar (5.2 GWh) was only 2.3% of the total energy supply and 13.7% of the electricity generation[10]. Also, electricity covered only 16% of the final energy consumption in 2018[11]. The required shift from fossil energy towards electricity from renewable energy sources poses major challenges to the energy system. This means that not only renewable supply should be developed, but drastic changes are needed in the demand sectors, in energy and heat infrastructure and in storage and conversion technologies that produce energy carriers, such as hydrogen (H_2), from renewable electricity.

Because of the drastic changes needed in the energy system on both the supply and demand side, it is extremely important to explore future energy systems and guide developments into the right direction. If all components of the system develop independently, it is possible that an unbalanced energy system is achieved. This means that the technologies chosen by consumers do not correspond to the energy supply that is available, for example H_2 cars without H_2 production. Another challenge is the weather dependency of wind and solar energy and the development of the required energy infrastructure. Without implementation of storage or conversion technologies, at some moment too much energy is generated and at others not enough. Both unbalances in the system could lead to black outs. As a society that is highly dependent on energy, it is undesired to have any blackouts. Therefore, it is of utmost importance to prevent those unbalanced moments. In addition, the inefficiently used technologies in an unbalanced system leads to unnecessary high financial costs for the energy transition and consecutive high costs to balance the system.

Because of these negative societal effects, the NVDE is interested in projecting balanced energy systems with 100% renewable energy supply and consumption. Energy models can be used to construct possible future energy scenarios. Several energy modelling studies have already been performed regarding a balanced, CO_2 neutral energy system for the Netherlands in 2050[12,13]. The studies focused on several scenarios. TNO has constructed two scenarios considering the intrinsic motivation of organizations and citizens and Berenschot & Kalavasta have constructed four scenarios – with regional, national, European, and international governance[12,13]. These studies will be discussed in more detail in section 2.

1.3. Research problem

The published CO_2-neutral scenarios lead to different shares of renewable energy in the total energy supply, but the *transform* scenario of TNO and the *regional* and *national governance* scenarios of Berenschot & Kalavasta have the highest share of renewable energy. One condition for the *transform* and *regional governance* scenarios is very significant structural economic changes in the Dutch industry[12,13]. This seems to imply that a largely renewable energy system is not possible without large decline of the industrial sector's size. No study has been performed yet that examines whether a renewable energy system could be achieved while maintaining the economic structure of the Netherlands, i.e. maintaining energy intensive sectors that produce substances that we will need in a decarbonized economy.

1.4. Research aim and questions

The goal of this project is to find a scenario for 2050 that leads to a fully renewable energy economy, rather than a CO_2 neutral one, with preservation of the economic structure of the Netherlands. The scenario gives insights in the required innovations in our energy system. Additionally, this study aims to identify innovation opportunities in the scenario and discuss which innovative technologies or policies could be implemented to improve the future energy system. This leads to the main research question to be answered in this study: 'How can the energy system of the Netherlands be innovated to become fully renewable in 2050?'.

In order to answer the main research question, three sub questions are defined that each examines a different element of the research problem. The three questions also require a different research approach, which is discussed in section 3. The sub-research questions to be studied are:

1. What are the realistic future potentials for the renewable energy supply, demand sectors, key conversion, and infrastructure options?
2. How can those future potentials be combined into one or more all-renewable scenarios for 2050 using the Energy Transition Model (ETM)?
3. What are the required innovations, and what are innovation opportunities in a fully renewable energy system and the ETM?

1.5. Scientific and societal relevance

This study is scientifically and societally relevant in several ways. First of all, by focusing on a renewable energy system with economic structure conservation, this study fills the scientific knowledge gap found in literature. It also adds to the already existing knowledge on possible scenarios for the Netherlands in 2050. This has a scientific and societal effect; the scientific knowledge on energy modelling and on renewable energy systems is broadened, and policy makers and organizations have more insight to base their political or operational decisions on. In addition, identification of innovation opportunities is a driving force for more research and innovation funds for the specific innovation gaps.

Besides the direct effects already mentioned, this study has high relevance for Dutch society. It is of utmost importance for the energy transition that we move towards a stable energy system without blackouts. Before policy on the energy transition can be made, a shared vision of the future energy system is necessary. Also, proving that a stable energy system is possible with high amounts of renewable energy could increase support among the Dutch people for the energy transition.

1.6. Thesis outline

The thesis is divided into several chapters that each describe a different part of the research. In section 2 literature about scenario studies and a renewable energy system is discussed, and the chosen conceptual framework for modelling the scenario is specified. Section 3 describes the methodology, e.g., the research approach and the different research methods. The projections and potentials of the future Dutch energy system are presented in section 4, per energy demand and supply section. The scenario modelled based on the found projections and potentials is presented in section 5. Section 6 discusses the results in light of previous scenarios studies and literature and shows innovative and unexpected outcomes. Possibilities for further research are presented in section 6 as well. The thesis is completed with the conclusion and recommendations in section 7.

Literature and conceptual framework

2.1. Energy system studies

Modelling the energy system of the Netherlands for 2050 is a relatively new area of interest that emerged in the last decade. The topic gained importance after the ratification of the Paris Agreement in 2015[6]. Governments around the world wished for quick GHG emission reductions and wanted to take swift action. In addition to this global emphasis on the energy transition, the Dutch Climate and Energy Exploration (Klimaat- en Energieverkenning) 2020 stated that the rate of emission reduction should be doubled to reach the 2030 Climate targets for the Netherlands[14]. To achieve this goal a good understanding of the future energy system is crucial. The energy system scenarios can be used as a vision or a guideline to lead energy infrastructure investments in the right direction.

Globally, many studies have been performed on the feasibility of a global renewable energy system[15–19]. The studies differed in perspectives on the future, with strong opposing views on the motivation of citizens and government to take action on climate change, on the influence of market and technology push, and on the expected costs of technologies, which leads to different outcomes[15]. Some studies found it possible to achieve a global 100% renewable energy system by 2050[16–18], and regard this future energy system to be more efficient and cost effective than the current fossil energy system[18]. Others project a different development and have fossil energy and CCS in their scenarios to aim for climate neutral energy systems[19]. In general, several main similarities were concluded that are required to achieve a secure energy system with a high share of renewable energy:

- Energy savings are necessary to balance demand and supply[16,17].
- Strong electrification of end-uses is necessary to reduce energy demand and to increase the amount of direct electricity use, thus lowering the need for conversion technologies[15,17,18].
- Changes in infrastructure and flexibility are required e.g., intermittent energy sources combined with conversion and storage options[15].
- Innovation in challenging sectors e.g., shipping, aviation and industry, is needed to decarbonize these sectors[15,17].

The studies on global scale mostly did not regard the regional potentials of renewable energy sources but looked at the total energy demand of countries and the total, global potential of renewables. Studies performed for the European energy system have considered the local potential of the European Union and came to the same conclusion as the global studies: a 100% renewable electricity or energy system is economically and technologically feasible[20,21]. This future system can even be more cost efficient than our current European energy system[20,22]. Alike in a global renewable system energy savings and electrification play an important role, but apart from that many similarities and differences in the scenarios were found[20,22,23].

All aforementioned scenarios show a strong increase in renewable electricity generation[20,22,23], but the extent to which renewable sources are implemented in the scenarios for electricity generation varies from 75% to 100%[23]. The generated electricity is then used in several ways. One direct use is through electrification of the built environment and the transport sector[20,23]. Another use is as energy source for the industrial sector. However, studies show a trade-off between electricity and hydrogen as industrial energy carrier[23]. An energy carrier that is used in increasing amount is biomass, with a share of up to 20% of the total energy demand[20,23]. One large uncertainty in the scenarios is the deployment of nuclear energy and new technologies, such as CC(U)S. For example, the European Commission states that CCS has to play an important role in the energy transition, while other studies reach a secure 100% renewable energy system without using CCS[20,22,23].

These similarities and differences were determined for the European Union, but they might also be applicable to countries. Case studies for Germany and Kazakhstan have shown that a 100% renewable energy system by 2050 is feasible, even with the high share of intermittent energy in Germany and the little potential for volatile energy sources e.g., wind and solar, and energy-intensive industry in Kazakhstan[24,25].

Over the last decade, the future energy system of the Netherlands has been explored as well. In 2020, Sijm et al. have published a review of scenario studies that analyzed the Dutch energy system, stating that most studies only explore some part of the energy system, while only a few have an holistic approach[26]. The studies reviewed by Sijm et al. with holistic approaches are *Net voor de toekomst* by CE Delft[27], *Beelden van een CO_2-arme samenleving* by Quintel Intelligence[28], *Elektronen en/of moleculen* by Berenschot[29], *Gasunie Survey 2050* by Gasunie[30], and *The future Dutch full carbon-free energy system* by KIVI[31]. A study not included in the review is *Nederland 100% duurzame energie in 2030* by Urgenda[32]. The two most current scenarios are also not included in the review: *Scenario's voor een klimaatneutraal energiesysteem* by TNO[13] and *Klimaatneutrale energiescenario's 2050* by Berenschot & Kalavasta[12]. The studies had different goals and perspectives and therefore modelled the future energy system using a wide variety of assumptions. An overview of the studies is given below. The ETM was used to model the scenarios, unless specified otherwise.

- TNO (2020) - Scenario's voor een klimaatneutraal energiesysteem: This study presented two CO_2-neutral energy system in 2050 – the *Transform* and *Adapt* scenarios. The main difference between the two narratives is the intrinsic motivation of Dutch people and organizations to move towards a more renewable energy system. The *Transform* scenario reasons from high intrinsic motivation, resulting in fast and far-reaching actions that transform the energy economy into a 96% renewable one including innovative technologies. The *Adapt* scenario, however, assumes low motivation which leads to a 74% renewable energy system. The OPERA energy model was used, which is based on cost-optimalization.[13]
- Berenschot & Kalavasta (2020) - Klimaatneutrale energiescenario's 2050: The goal of this study was to model four different CO_2-neutral energy systems for 2050. This study was a follow-up of *Net voor de toekomst* by CE Delft. An updated scenario study was requested due to the new insights in the energy transition that were gained after the ratification of the Climate Agreement. The narratives of the four scenarios were based on the previously determined narratives in *Net voor de toekomst*. This resulted in the *Regional governance, National governance, European governance,* and *International governance* scenarios. All lead to 100% CO_2-emission reduction, while the pathway towards emission reduction differs much. The *Regional governance* and *National governance* narratives assume strong renewable self-sufficiency with limited space for import, while the other two narratives reason from a more international approach, relying more heavily on biomass and hydrogen, and a much lower share of renewables. Another important difference between the scenarios is the rate of energy demand reduction in the industrial sector. In *Regional governance* the energy-intensive industry shrinks in size and in *National governance* it maintains its size, while the industry is assumed to grow in *European governance,* and *International governance*.[12] The share of renewable energy in the modelled system is 95% for *Regional governance*, 95% for *National governance*, 69% for *European governance*, and 58% for *International governance*, according to the results in the Energy Transition Model.
- CE Delft (2017) - Net voor de toekomst: This study modelled four CO_2-neutral energy systems for 2050 – *Regional steering, National steering, International steering,* and *Generic steering*. The narratives for the scenarios are comparable to those from the follow-up study by Berenschot & Kalavasta[12]. Again, all scenarios result in 100% CO_2-emission reduction.[27]
- Quintel Intelligence (2015) - Beelden van een CO_2-arme samenleving: Two narratives for the future Dutch energy system were modelled: 80% and 95% CO_2-emission reduction. The 80% CO_2-emission reduction scenario results in renewability of 65%, and the 95% CO_2-emission reduction in 91%.[28]

- Berenschot (2018) - Elektronen en/of moleculen: Two scenarios for a CO_2-neutral energy system – the *Electrons* and *Molecules* scenarios, which reach 100% CO_2-emission reduction. Both scenarios have a different perspective on the energy carrier most used in the energy system. The *Electrons* scenario assumes strong electrification of all energy demand sectors, while the *Molecules* scenario assumes the deployment of hydrogen as main energy carrier. The share of renewability of these scenarios could not be determined.[29]
- Gasunie (2018) - Gasunie Survey 2050: Two CO_2-neutral scenarios – for the 2030 and 2050 energy system. The 2050 scenario is based on strong electrification, combined with the use of hydrogen. The addition of battery storage, conversion to hydrogen, and hydrogen turbines leads to an 88% renewable energy system.
- KIVI (2017) - The future Dutch full carbon-free energy system: This study proposes a design for the Dutch energy system of 2050 that has not been simulated yet. The scenario results in 100% renewability, with mainly national electricity generation by wind and solar photovoltaic (PV) sources. The end-use sectors are electrified, except from high temperature processes, which are fueled by hydrogen. For securing the system battery storage and conversion to hydrogen was introduced.
- Urgenda (2014) - Nederland 100% duurzame energie in 2030: The goal of this study was modelling a 100% renewable energy system for the Netherlands in 2030. The result was a 97.5% renewable system, but far-reaching assumptions were made. For example, the energy-intensive industry was assumed to reduce its energy demand with 50% due to an increased demand in circularity and a decreased demand for industrial products. Furthermore, it was assumed that in 2030 the transition would be made to a plant-based diet and energy-neutral agriculture.[32]

The scenarios have many similarities. The same trends were determined for the Dutch energy transition as previously concluded for the global and European energy transition: energy savings, electrification of energy demand end-uses, such as heat pumps in the built environment and electric cars, electricity generation by renewable energy sources, mostly wind and solar PV, and addition of battery storage and power-to-hydrogen to stabilize the system[12,13,26–33]. Differences in the scenarios are due to contradicting assumptions about the amount of energy demand reduction and electrification[26]. These two factors also influence the energy supply mix required. Although most of the scenarios include wind, solar PV, and hydrogen, their share and installed capacity differs much[12,13,26–32]. The wide variety of outcomes is shown in Figure 5, where the primary energy demand of multiple discussed scenarios is shown, divided in fossil and renewable share of the total demand. Not all studies made a clear distinction between energetic and non-energetic primary energy demand. Energetic demand defines the demand for energy generation purposes and non-energetic for feedstock purposes for industrial processes.

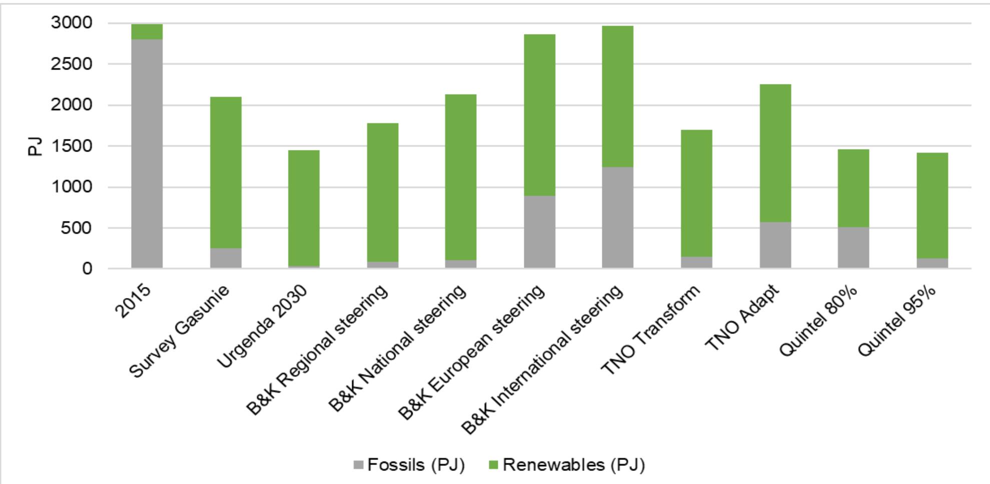


Figure 5. The primary energetic and non-energetic energy use in 2050 for multiple Dutch energy system scenarios compared to 2015[12,13,28,30,32].

Figure 5 illustrates that most scenarios model the energy system with a large reduction in energy demand. However, the reduction in energy demand seems to be coupled to the share of renewables. The scenarios that aim for a large, towards 100%, share of renewable energy in the total supply (*Urgenda*, *KIVI*, *TNO Transform*, *B&K Regional governance* and *B&K National governance*) have a significantly larger energy demand reduction than scenarios that have larger shares of fossil energy. In the *Urgenda*, *B&K Regional governance* and *B&K National governance* scenarios the energy-intensive industry is limited in growth or even shrunk. It is not clear whether constraining industrial growth is a condition for achieving an energy system with a high share of renewables or a result of other assumptions.

2.2. Conceptual framework

Based on the knowledge gap found in literature and the relevance to the NVDE, this study explores the possibility of an energy system scenario for the Netherlands in 2050 with two specific assumptions:

- The energy system is 100% renewable.
- The energy-intensive industry is not forced to decrease in size due to energy supply constraints.

This exploratory study has the technological feasibility of such a scenario as focal point and does not focus on the most cost-efficient decarbonization options. Therefore, the costs of the scenario are left outside the scope of the project.

2.2.1 Modelling approach

The focus on technological feasibility influences the modelling approach. There are different energy system models available, but in general two distinct modelling approaches can be chosen to model the energy system: the top-down and bottom-up approach[34,35]. Both have a very different perspective on the coupling of economic growth and the energy system:

- The top-down approach models the energy demand sectors as energy sinks, and does not differentiate between technologies or end-uses in the sectors[35]. c. The energy system is treated as a black box, influenced by these macro-economic parameters and their historical trends[34]. If a technology is more expensive, it will not be introduced in the scenario at that point[36]. This approach tends to result in a non-renewable economy since the non-renewable energy sources are more developed and therefore less expensive.
- Contrary to this macro-economic modelling, the bottom-up approach models different elements or compartments of the energy demand sectors[35]. The technological options or potentials can be determined by the user, and from these technological inputs the energy system scenario is modelled[34]. This gives the opportunity of introducing technologies that would be too costly in macro-economic models. The bottom-up approach is divided into statistical methods, which rely on historical trends, and engineering methods, which calculates the energy consumption through power ratings and the use of equipment[34].

Since this study is interested in fundamental technological changes in the energy system, the bottom-up engineering approach is the most suitable modelling approach. It allows the inclusion of more expensive renewable energy technologies in the scenario, and it provides the possibility to design the future energy system without economic boundaries. The costs of the scenario are outside the scope of this project, so cost optimization is not required.

One engineering approach model that is applicable to the Dutch energy system is the Energy Transition Model (ETM)[37]. This model is also used in previous studies into the Dutch energy system for 2050, for example by Urgenda, Quintel, CE Delft, and Berenschot & Kalavasta[12,27,28,32]. By using the ETM, the modelled scenario can easily be compared to previous scenarios, and to future scenarios made by these organizations. The ETM is discussed in more depth in section 3.4.

2.2.2. Trias Energetica

Another part of the modelling approach is the construction of a narrative, which is based on assumptions and literature potentials. Therefore, it is important to determine a framework beforehand to build the scenario narrative that can later be modelled using the ETM. For this, the Trias Energetica framework is used. This framework is a guideline towards a most sustainable scenario. The Trias Energetica was initially described by Duijvestein as guideline for sustainable building in 1993[38]. Later, the Trias Energetica has also been used in energy system studies, for example by Ecofys[17].

The Trias Energetica is based on three pillars, as illustrated in the left graph in Figure 6. In energy system studies the three pillars are based on the following principles:

1. Reducing the energy demand of all sectors through extensive energy savings measures.
2. Implementing renewable, local, energy sources to generate sustainable energy.
3. Adding fossil fuels to the system in the most efficient way to meet energy demand.

Examples of these principles in the built environment are insulation, adjustable lighting, and home information technology (1), solar panels and geothermal electricity (2), and heat recovery and efficient condensing boilers (3)[39,40].

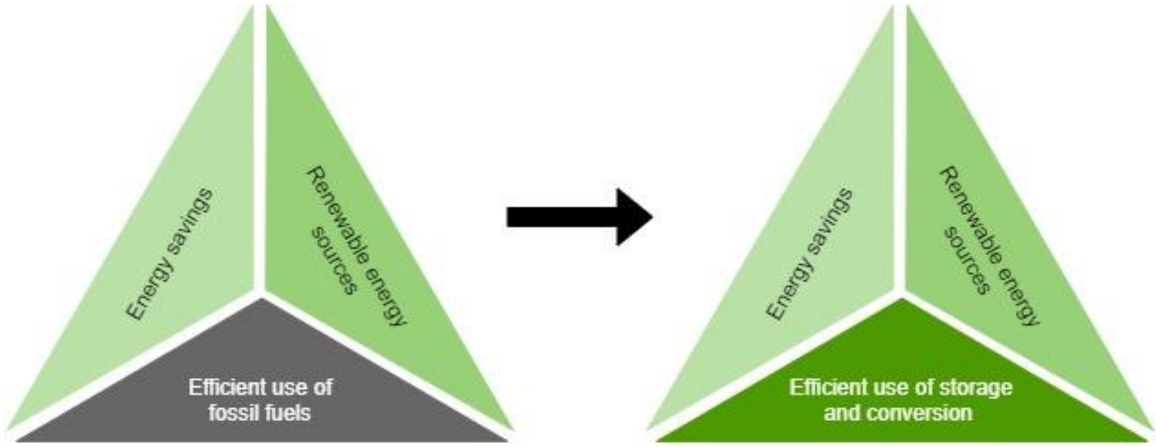


Figure 6. The three pillars of the Trias Energetica, as used in previous studies (left), and as used in this study (right).

The third pillar of the Trias Energetica does not fit the aim of the study – fossil fuels play no role in a fully renewable energy system. Therefore, the third pillar is changed from *Efficient use of fossil fuels* into *Efficient use of storage and conversion*. The idea behind this is that the demand of the energy system is not met through addition of fossil fuels, but through deployment of flexibility options in the new energy system, such as storage in batteries, conversion to hydrogen, and conversion to heat. This corresponds to the main similarities found in 100% renewable energy system scenarios in literature: energy savings, implementation of renewable energy sources, and increased flexibility of the system through storage and conversion technologies.

Methodology

3.1. Research approach

The scheme in Figure 7 gives an overview of the research approach followed in this study. The research aim and main and sub- research questions are described in section 1.4. The main research question, the starting point in Figure 7, was answered by studying the sub-questions consecutively. To answer the first research question, two steps were involved. First, a literature research was conducted to explore the potentials of different parts of the future energy system. The second step was conducting semi-structured expert interviews to gain more insights in new developments. This approach yielded accurate potentials on the energy supply, key conversion, and infrastructure options for 2050. In addition, some projections about the Netherlands in 2050 were examined, for example the population size and the number of households. Then, these potentials and projections were combined into assumptions that formed the story line for the energy system of 2050. The energy system was modelled using the open-source Energy Transition Model (ETM)[37] with technological feasibility as focal point. The modelled energy system was then analyzed in more depth, with a focus on innovation opportunities for both the future energy system and the ETM model. To ensure support of the NVDE members for the scenario, two digital member sessions with feedback moments were organized. The research methods are elaborated on further in the successive sections.

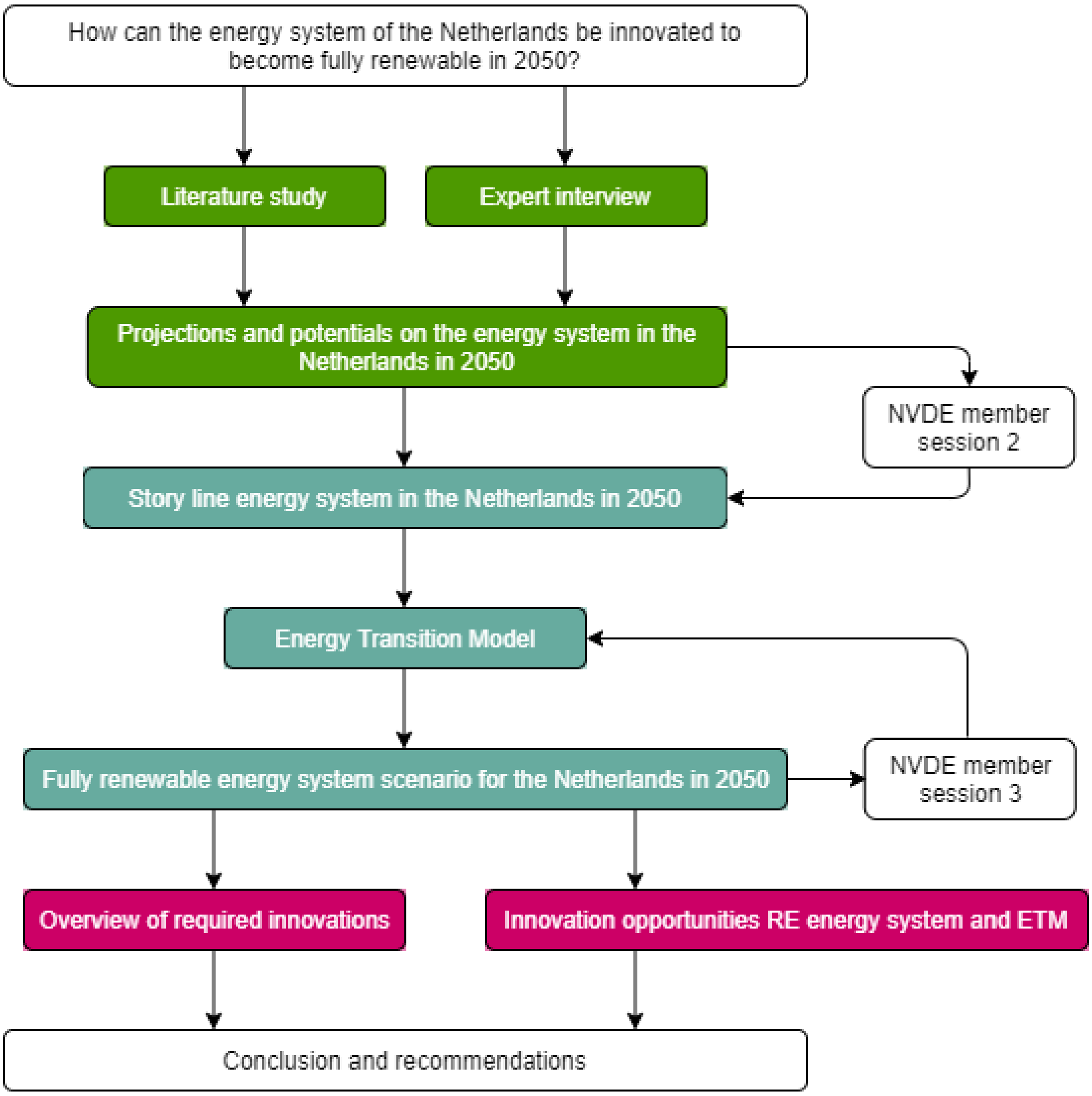


Figure 7. Flow chart of the research approach followed in this study. The green boxes indicate steps corresponding to RQ1, the blue boxes to RQ2, and the pink boxes to RQ3.

3.2. Literature study

A literature study was executed to explore previous energy system studies relevant for this research. The aim was to find secondary, quantitative data about the potential capacity of renewable supply options, such as wind, solar, geothermal and biomass, and the potential energy demand, such as the potential heat demand of households and the amount and share of technology in the demand sectors. Another element of the literature study is the exploration of projections of the basic elements of the Dutch society, such as the population size, number of households etc. For the literature search there was a focus on a combination of scientific and grey literature e.g., from previous energy system studies, statistical organizations, and energy sector reports.

Since the required data is very spatially and temporally specific for the Netherlands in 2050, it was expected that grey literature from local institutions would yield most suitable results. Besides, scientific literature has a stronger focus on global and theoretical energy systems instead of the applied focus on Dutch energy required for this research. An overview of the European Commission has shown that indeed most energy scenario studies were published by governmental organizations and the private sector[23]. Therefore, Google was used as a search engine to find most literature. In addition, ScienceDirect was used to find more general information on renewable energy systems. Because it was expected that most scenario studies about the Dutch energy system would be written in Dutch, one search term was applied in English and Dutch. The search terms used were:

- Energy system scenario the Netherlands 2050
- Energiesysteem scenario Nederland 2050
- 100% renewable energy

The first twenty hits were analyzed on their applicability for creating the story line of a renewable scenario and a scenario for 2050. Studies that gave background information and strong basis for assumptions were used as well. Section 2.1 provides an overview of such studies. For projections on the population size and number of residences, data from Planbureau voor de Leefomgeving (PBL)[41] and Centraal Bureau voor de Statistiek (CBS)[42] was searched for, because these organizations have expertise in this area.

3.3. Expert interviews

In addition to the literature research, semi-structured interviews were conducted to obtain more secondary qualitative information about future innovations that could enhance the energy transition. Two experts were interviewed; one expert from TKI (Topconsortia voor Kennis en Innovatie) Energy and Industry who has knowledge on the future industrial developments and innovations, and one expert from Berenschot (a consultancy) who has knowledge on the energy system and scenario studies.

The interviews were meant to yield more theoretical insights in addition to the information found in literature, so they were held after conducting the literature study[43]. Besides determining the timing, the goal of the interviews also imposed the interviewing method. Two distinct choices have to be made for interviews: the amount of pre-structuring and the openness of questions[43,44]. Out of the three types of interview methods – e.g., structured, semi-structured, and unstructured[44] – the semi-structured interview method was chosen. A semi-structured interview is positioned between the structured and unstructured interview: it makes use of prepared questioning, like the structured interview, but it allows for elaborate responses of the interviewee[44]. Therefore, it is the most suitable method for the goal of obtaining deeper insights into literature but still focusing on specific, identified themes.

In semi-structured interviews an interview guide is needed to guide the interview in the direction of the topics to be discussed[44]. For the purpose of this study, two different interview guides were constructed, because both interviewees have a different area of expertise. The questions are different, but they involve the same topics. The questions for the interview guides were prepared as open-ended questions without a pre-defined set of answers[43,45]. This allowed the interviewees to give elaborate answers to the questions and to discuss themes that were not found in literature. The interview guides can be found in Appendix A. Because of COVID-19, the interviews were held digitally via Microsoft Teams and were also recorded in Microsoft Teams. The recording was transcribed into text after the interviews. The 'uhs' and pauses were left out of the transcript and mispronunciations were corrected[46].

3.4. Energy Transition Model

The projections and potentials found in literature and the interviews for the future Dutch energy system were used to construct a story line for the scenario. This story line was then used as input in the Energy Transition Model (ETM)[37]. The ETM is an open-source, open-data, bottom-up engineering approach energy model and freely available on the internet. It was developed by the consultancy Quintel Intelligence[47] in 2008 with the goal to improve the understanding of the energy system[48]. The development was financed by a broad group of organizations, including NGO's, consultancies, energy companies and the government[49]. Because of this wide range of partners, the model is regarded as an independent method to develop scenarios. Nowadays, Quintel Intelligence has improved the ETM in such manner that it supports nine countries and many provinces and municipalities. It has been used in several scenario studies already, for example by Berenschot & Kalavasta[12] and Urgenda[32], and is being used by more and more organizations. Therefore, utilizing the ETM allows a good comparison of the modelled scenario with previous and future energy system studies.

The ETM is easy to use, and does not make use of implicit developments such as technology learning curves or price developments[48]. A simplified schematic overview of the ETM is shown in Figure 8. For each of the supply and demand sectors of the energy system the potentials or projections can be filled in by the user. Some parameters can only be adjusted through sliders and thus have a fixed maximum potential. The ETM does not make use of an optimization method. If the installed supply does not generate enough energy to meet demand, the energy system is unbalanced, and blackouts can occur. This can be solved by installing flexibility options, such as storage and conversion technologies. Storage can balance hourly or monthly imbalances in the system, while conversion options can balance the imbalance in energy carriers. In addition, dispatchable power or heat plants can be installed that can generate electricity and heat from other energy carriers. Those can be used as back-up for moments with low electricity and heat generation.

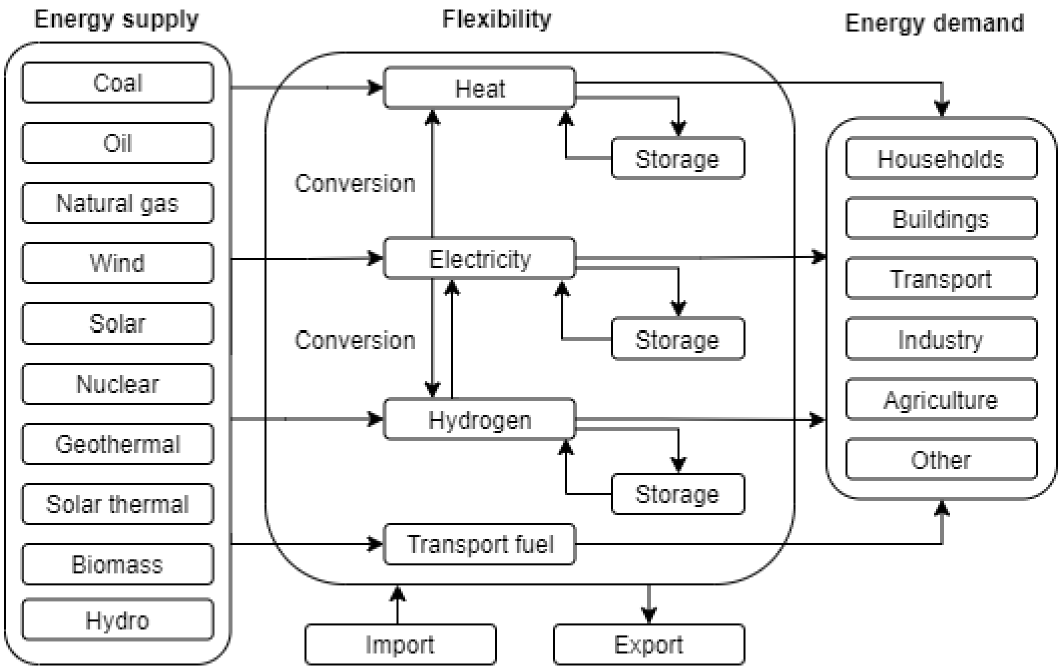


Figure 8. General overview of the energy system in the ETM.

Import and export also provide flexibility to the energy system. The ETM calculates the required import and export automatically based on the surpluses and shortages of the system. For example, if more hydrogen is produced than demanded, the hydrogen surplus is exported. For electricity, an interconnection capacity is defined. If that capacity is fully used, black-out moments without electricity supply occur. The costs for different parts of the system can be adjusted as well, but this does not influence the system. Because the aim of this study is the technological feasibility of a stable, fully renewable energy system, the costs were not included in the analysis.

The base year in ETM is 2015 and all parameters are modelled from 2015 to 2050, except CO_2-emission reduction which is modelled compared to 1990. Detailed results of the scenario were shown in charts or tables for all sectors modelled in the ETM throughout the modelling process. Although these charts gave a good overview of the results, they did not always match each other in color and detail. Therefore, the data of the scenario was exported to Excel for further analysis and visualization.

3.5. NVDE member sessions

In energy modelling studies it is not only important to develop a scenario that has strong scientific foundation, but the scenario should have a strong support from accredited organizations as well for it to be applicable in practice[50]. To make sure NVDE members had a moment to reflect on the scenario, NVDE member sessions were organized. Three digital sessions were held in total.

1. The first session was organized by the NVDE before this research project was conducted. This session provided an overview of the scenario studies in literature and the knowledge gaps. Also, the vision of the NVDE was tested by presenting multiple choice statements. The answers were collected via Mentimeter[51].
2. The second session was organized in collaboration with the NVDE. In this session, the research project was introduced, and assumptions about projections and the scenario story line were discussed. For example, how maintenance of economic structure growth can be defined, what the importance of circularity can be in industry in the scenario for 2050, how potentials for volatile sources from literature correspond to the expectations of energy sector organizations, and on the importance of self-sufficiency. The answers were again collected via Mentimeter[51].
3. In the third webinar, the conceptual results of the modelled scenario were presented. The results were shown in five segments: (i) final energy demand, households, transport, and agriculture, (ii) energetic and non-energetic demand in industry, (iii) renewability of the energy supply, electricity generation, a heat network, and hydrogen supply and demand, (iv) flexibility options included in the scenario, and (v) preliminary conclusions and observations. After each segment, a discussion moment was held.

Projections and potentials for 2050

In this section projections and potentials for the Dutch energy system in 2050 are discussed. The main projections that are relevant for this study are the population growth and increase in the number of residences. PBL and CBS project population growth towards 18.5 million inhabitants in 2050 and a growth in the amount of residences up to 8.8 million[52].

Another projection that needs to be addressed is the percentage of efficiency improvement of appliances in the built environment and efficiency improvement of industrial processes. The Dutch energy law determined that the energy efficiency improvements should be 1.5% per year between 2014 and 2020[53]. The energy improvement of appliances and industry used in studies was 1% per year[12,28,54].

4.1. Built environment

The households and buildings sectors in the ETM are discussed as the built environment, corresponding to the built environment sector defined in the Climate Agreement[8]. The scenarios for the built environment are very diverse. Sijm et al. reported a final energy demand ranging between 200 and 600 PJ, while the more recent study by Berenschot & Kalavasta resulted in a final energy demand between 221 and 268 PJ[12,26]. This difference between scenarios is mainly due to the amount of energy savings and rate of electrification. Scenarios with low final demand have a high share of heat pumps combined with insulation, while scenarios with high demand make more use of green gas or hydrogen to supply heat[12,13,26]. The share of heating technology depends on the chosen energy supply mix[26].

In addition, heat networks fed by geothermal and residual heat sources play a role in meeting the heat demand in the built environment. The amount of geothermal energy used in the Berenschot & Kalavasta scenarios ranges from 4 to 78 PJ[12]. However, a recent study into the potential of geothermal energy in the Netherlands showed that there is a potential of 88 PJ for the built environment[55]. Another option for heat supply in the built environment is the use of solar thermal energy. Quintel Intelligence deployed between 34 and 43 PJ[28] of solar thermal heat and Berenschot & Kalavasta 8 to 26 PJ[12]. The potential for the Netherlands was recently determined to be 64 PJ[56], which is almost double the amount used thus far.

Besides implementing renewable energy sources for heating, rooftop solar panels were modelled for electricity generation. The installed capacity on roofs was 32 GW by Gasunie[30], 28-29 GW by TNO[13], and 13 – 42 GW by Berenschot & Kalavasta[12]. Moreover, there is a strong focus in the built environment on energy savings through insulation and efficiency improvement of appliances. The average insulation level does not exceed level A/B in most studies, because of the high costs involved[12,26].

4.2. Transport

Not many scenarios have modelled and presented quantitative results for the transport sector in detail[26]. Berenschot & Kalavasta did and showed a final energy demand ranging between 143 and 377 PJ. As for the built environment, the main difference between scenarios is caused by different electrification rates. One robust element of all transport scenarios and projections is the fast and high electrification rate of personal transport, combined with the use of hydrogen or biomass as additional energy carriers[26]. In the study by TNO 31-44% of the transport sector was electric, and 32-44% was fueled by hydrogen[13]. The share of electric demand in Berenschot & Kalavasta was 26-77%, the share of hydrogen 8-29% and the share of biomass 15-46[12].

The amount of growth of the transport sector is uncertain. A growth could be expected when only the increase in number of cars is considered, which was 1.4% in 2020 compared to 2019[57]. However, innovation could decrease the growth of the transport sector, for example a modal shift, self driving cars, or increased use of taxi's and car sharing[58].

4.3. Industry

The final energy demand for the industrial sector could only be found for the scenarios of Berenschot & Kalavasta and was 406-760 PJ[13]. This study also resulted in an electricity share of 50-58% and a hydrogen share of 23-35% in the final demand, for this sector[13]. The remaining energy carriers demand were mainly heat, and partly biomass, (green) gas, oil, and coal.

This ratio is in agreement with the electrification that Sijm et al. found to be a robust element in scenarios exploring the future industrial sector. Between scenarios, a trade-off between electricity and hydrogen as final energy carrier was found. Other robust elements in the decarbonization of industry are the deployment of CC(U)S and biomass[26]. For heating, electric boilers and heat-coupling were mainly applied. However, recent studies showed that geothermal and solar thermal energy have a potential of 147 PJ[55] and 12 PJ[56] for supplying heat to the industrial sector.

Another element that affects the energy demand is the amount of circularity and energy-intensity in industry. Some scenarios assume that energy-intensive industries will move their production sites to regions with cheap electricity generation, and that in turn the less energy-intensive industry will grow in size[30,32]. Other scenarios expect much from circularity[12,13]. In contrast, scenarios from the same studies do not include circularity at all[12,13]. During the NVDE member session, it was concluded that circularity will likely play an important role in decarbonizing the industry, but it should not be a condition for the scenario because of the many political and social uncertainties surrounding the topic.

4.4. Agriculture

Alike for the transport sector, Sijm reported that not many studies have been performed for the agricultural sector[26]. The two current studies by TNO and Berenschot & Kalavasta did report about the final energy demand. The final heat demand was between 197 and 267 PJ in the scenarios from TNO[13], and the final energy demand was between 128 and 167 PJ in the scenarios by Berenschot & Kalavasta[12]. The common robust elements were decarbonizing the heat supply by deploying electric heaters and heat networks fueled by geothermal energy and residual heat. The potential of geothermal energy modelled by TNO was 39 and 44 PJ[13] and by Berenschot & Kalavasta 29 and 43 PJ[12]. The estimated potential of geothermal energy in the Dutch agricultural sector has recently been determined to be 55 PJ[55].

4.5. Energy supply

In most scenarios, the role of fossil fuels decreases significantly and in some they even phase out almost entirely. Instead, wind and solar energy sources are installed for electricity generation, while geothermal energy, residual heat, solar thermal energy, and ambient heat are used for heat supply, and hydrogen and biomass are deployed for other non-electric end-uses[26].

Although all scenarios make use of the same technologies, the installed capacity differs much between scenarios. This is illustrated in Table 1[12,13,29–32]. The installed capacity ranges between 18-105 GW for offshore wind, of which 12-20 GW is used for hydrogen production, 6-20 GW for onshore wind, and 27-96 GW for solar PV, of which 1-47 GW is installed on fields and 13-42 GW on roofs. This diversity explains the wide variety in scenario outcomes.

The potential theoretical capacity has also been estimated for the purpose of the Dutch Climate Agreement[59]. This led to a theoretical capacity of 72-108 GW wind offshore, with the disclaimer that 80 GW would already be a big exercise since it would cover 40% of the North Sea. The potential for wind onshore was determined to be 50GW, but 17 GW when taking 500-meter distance from the built environment into account. The potential for solar PV on roofs is estimated to range between 30-50 GW, and that on fields between 150-250 GW. When considering 500-meter distance from the built environment, the potential for solar PV fields decreases to 45 GW. The reason for defining the potential for the 500-meter distance was not described in the study. The estimated potential of geothermal energy for electricity generation is 1.35 GW, with a disclaimer of possible risk for earthquakes.

Geothermal energy could also for heat supply. The estimated potential for geothermal energy is 290 PJ, divided over sectors as described before[55]. The different potential for each sector is determined by the location of available geothermal energy sources and the temperature required for the end-uses. The total potential for solar thermal heat is estimated to be 72 PJ[56]. The potential of residual heat from the industrial sector is directly related to the size of the industry in the scenarios.

Table 1. The installed capacities of offshore wind, onshore wind and solar PV in reviewed scenarios in GW[12,13,29–32]. For offshore wind, the total capacity and the capacity exclusively installed for hydrogen production is described. For solar PV, the total capacity and the capacity on roofs and fields is described.

	Offshore wind		**Onshore wind**	**Solar PV**		
	Total	*H_2 prod.*		*Total*	*Field*	*Roof*
KIVI	63		6	78		
Gasunie	55	15	10	66	34	32
Urgenda 2030	30		12	27		
Berenschot Elektronen	105		8	62	34	28
Berenschot Moleculen	18		8	30	1	29
TNO Transform	60		12	88		
TNO Adapt	35		8	96		
B&K Regional governance	43	12	20	89	47	42
B&K National governance	72	20	20	76	41	35
B&K European governance	42	12	10	42	25	17
B&K International governance	38	10	10	38	25	13

Energy system scenario 2050

The potentials and projections found in literature and the information gathered in the interviews were combined to build the narrative for the scenario. Because broad ranges in potential and assumptions were found, the adjusted Trias Energetica was used to determine the numbers used in the scenario. Because the first pillar requires energy savings, the options leading to most efficiency improvement and electrification was chosen for the demand sector in the scenario. The second pillar dictates the use of renewable energy sources. Therefore, the highest potential for energy sources was deployed in the energy supply sectors. Those assumptions were combined in the ETM. The modelled scenario was highly unbalanced. Therefore, some of the potentials and energy saving measures were adjusted and flexibility options were included corresponding to the need of the energy system. This led to the energy system discussed in this section. A simplified overview of the renewable energy system is depicted in Figure 9. Although no fossil energy was introduced in the scenario, the results indicate residual flows of fossil energy. This is caused by fossil flows in the ETM that cannot be manually adjusted or deleted. However, these flows are not significantly high, and therefore the scenario is regarded to be fully renewable.

Besides full renewability, the industrial growth without energy supply constraints is a condition for the scenario. Therefore, the energy system is modelled for 0% industrial energy demand growth (2050a) and 1% industrial energy demand growth (2050b) per year[12], to examine the possibilities and effects of industrial growth within this renewable energy system. The ETM results are discussed per demand sector – built environment (households and buildings), transport, industry, and agriculture – and per energy supply sector – electricity, hydrogen, heat, and biomass. The ETM scenarios can be accessed through the links in Appendix B.

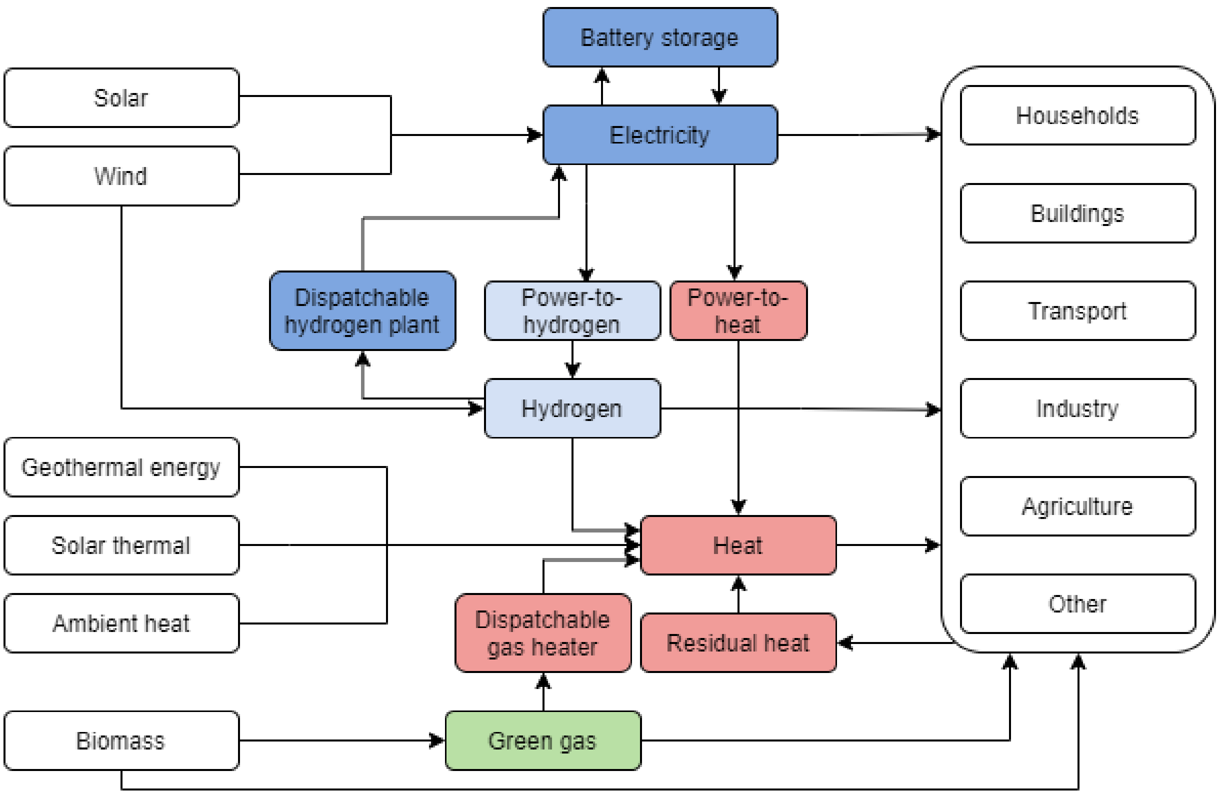


Figure 9. Schematic overview of the modelled energy system including the energy supply (left), flexibility options (middle), and the energy demand (right). The overview is highly simplified, and many components are left out for clarity purposes. Darker blue corresponds to the electricity component of the scenario, light blue to hydrogen, red to heat, and green to green gas.

5.1. Energy demand

The total energetic and non-energetic primary energy demand decreases from 3057 PJ in 2015 to 1778 PJ for 2050a and 2192 PJ for 2050b. The final energetic energy demand decreases from 2042 PJ in 2015 to 1330 PJ (-35%) for 2050a and 1494 PJ (-27%) for 2050b, as illustrated in Figure 10. The built environment and transport sector mainly decrease their energy use. The final energy demand of the industrial sector decreases for 2050a, but increases for 2050b. However, the share of the industrial sector increases for both 2050a and 2050b from 37% in 2015 to 49% and 54% in 2050, respectively. For 2050a, the CO_2-emission reduce with 97.7% compared to 1990, and for 2050b with 97.4%.

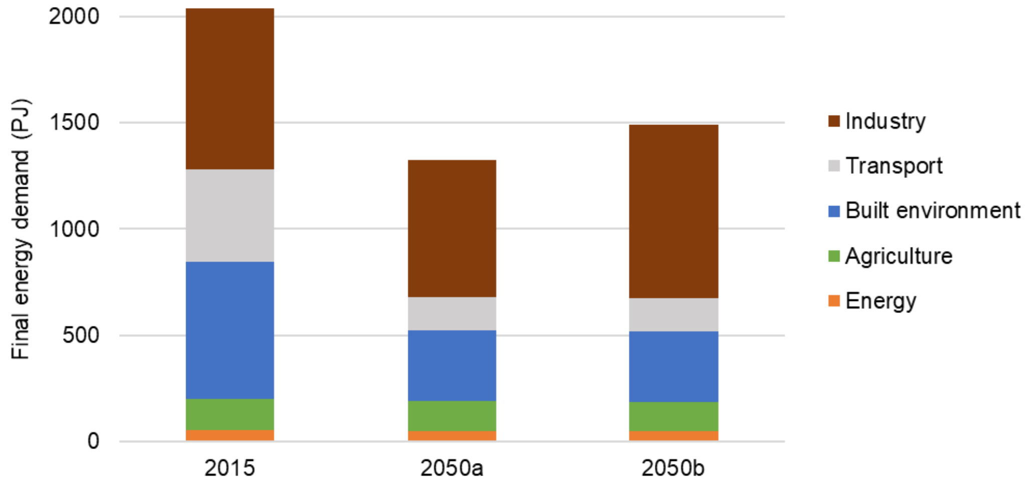


Figure 10. The final energy demand of the two modelled scenarios compared to 2015. The final demand is divided into the final energy demand of the five main sectors defined in the Dutch Climate Agreement.

5.1.1. Built environment

In the built environment, many energy saving measures and efficiency improvements were introduced. Since there is no difference in assumptions and results for the built environment for 2050a and 2050b, the results are discussed as scenario 2050. The population size is set to 18.5 million and the number of residences to 8.8 million[52]. The following energy saving measures and efficiency improvements were introduced:

- Insulation to label B/A for households and label B for buildings. Because of the high costs involved to renovate houses, it is expected that an average of B/A is the highest label achievable[12], which the energy system expert agreed with.
- It is assumed that the cooking technology will be 50% electric and 50% induction, for energy saving purposes.
- Installment of 100% of the ETM potential for solar panels and thermal collectors. This leads to 57 GW installed solar (PV) on almost all roofs[12,59].
- Efficiency improvement of appliances to label A+ (households) and 1% per year (buildings)[26].
- The share of technologies used for space heating was determined by (i) the potential of geothermal energy for supplying heat to the heat network in the built environment[55], (ii) by a 10% requirement of hybrid hydrogen (H_2) heat pumps for houses that cannot be connected to a heat network and for houses that are not easy to insulate according to the energy system expert, and (iii) by complementing the space heating demand with electric heat pumps.
    - Space heating households:
        - 65% air and ground heat pumps
        - 10% hybrid H_2 heat pumps.
        - 25% heat network
    - Space heating buildings:
        - 50% heat network
        - 50% heat pump with thermal storage

These measures lead to a decline in final energy demand from 647 PJ in 2015 to 337 PJ (-52%) in 2050. The two main energy demands are electricity demand for lighting, cooking and appliances, and the heat demand for heating, cooling and hot water. The electricity demand is met by the electricity generated by solar panels on roofs (84%), electricity stored in batteries at home (10%), and by some electricity from the grid (6%), as illustrated in Figure 11.

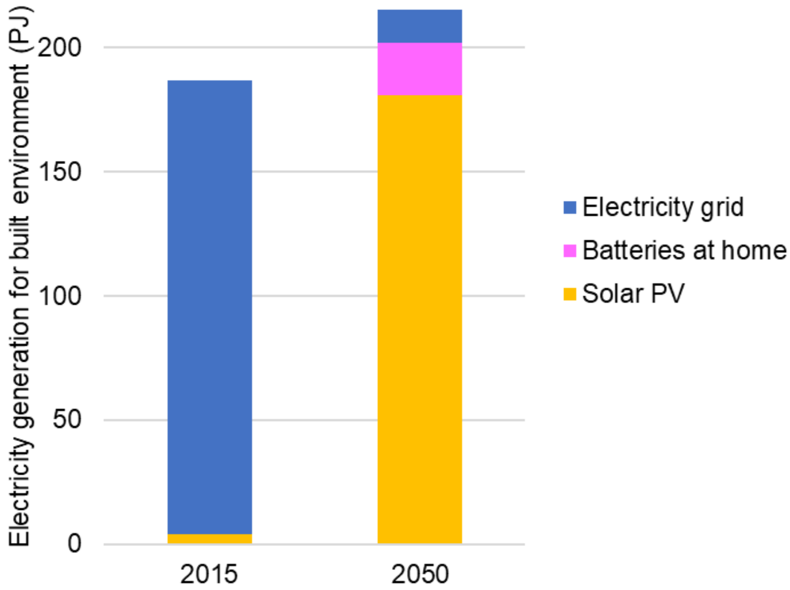


Figure 11. The final electricity demand for 2050 compared to 2015 in PJ per source of electricity generation.

The final heat demand is shown in Figure 12. The heat demand already decreased 15% due to energy saving measures but decreased an additional 38% by introducing the heat pumps that make use of ambient heat. The remaining demand is met by the heat network (103 PJ), electricity used by heat pumps (59 PJ), solar thermal heat (37 PJ), and hydrogen (11 PJ).

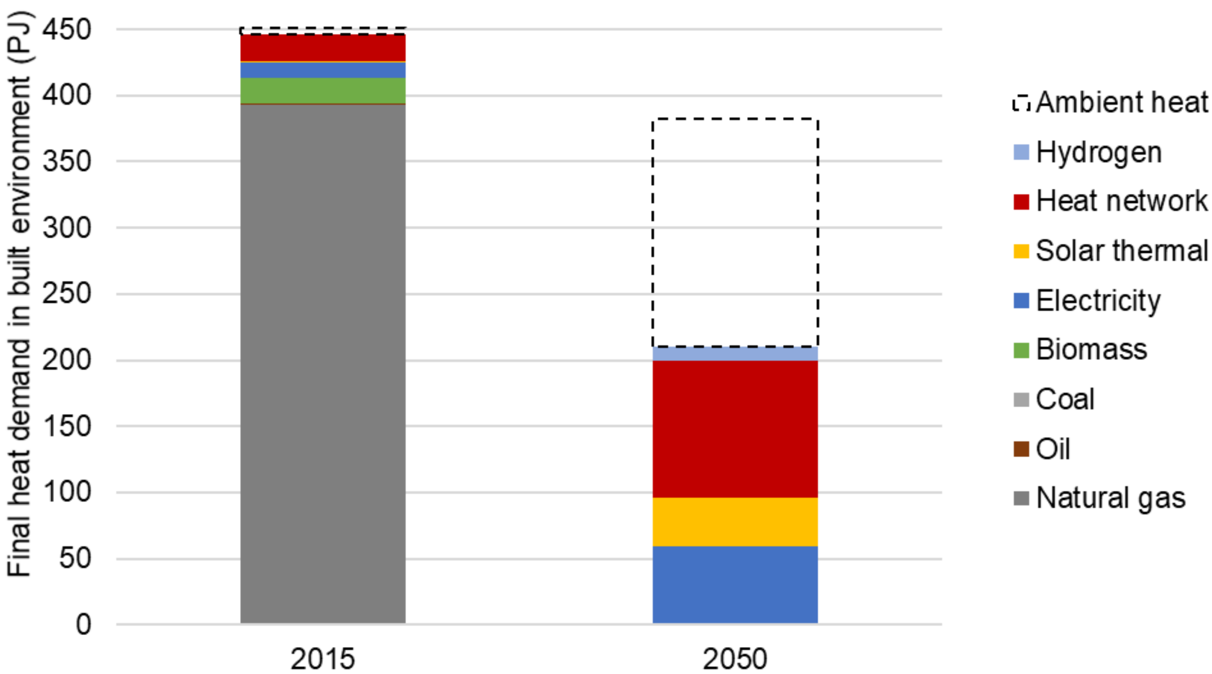


Figure 12. The final heat demand in the built environment in 2050 compared to 2015 in PJ.

5.1.2. Transport

The assumptions and results for the transport sector are equal for 2050a and 2050b and are discussed as scenario 2050. It is assumed that large electrification will decarbonize the transport sector. Therefore, the following assumptions are made:

- There will be no volume growth of the transport sector because the increase in transport movements will be cancelled out by new innovative transportation[12,58].
- Strong electrification of the whole sector leading to[12,26,28,30–32]:
  - 100% electric passenger cars, motorcycles, trams, metros, and trains.
  - 80% electric and 20% hydrogen busses for longer distances.
  - 15% of all bikes is electric.
  - 50% electric and 50% H_2 trucks for long distance freight transport
- A 1% efficiency improvement per year for national transport[26].
- International transport (aviation and shipping) will be fueled by biofuels or synthetic fuels[12,13,26,31].

These assumptions result in a decline in final energy demand of the national transport sector from 437 PJ in 2015 to 156 PJ (-64%) in 2050, as illustrated in Figure 13. The decline is mostly due to the change from fossil fuels to more energy efficient electric vehicles. Electricity will be the main energy carrier used in the transport sector with a share of 60%, completed with hydrogen (29%) and biofuels (11%).

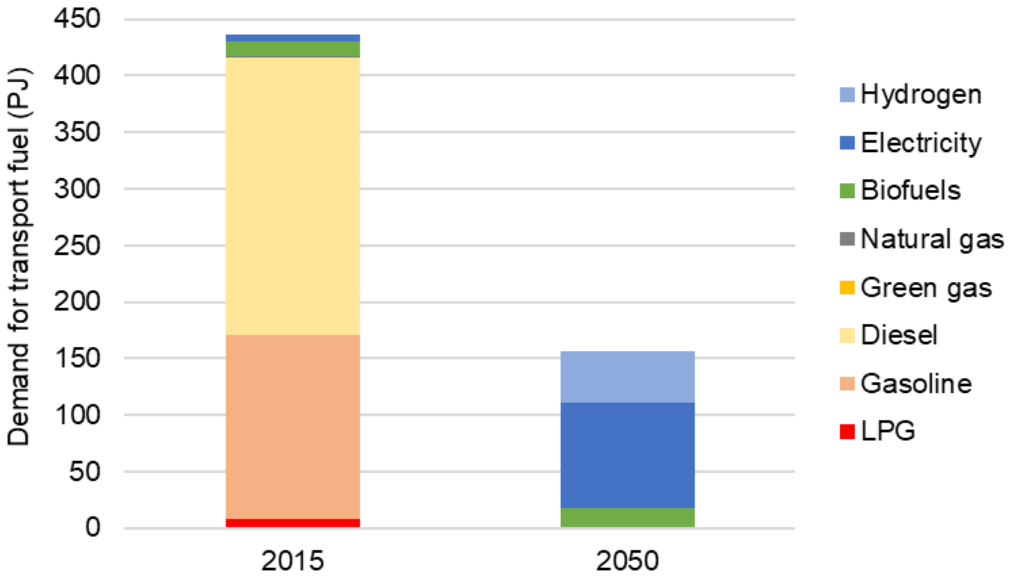


Figure 13. The energy carriers used as transport fuel for national transport in 2050 compared to 2015 in PJ.

The fuels required for international shipping and aviation are not included in this scenario, since the feedstock of the refineries cannot be changed to a renewable one. International transport is also excluded from the Paris Agreement, since its emissions do not belong to a specific country[6]. Although the energy use and emissions are hard to assign to any country, CE Delft has proposed to assign 50% of the sectors movement from and towards the Netherlands to be part of the Dutch energy system[60]. This would yield a final energy demand of 79 PJ for aviation and 256 PJ for shipping (335 PJ total).

5.1.3. Industry

As shown in the overview of the final energy demand, the industrial sector has the largest share in the final demand of 49% (2050a) and 54% (2050b). The main difference between the two scenarios is the yearly growth in energy demand of 0% in 2050a and 1% in 2050b. Combined with a yearly growth of 1.6% between 2015 and 2019, this resulted in a total sectoral growth to 107% (2050a) and 145% (2050b) of the industrial energy demand in 2015.

These increases in size are implemented for all industrial sectors, except from the refinery, fertilizer, and ICT sectors. It is assumed that with the electrification of the transport sector, the demand for fossil fuels from the refineries will decline. However, refineries still play an important role in the production of biofuels for international transport and feedstock for the chemical industry. In addition, NVDE members pointed out during the NVDE member sessions that that Dutch refineries have a strong position in the international market and will thus be the last of the international refineries to stop producing fossil fuels. Therefore, the size of refineries is set to 50% of their 2015 size[12,32]. A decline in product demand is also expected for the fertilizer sector. A strong demand for circular and more efficient agriculture is assumed to decrease fertilizer use. Therefore, the fertilizer sector is set to 40% of its 2015 size[12]. The last sector with a different growth rate is the ICT sector. It is assumed that this sector will increase to grow rapidly to 700% of its 2015 size[12].

Besides the industrial size in 2050, assumptions were made about the process technologies used in some sectors and the heating technologies used in other sectors. The main pathways to decarbonize the industrial energy demand are electrification and implementation of hydrogen as a baseload for heating. The ratio between electricity and other energy carriers, such as hydrogen, biomass, and heat, is determined trough multiple iteration of adjusting the energy supply technologies, the flexibility options, and the energy carrier ratio. The following technologies are implemented in the scenarios:

- For the steel sector, a production using 50% cyclone (Hisarna) furnaces fueled by biomass and 50% electric furnaces is assumed. When using electric furnaces, scrap iron is recycled, making it a more circular process. The energy system expert expects circularity to play an increasingly important role in the steel production.
- Circularity is also assumed for 20% of the aluminum production, using smelt ovens for recycling. In addition, best available technology electrolysis and the newly developed carbothermal reduction have a 60% and 20% share in the production.
- For the refinery and chemical sector, the heat supply is divided in 20% heat network and 80% hydrogen fired heaters. The hydrogen fired heaters can supply high temperatures more easily than the heat network. Since these sectors produce their products at high temperature, the hydrogen fired heaters are assumed to have a higher share in heat supply.
- The food and paper sectors accommodate more processes with lower temperature, thus a distribution between 20% hydrogen fired heaters and 80% heat network is assumed.
- The heat demand for fertilizers is met by 20% biomass-fired heaters and 80% hydrogen fired heaters.
- For the ‘other’ sectors, only the energy carriers could be chosen. The share of different energy carriers is assumed to be 40% hydrogen, 10% electricity, and 50% heat without specified heat supply source.
- The source for the heat network is geothermal energy, of which 5.8 GW is installed[55].
- An efficiency improvement of 1% year is assumed throughout the industrial sectors[54].

These assumptions lead to change in the energetic final energy demand from 756 PJ in 2015 to 646 PJ in 2050a and 814 PJ in 2050b, as illustrated in Figure 14. Without industrial growth, the energy savings and efficiency improvements thus lead to a 110 PJ reduction in final demand. The industrial growth of 1% per year leads to an additional 168 PJ in 2050b compared to 2050a. The energetic demand is met by hydrogen (37% and 38%), electricity (32% and 29%) and the heat network (29% and 30%). In 2050, some coal, oil, and network gas are used in the industrial sector. They are not prescribed to the ETM, but due to residual flows in the sector ‘other metals’ they still play a role in the scenario for 2050.

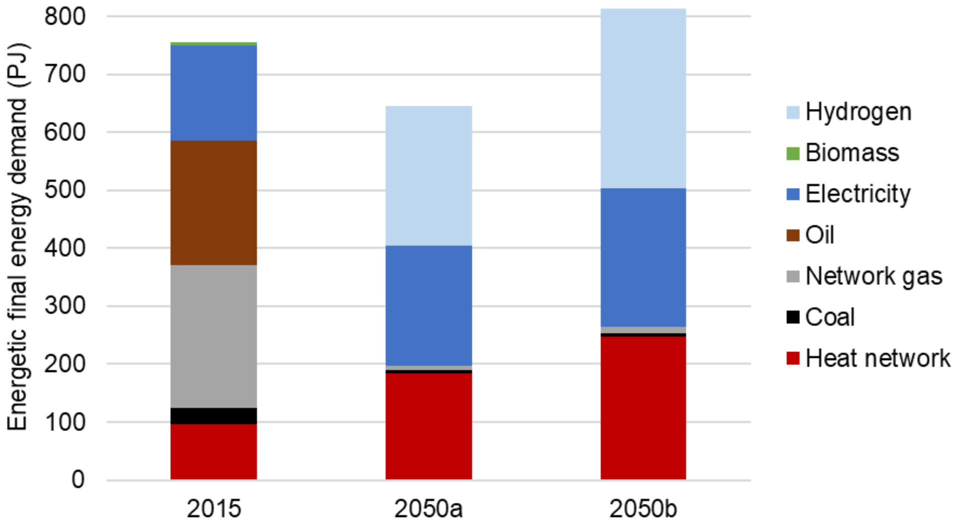


Figure 14. The energetic final energy demand of the industrial sector for scenario 2050a and 2050b compared to 2015 in PJ.

The feedstock for refineries, fertilizers and the chemical industry is oil, natural gas, and oil products. The resulting non-energetic final energy demand is illustrated in Figure 15. The non-energetic demand decreases from 2818 PJ in 2015 to 1398 PJ in 2050a and 1409 PJ in 2050b. The increase in demand between 2050a and 2050b is due to the growth of the chemical sector, which uses oil products as feedstock. Oil (products) contribute most to the final demand (1352 and 1356 PJ) compared to gas supplied through the gas network (46 and 53 PJ). The gas network is fully supplied by green gas in 2050, compared to natural gas in 2015. When developing the scenario, it was not possible to change the feedstock of these sectors in the ETM. Currently, the feedstock in the chemical industry and for the hydrogen production in the fertilizer industry can be changed to renewable feedstock.

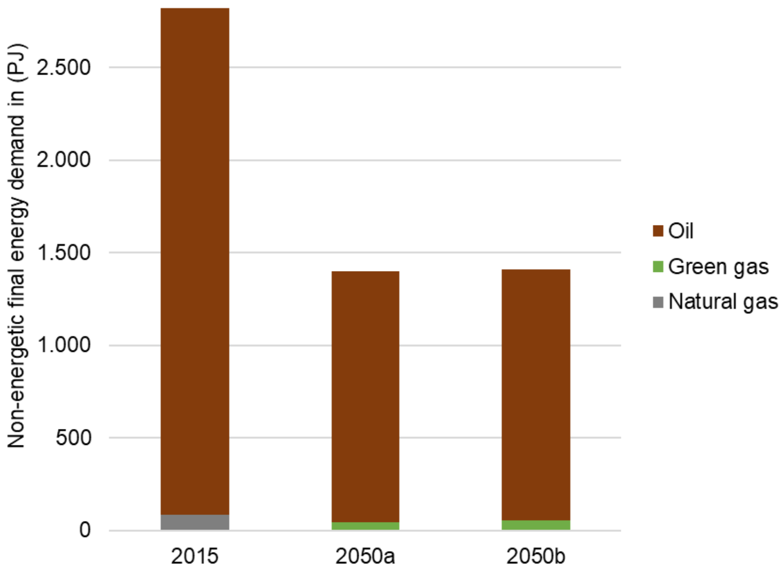


Figure 15. The non-energetic final energy demand (feedstock purposes) of the industrial sector for scenario 2050a and 2050b compared to 2015 in PJ.

Changing the feedstock from fossil energy to renewable sources has an impact on the final energy demand. Using the updated version of the ETM, the final demand decreases with 3 PJ for 2050a and 112 PJ in 2050b when replacing natural gas by hydrogen for the fertilizer industry and oil by biomass for the chemical industry, as shown in Table 2. It leads to an increased demand of 26 PJ hydrogen and 492 PJ and 557 PJ biomass. For simplification of these calculations, it is assumed that conversion losses of renewable processes are equal to those of fossil production processes.

Table 2. The change in energetic and non-energetic final energy demand of the fertilizer and chemical sector when shifting from fossil feedstock to renewable feedstock.

	2050a	2050b
Hydrogen	26	26
Biomass	492	557
Electricity	0	0
Oil	-474	-642
Network gas	-47	-53
Heat	0	0
Total	-3	-112

The refinery sector exports 1210 PJ of fossil transport fuels in 2015 and 984 PJ in 2050. Although the size of the refineries decreases to 50% of the 2015 size, the export of transport fuels decreases to 81% of the 2015 exported amount. This is due to the electrification of the transport sector, causing a strong decline in the national fossil fuel demand. The fossil transport fuels are exported since there is no use for them in the Dutch system. It is assumed that part of the refinery sector will start producing biofuels or synthetic fuels for international transport in 2050[12,13]. Considering a 335 PJ international transport fuels demand, the size of the refinery sector could accommodate producing the fuels for international shipping and aviation.

5.1.4. Agriculture

Similar to the assumptions and results for the built environment and transport sector, the scenarios 2050a and 2050b do not differ for the agricultural sector and are discussed as scenario 2050. The options for the agricultural sector are very limited in the ETM. The only possibilities are to change the demand growth and the technologies used for heating.

For demand growth, literature ranges from reduced demands due to energy saving measures to increased demand based on statistical data[12,26]. Because of these uncertainties, the demand growth is set to 0% for both electricity and heat. The heating technologies chosen for 2050 are a share of 53.8% geothermal energy[55] combined with 46.2% electric heat pumps with thermal storage that follow the principle of the adjusted Trias Energetica. This resulted is a decline in final energy demand from 144 PJ in 2015 to 137 PJ in 2050 (-95%) when including ambient heat, and 90 PJ without ambient heat, as illustrated in Figure 16.

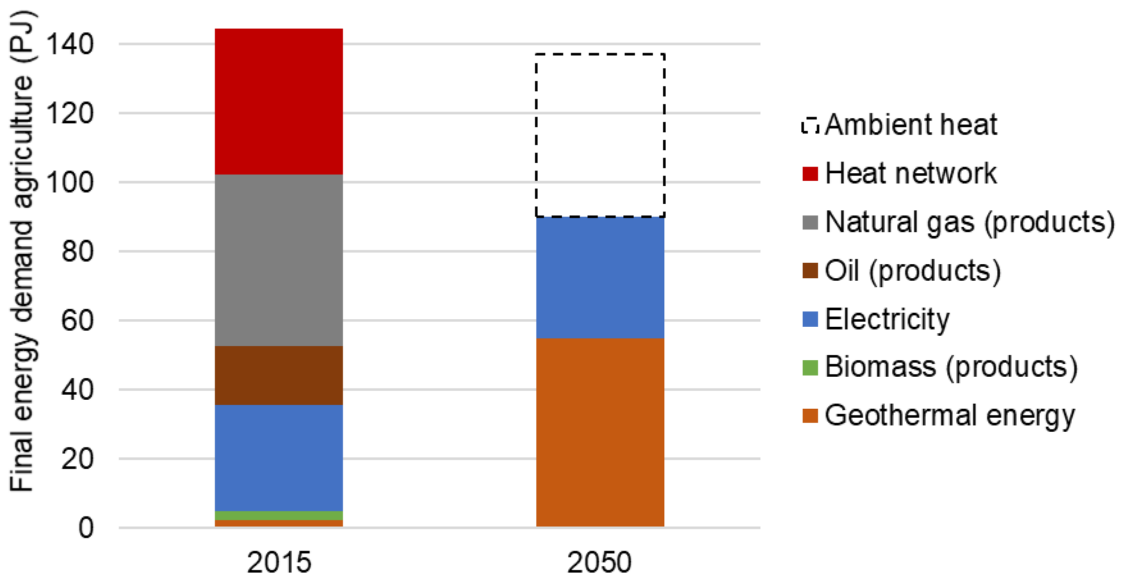


Figure 16. The final energy demand for the agricultural sector for 2050 compared to 2015 in PJ.

5.2. Energy supply

The renewability of the final energy demand is illustrated in Figure 17. The total share of renewable energy in the energy system has increased from 6% in 2015 to 97% in both 2050 scenarios. Although this study aimed to present a 100% renewable energy scenario, 100% renewability was impossible to reach using the ETM. Residual flows that cannot be adjusted implement fossil electricity, heat, oil, and coal in the industrial ‘other metals’ sector, in the building sector and in the demand sector ‘other’. However, these residual flows seem negligible in the sectoral demand, they add up to 3% of the final energy demand.

Furthermore, the electrification of end-use sectors is visible in the share of electricity, which increased from 20% to 36% for 2050a and 34% for 2050b. Other important energy sources are renewable heat and cold (33%), hydrogen (20% and 22%) and to a smaller extent geothermal energy (4% and 3%), solar thermal energy (3% and 2%), and biomass (1%).

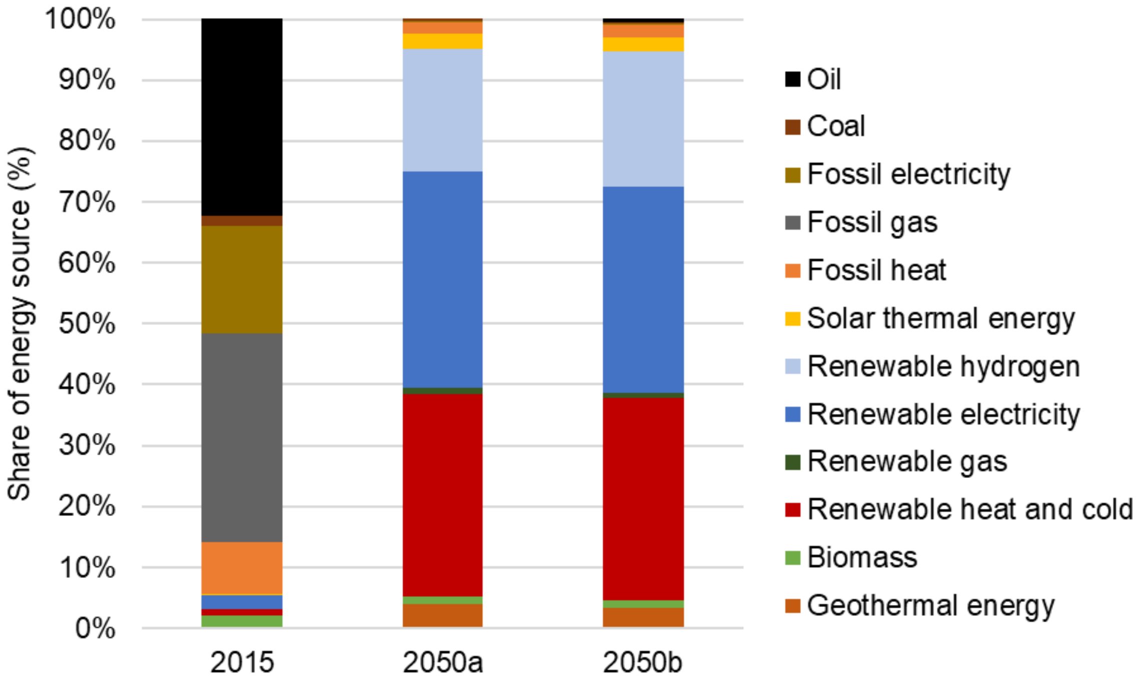


Figure 17. Share of energy sources in the final energy supply of scenario 2050a and 2050b compared to 2015.

5.2.1. Electricity generation

The energy demand should be met by the energy supply. One important part of the supply is the electricity generation. Because of the 100% renewability goal, it is assumed that all electricity is generated by renewable sources and that coal, gas and nuclear power plants are closed, or retrofitted into hydrogen plants. Instead, the following total capacity of renewable energy sources is installed[12,31,56,59]:

- 45 GW offshore wind plants
- 20 GW onshore wind plants
- 35 GW solar PV plants with 24% efficiency as indicated in an expert interview (57 GW on roofs)
- 0.7 GW waste combined heat and power plant
- 25 GW dispatchable hydrogen power plants

This results in a primary electricity generation of 1022 PJ and 1028 PJ in 2050, compared to 426 PJ in 2015, as illustrated in Figure 18. Because the result for 2050a and 2050b is similar, only the result for 2050a is shown in the figure. For both scenarios, more electricity is generated than is demanded. The total final electricity demand is 581 PJ for 2050a and 607 PJ for 2050b, yielding an electricity generation of 1.76 and 1.68 times the electricity demand. The excess electricity is used for flexibility options such as storage, conversion, and export to stabilize the energy system. This is discussed further in section 5.3.1. Wind (714 PJ) and solar PV (290 PJ) generate most of the electricity, but dispatchable hydrogen power plants and import are needed at moments with unfavorable weather conditions for volatile energy sources e.g., no wind and no sunshine.

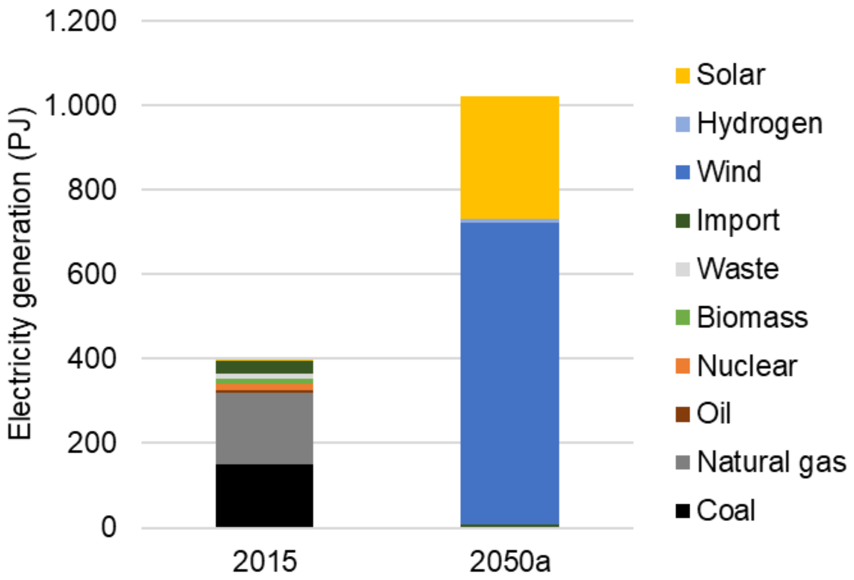


Figure 18. The electricity generation by energy sources in 2050a compared to 2015 in PJ.

5.2.2. Heat network

Besides electricity, renewable heat is also an important energy source in the future energy system. The heat network supply is 100% renewable in 2050, as illustrated in Figure 19. The supply increases from 94 PJ in 2015 to 193 PJ for 2050a and 188 PJ for 2050b. The main energy sources are geothermal energy (88 PJ)[55], excess electricity converted to heat (69 and 62 PJ) and residual heat from industrial processes (30 and 33 PJ). The differences in power-to-heat conversion is discussed in flexibility section 5.1.3. The difference in residual heat is due to the increase in industrial size for 2050b, resulting in more residual heat. In addition to the aforementioned energy sources, solar thermal energy provides 5 PJ of heat to the heat network in 2050.

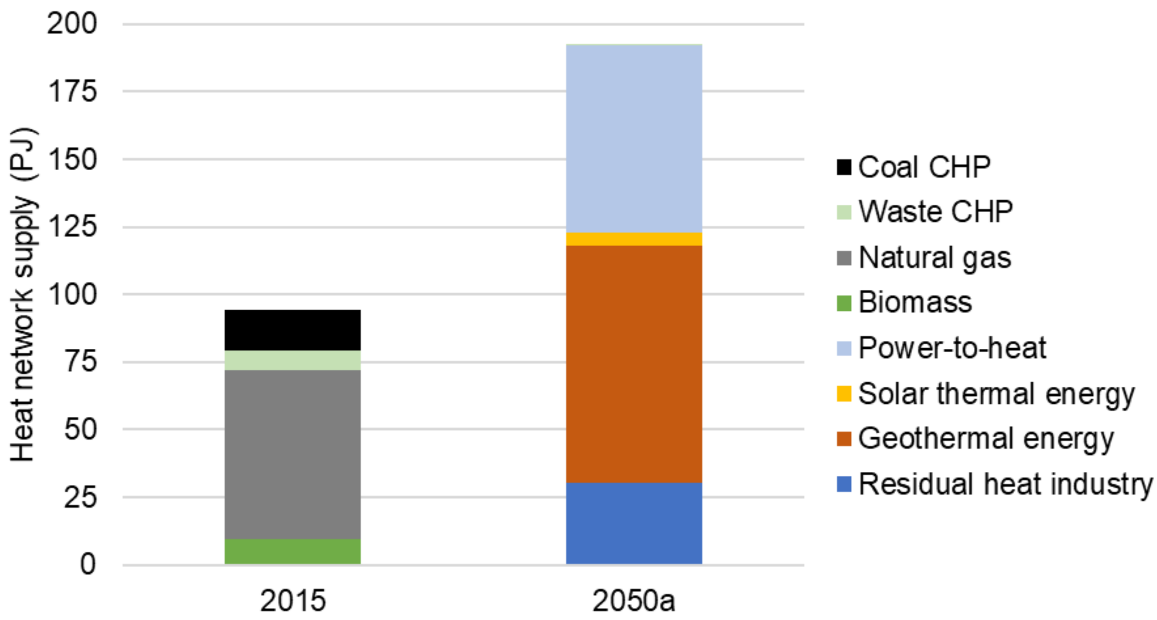


Figure 19. Sources of heat supplied to the heat network in scenario 2050a compared to 2015 in PJ.

5.2.3. Hydrogen

Hydrogen plays an important role in both the 2050a and 2050b scenario. The hydrogen demand and supply is a result of multiple iterations of adjusting the energy supply technologies, the flexibility options, and the energy carrier ratio. The hydrogen demand and supply is depicted in Figure 20. The hydrogen demand and supply is 433 PJ for 2050a and 418 PJ for 2050b. All hydrogen is produced using electrolysis and is thus green or renewable hydrogen. The share of H_2-production in offshore wind parks (20 GW) is 44% in 2050a and 46% in 2050b[12,31].

The hydrogen demand differs between the scenarios. In scenario 2050b, the industry has 30% more hydrogen demand for heating purposes due to 1% industrial growth, compared to scenario 2050a. The industrial growth also increases the industrial electricity demand for 2050b. This leads to a 10 PJ increase in hydrogen demand used in the dispatchable hydrogen power plants, which generate electricity from hydrogen at peak demand and low electricity generation.

Yearly hydrogen supply is higher than demand for both scenarios. This is caused by a relatively stable H_2-production from offshore wind parks, and the large amount of excess electricity available for conversion to hydrogen. The hydrogen surplus is 105 PJ for 2050a and 10 PJ for 2050b. Because there is no demand, the ETM attributed this hydrogen surplus to hydrogen export. However, the hydrogen could also be stored for later use.

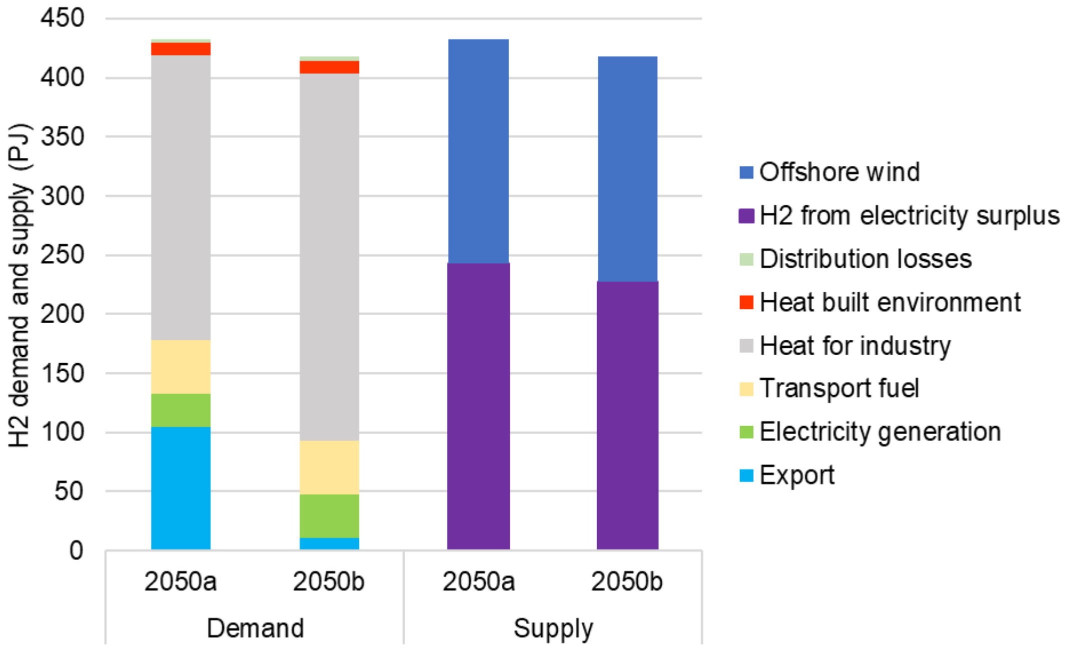


Figure 20. Hydrogen balance divided in energy sources and energy uses of hydrogen for scenario 2050a and 2050b in PJ.

5.2.4. Biomass

Although biomass only represents 1% of the final energy demand, it plays a pivotal role in balancing the energy system in moments of peak demand and low electricity generation. The demand for biomass increases from 127 PJ in 2015 to 139 PJ for 2050a and 204 PJ for 2050b, as shown in Figure 21. The main differences between 2015 and 2050 are the shift from using biomass for combined heat and power plants, for electricity generation and as wood for personal use in households towards use of biomass for the production of green gas and for supplying heat to the heat network. In addition, the use as liquid bio-fuels doubles.

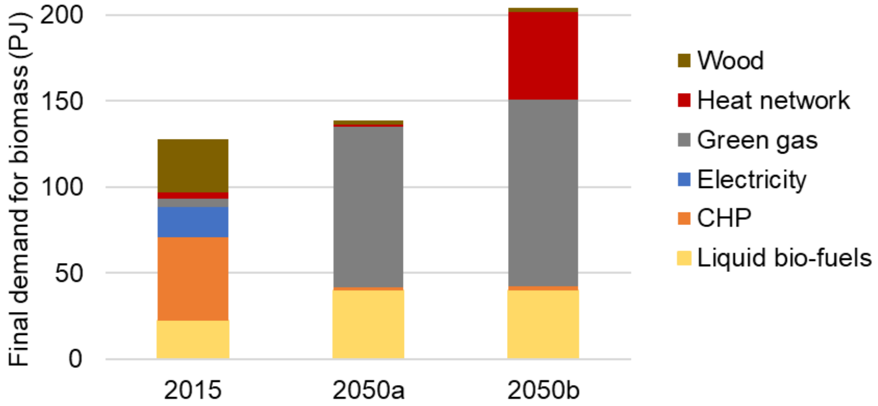


Figure 21. The final demand for biomass in scenario 2050a and 2050b compared to 2015 in PJ.

The green gas is supplied to the gas network. The amount of network gas in the energy system decreases from 1183 PJ to 61 PJ (2050a) and 102 PJ (2050b). The supply of gas for the gas network changes from 98% natural gas in 2015 to 100% green gas in 2050. The green gas is used for feedstock purposes in the fertilizer sector with corresponding 43 PJ (2050a) and 71 PJ (2050b) conversion losses. Those losses make up a significant part of the total green gas demand. In addition, the green gas is used in dispatchable back-up heaters to supply heat to the heat network at peak demand. With the industrial growth of 1% for 2050b, the heat demand exceeds supply more often than for 2050a. Therefore, the dispatchable gas heaters are used more, which explains the increased heat network demand for 2050b, compared to 2050a, depicted in Figure 21.

5.3. Flexibility

In an energy system with high shares of renewable energy sources, flexibility by means of dispatchable power plants, storage and conversion options is highly necessary to stabilize the system. The modelled energy system does not experience black-outs hours, but there are many moments during which the intermittent energy generation exceeds or falls behind energy demand. The monthly imbalance of the supply and demand volumes without addition of flexibility options to the energy system is shown in Figure 22. The surpluses and shortages are shown from the demand perspective, so negative values mean energy surpluses and positive values show energy shortages. The overview shows the imbalance between inflexible supply e.g., volatile sources (wind, solar PV), and base load demand e.g., the final energy demand in end-use sectors. The imbalance profile of scenario 2050b is similar to 2050a.

It is clear that for all months, except October, electricity generation exceeds final demand significantly. Therefore, the energy system needs storage or conversion of excess electricity. The same can be concluded for gas. There is a surplus of around 6.5 PJ during the year, that can be used in dispatchable power plants to stabilize the system.

On the other hand, there is a shortage of hydrogen and heat during the year without any installed flexibility options. For hydrogen, the shortage occurs every month of the year. Hydrogen is produced in offshore wind parks dedicated to H_2-production. The wind parks have some production peaks during the winter due to the favorable wind conditions. Therefore, the hydrogen shortage is a little smaller in November and December. Since there is a shortage in hydrogen production throughout the year, conversion of excess electricity to hydrogen seems a reasonable option.

The imbalance in supply and demand of heat behaves differently than for the other three energy carriers. In summer, heat demand is low due to higher outside temperatures, while heat production from geothermal and solar thermal energy sources and residual heat from industry exceeds demand. On the contrary, the energy sources cannot produce enough heat to meet the high demand for space heating in winter. Besides conversion of excess electricity to heat, seasonal storage also plays an important role in stabilizing the heat supply and demand.

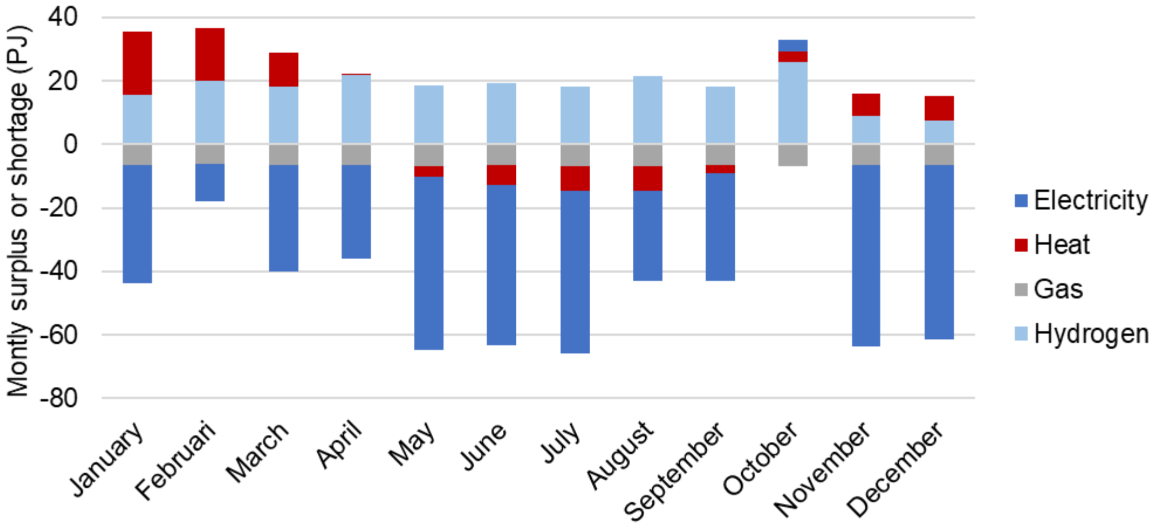


Figure 22. An overview of the energy surplus and shortage summed from hourly to monthly for scenario 2050a per energy carrier, with negative values as surpluses and positive values as shortages.

5.3.1. Storage and conversion technologies

After the flexibility analysis, storage and conversion technologies were implemented in the scenario. The excess electricity from generation peaks is stored or converted by the following technologies to stabilize the system, discussed in merit order position:

- Storage:
  - 100% of the ETM potential of batteries in electric cars (30 GW)
  - 100% of the ETM potential of batteries in households (44 GW)
  - 20 GW large-scale batteries (medium voltage)
  - 10 GW underground pumped hydro storage (high voltage)
- Conversion:
  - 40 GW power-to-hydrogen
  - 10 GW power-to-heat boiler
  - 10 GW power-to-heat heat pump
- Export with an interconnection capacity of 5.85 GW

This combination of flexibility options results in the use of excess electricity as illustrated in Figure 23. Of the excess electricity, 42% and 41% is converted to hydrogen and 12% is converted to heat, which results in conversion losses of 24%. Furthermore, 9% is stored in batteries and 1% is exported. This yields 15 PJ and 13 PJ curtailment of volatile energy sources per year.

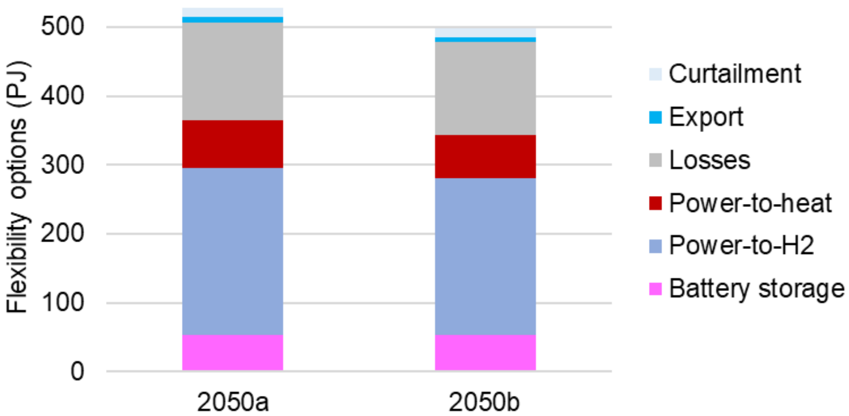


Figure 23. Use of excess electricity by flexibility options deployed in scenario 2050a and 2050b in PJ.

Due to the peaks in electricity generation, the conversion of excess electricity to hydrogen and heat leads to peaks in hydrogen and heat production. As a result, there is a need for hydrogen storage of 19 TWh, which corresponds to 68.4 PJ. For heat, seasonal storage with a volume of 17 TWh (2050a), and 16.5 TWh (2050b) is required, which corresponds to 61.2 PJ and 59.4 PJ.

5.3.2. Import and export

The scenarios result in an import of 1602 PJ in 2050a and 1867 PJ in 2050b, as illustrated in Figure 24. Most of the imported energy is used for feedstock purposes, which leaves 132 PJ import for energetic use for 2050a and 224 PJ for 2050b. The total import is 265 PJ higher in 2050b compared to 2050a, because of the larger size of the steel sector and the larger size of chemical industry. The steel sector requires biomass for heating and the chemical industry has a higher feedstock demand.

The export consists mainly of oil products from the refinery sector. The total export is 1096 PJ for 2050a and 1001 PJ for 2050b, of which the energetic export is 112 PJ for 2050a and 17 PJ for 2050b. The high difference in energetic import is due to the 95 PJ decrease in hydrogen export as discussed in the hydrogen section 5.2.3.

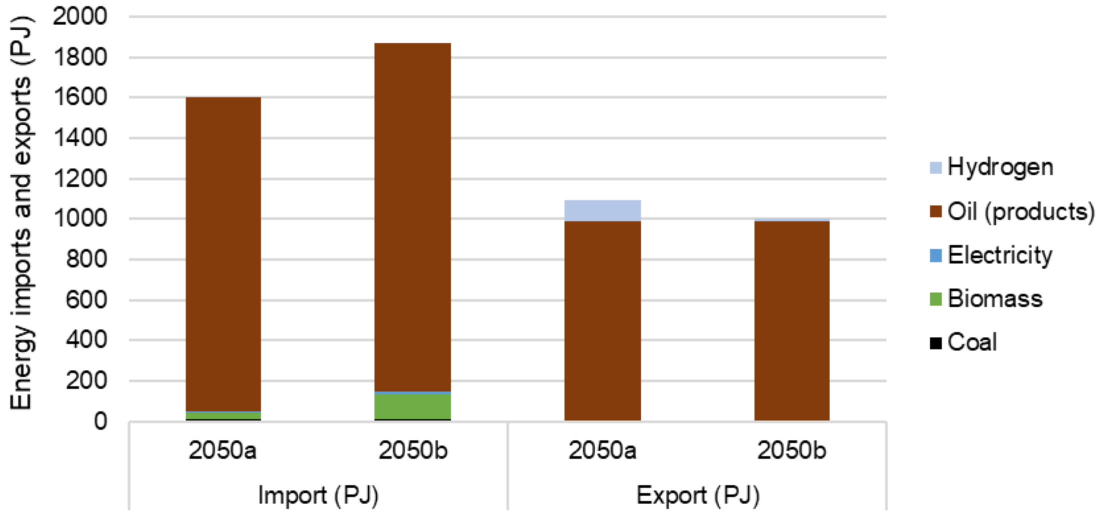


Figure 24. The energy import and export of the energy system for scenario 2050a and 2050b in PJ.

Discussion

The aim of this study was to explore a fully renewable energy system for the Netherlands by 2050 without constraining the energy demand or growth of the industrial sector. The modelled energy system has a renewability of 97% for both 0% and 1% growth of the industrial sector per year. Although the system could not be modelled as a 100% renewable system due to some model technical constraints in the ETM, the residual fossil demand of the sector is low enough to consider the scenarios fully renewable.

The results show that the modelled scenario has a reduction in primary and final energy demand compared to the Dutch energy system of 2015. The reduction in demand was not a condition set beforehand, but a result of the efficiency improvements and electrification introduced in the scenario. The primary energy use is comparable to the results of *Survey Gasunie 2050*, *B&K Regional governance*, *B&K National governance, TNO Transform,* and *TNO Adapt*, as discussed in section 2.1[12,13,30]. The primary energy demand of the *Urgenda 2013* and the two Quintel Intelligence scenarios is much lower[28,32], but those seem to consider the primary energetic energy demand, compared to the combined energetic and non-energetic energy demand in this and other studies. Also, in the *Urgenda 2013* study, the industrial size was shrunk significantly.

The 2050a and 2050b scenarios show that the modelled energy system is technologically feasible with and without industrial growth of 1% per year, making it more adaptable to different economic developments. With an industrial growth of 1% per year, there is an increased demand of 31 PJ electricity, 69 PJ hydrogen, and 63 PJ heat from the heat network. This increase can be met through more direct use of electricity, a decline in hydrogen export and an increased heat supply to the heat network by the dispatchable green gas plants.

6.1. Feasibility of energy supply

The presented scenario includes many innovations. Both the flexibility options and the volatile energy sources can be seen as innovations, either as innovative technologies or the implementation of current technologies at high capacities. The inflexible innovations deployed in the scenario are the following:

- 65 GW wind (45 GW offshore and 20 GW onshore)
- 93 GW solar PV with 24% efficiency (35 GW on fields and 57 GW on roofs)
- 290 PJ geothermal energy for heating
- 42 PJ solar thermal heat for heating
- 25 GW wind offshore for H_2-production
- Heat pumps and boilers in the built environment and industry
- Electric vehicles in the transport sector

These innovations were based on projections and potentials found in literature, as discussed in section 4, and the flexibility needs of the modelled scenario. The installed capacity of wind and solar PV is within the estimated maximum theoretical range of 72-108 GW offshore, 50 GW onshore wind, and 45 GW solar PV fields[59]. The 57 GW of solar PV on roofs exceeds the estimated potential of 50 GW for roofs. If 57 GW is not feasible on roofs, the additional 7 GW could be installed on fields close to households. Also, the installed capacity of onshore wind exceeds the potential of 17 GW considering the 500-meter distance for the built environment. The additional 3 GW wind parks could be installed within the 500-meter distance or, for example, on agricultural land. Efficiency improvement of wind parks has not been considered in this study, so taking this into account could also affect the spatial feasibility of the scenario. Furthermore, the installed geothermal energy and solar thermal energy do not exceed the estimated potentials[55,56]. This means that the scenario is spatially feasible in the Netherlands. However, the sociological effects of the spatial utilization should be considered as well[26].

6.2. Feasibility of flexibility innovations

The flexibility of the system is extremely important in a renewable energy system with high shares of intermittent electricity generation. For balancing supply and demand during every hour of the year, flexible supply was added to the energy mix. The deployed flexible innovations are the following:

- 25 GW dispatchable hydrogen plants for electricity generation
- 30 GW batteries in electric cars
- 44 GW batteries in households
- 20 GW large-scale batteries (medium voltage)
- 10 GW underground pumped hydro storage (high voltage)
- 40 GW power-to-hydrogen elektrolyzers
- 10 GW power-to-heat boiler
- 10 GW power-to-heat heat pump

The installed dispatchable hydrogen plants convert hydrogen to electricity during peak electricity demand and low supply. These hydrogen plants only have 107 yearly full load hours in the modelled system and would therefore be unprofitable. Other flexibility options might be more economically feasible. However, the introduced 25 GW corresponds to the dispatchable power plants in other studies: KIVI deployed 21 GW, Gasunie 28 GW, and Berenschot & Kalavasta 38-45 GW in dispatchable H_2-fueled power plants[12,30,31]. In the other two Berenschot & Kalavasta scenarios (European and International) 45-53 GW dispatchable H_2-fueled power plants were used[12].

The other flexibility options play a more significant role in the energy system. The total installed storage capacity is 104 GW, and the total conversion capacity is 60 GW, of which 40 GW is for power-to-hydrogen and 20 GW for power-to-heat. The storage capacity surpasses the capacities installed in previous studies. In *Survey Gasunie 2050* 20 GW batteries were included, in *B&K* 1-17 GW and in *KIVI* 115 GWh of one day storage was included[12,30,31]. Gasunie mentioned that use of this excess electricity might not be profitable, and therefore the intermittent energy sources will be shut down instead of producing for storage purposes[30]. Berenschot & Kalavasta stated that batteries in households and larger-scale batteries were not included in their analysis because of unrealistic effects on the network and costs[12].

For conversion to hydrogen and heat, the installed capacities are more in agreement with literature. The 40 GW power-to-hydrogen compare to 7.5 GW in *Survey Gasunie 2050*, 30 GW in *KIVI*, and 42/45 GW in *B&K Regional* and *National governance* and 3 GW in *B&K European* and *International governance*[12,30,31]. The 20 GW power-to-hydrogen compare to 6 GW in *Survey Gasunie 2050*, 40 TWh in *KIVI*, and 26 GW, 17 GW, 6 GW and 7 GW in *B&K Regional, National, European,* and *International governance*.

6.2.1. Import

Import is another flexibility option. An interconnection capacity of 5.9 GW for electricity import is used in the energy system, compared to 4.5 GW in *KIVI* and 15 GW in *B&K Regional, National*, *European* and *International governance*[12,31]. The interconnection capacity was not changed from the 2015 levels, for several reasons. The electricity import and export is based on the cost of electricity generation. Whenever producing electricity nationally is more expensive, electricity is imported. Because the costs are outside the scope of this study, no assumptions were made on the costs of import. In addition, the import of electricity in the ETM is not dependent on weather conditions of the countries from which electricity would be imported, while in reality weather conditions greatly impact the electricity generation by volatile sources. It is possible for several interconnected countries to all experience days without wind and sunshine simultaneously, which would not allow import of renewable electricity.

Not including more interconnection capacity resulted in a highly self-sufficient energy scenario, in which almost all energy for energetic purposes is generated in the Netherlands. Although this is technologically possible, it is probably not the most cost-effective. Mikova et al. and Caglayan et al. have concluded that a north-west European energy system (the Netherlands, Germany, France, Belgium, Denmark, and the UK) might be more energy and cost effective, and therefore an easier way to reach the emission reduction targets[61,62]. In addition, Caglayan et al. investigated the possibilities of electricity generation by volatile energy sources within the European energy system[62]. They concluded that volatile sources could be placed in regions with high electricity generation potential, leading to a less expensive fully renewable energy system than in the country-based approach. The production of hydrogen was also cheaper, because the cheaper excess electricity led to lower overall costs[62]. Therefore, import of electricity or hydrogen could decrease the overall costs of the Dutch energy system, for example, when instead of the unprofitable dispatchable H_2-to-power plants, electricity would be imported.

6.2.2. Other flexibility options

The aforementioned flexibility options could all be installed to balance the energy system. The ratio in which they will be installed depends on the chosen electrification and energy supply mix options, and thus remains a political and societal choice. However, certain options are economically more feasible, such as a highly international energy system[61,62]. New innovations in flexibility options can also lead to economically more beneficial energy systems. In 2015, Quintel Intelligence stated that innovations that still need to be developed will not play an important role in the energy system of 2050 and that at least 70-85% of the technologies used in 2050 will be (although innovated) current technologies[28]. This assumption is based on the long research and development trajectory. The most promising innovation expected is the incremental improvements on the present-day technologies e.g., windmills, solar PVT, heat pumps, batteries, and conversion techniques. This idea is supported by the industrial innovation expert interviewed.

Two innovative technologies that are not included in the scenario are deep geothermal electricity generation and marine energy, such as tidal and wave energy. Sijm et al. concluded that those technologies were missing in the reviewed energy system scenarios[26]. For deep geothermal electricity generation, an estimated potential of 1.35 GW was found in literature[59]. However, the report stated that there is a risk on earthquakes, which makes it socially controversial after the earthquakes in Groningen. For hydro energy in the Netherlands, no potentials have been found.

In addition, studies concluded that the focal point of most studies is on the energy supply side, while the innovations in the energy demand sectors are often neglected[26,63]. The energy transition towards 100% renewable sources demands a more holistic approach[63]. The International Renewable Energy Agency (IRENA) has determined that electrification, digitalization and decentralization will play an important role in the energy transition[64]. Electrification and decentralization will make it possible for consumers to become an active participant in the power market, for example, by storing electricity in home batteries at peak generation and selling it later at higher prices[64]. The digitalization will help advanced forecasting methods to balance the energy system better, for example, by turning volatile energy sources off at moments with peak production through internet of things and artificial intelligence[64].

Other innovations in the energy system are grid extensions, demand-response interaction and sector coupling[63,64]. The grid extensions are required to enhance the capacity of electricity transmission from renewable sources to demand end-users. The quantity of grid extension can be reduced by demand-response interaction and sector coupling. For example, demand-response by batteries of electric vehicles at home or home batteries can store electricity of solar PVs and through sector coupling residual heat is used to supply heat to other sectors[64]. Another possibility for demand-response is the industry turning off production at weather conditions unfavorable for electricity generation.

6.3. Future industry

The feedstock of the industrial sector is not renewable in the modelled scenario. At the time of modelling, it was not possible to change this in the ETM. However, the effects of a renewable feedstock have been explored in section 5.1.3. The shift to renewable feedstock led to an increased demand of 26 PJ for hydrogen and 492 PJ (2050a) and 557 PJ (2050b) for biomass and an additional 335 PJ of biofuels or synthetic fuels for international transport.

The additional demand for hydrogen can be met by reducing the hydrogen export. For scenario 2050a with 105 PJ of hydrogen exported, this would suffice. The 10 PJ of export in scenario 2050b are not sufficient, thus an additional 16 PJ of hydrogen should be generated or imported. With a conversion efficiency of 66%, 24 PJ electricity is needed to produce hydrogen. This is approximately 2.5% of the electricity generated in the scenario. Therefore, it is expected that the energy sector can accommodate this shift to renewables in the fertilizer sector.

Much more additional renewable energy is needed for the chemical and refinery sector. If biomass replaces oil, the additional biomass demand is 827 PJ (2050a) and 892 PJ (2050b). This is 5.9 (2050a) and 4.4 (2050b) times the demand in the scenarios. Instead of using biomass, synthetic fuels could be produced to meet fuel demand for international transport. Synthetic fuels are produced using electricity, for example, at moments with excess electricity. Therefore, synthetic fuel production cab be regarded as flexibility of the industrial sector. VNCI deemed the replacement of fossil feedstock by renewables possible, but combined it with a circular pathway that reduces the required input of feedstock[54].

6.4. ETM limitations

The ETM has proven to be an easy to use and accessible model, that still provides enough detail to cover the entire energy system. Because the ETM is still being developed further, new insights in the energy system and innovations can be implemented in the model. The observations made during this study might be relevant for the further development of the ETM.

One small remark on the ETM is the non-changeable fossil streams in the energy demand sectors that inhibit a 100% renewable scenario. Although these residual fossil streams are small, they do add up to 3% of the total energy supply. The fossil energy should be replaced by renewable energy, which could affect the energy supply mix and the flexibility requirements of the system. Another small remark is on the maximum potential of solar thermal energy in the ETM. In this scenario, solar thermal energy is set to 100% of the potential, which yields 42 PJ energy, while the estimated potential is 72 PJ[56].

Fossil energy sources are also required as feedstock for the refinery sector. Besides the limited feedstock options, the industrial sector is modelled inconsistently. For some sectors, production processes can be chosen, while for other sectors only the heating technology can be selected. Because of the expected innovations and changes in the industrial infrastructure due to the transition towards a renewable and circular economy, it would be interesting to study the effects of future processes and their corresponding heating and electricity demand on the total energy system. Besides, innovations such as synthetic fuel production, demand response and sector coupling could influence the flexibility needs of the system.

Moreover, the electricity profile of the ETM is modelled on hourly basis. This means that the electricity supply and demand is modelled per hour. However, in a system depending on intermittent energy sources, it might be more relevant to model the electricity profile on a smaller time-interval. This would yield a more precise profile for the flexibility needs in the system.

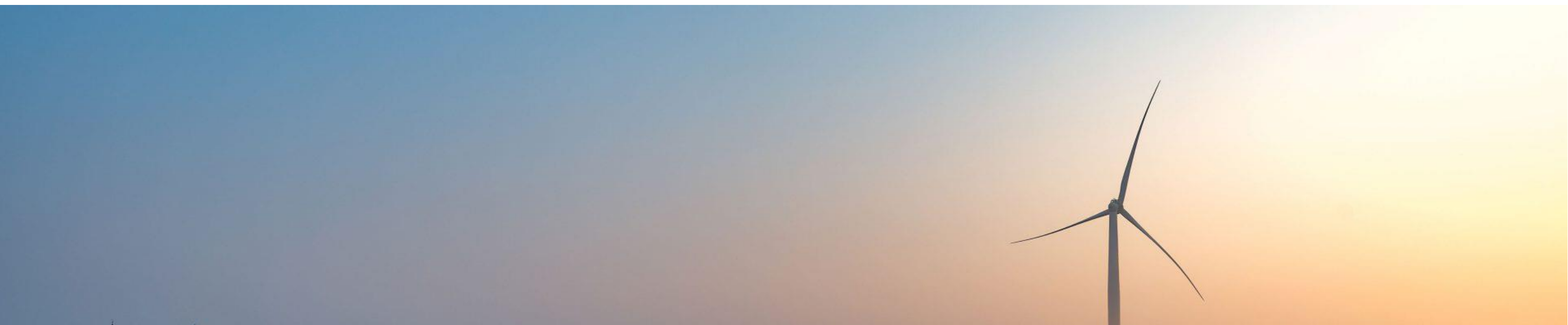
Interconnection capacity with neighboring countries also influences the flexibility of the system. Currently, import is modelled on a fixed-cost basis. In the future, the capacity for electricity import is determined by other factors than just costs. Since all countries in north-west Europe are transitioning towards an energy system with a high share of renewables, the capacity of import will also depend on the fluctuating weather conditions in those neighboring countries. Coupling the import capacity to statistical weather profiles could give more insights into the usefulness of import for flexibility purposes. The connectivity with neighboring countries can also lead to a more cost-effective energy system[61,62]. It would be interesting to study the effects of regional-based energy system instead of country-based. Currently, the ETM does allow regional modelling for the EU-28 region, but not for other international regions. Coupling multiple countries that are already available in the ETM, such as the Netherlands, Belgium, Denmark, France, Germany, and the UK allows studies with a more international approach or vision to the energy transition to use the ETM.

Furthermore, the implementation of new innovations in the ETM is currently not possible. It is interesting to estimate what the effect of innovations will be on the energy system. The preliminary results of the scenario could troubleshoot problematic interactions in a highly renewable energy system. Therefore, it would be of use during the R&D of new innovations. In addition, it could boost the use for scientific evaluation of innovations and innovation gaps in future systems. Implementing innovation and regional modelling allows the use of the ETM for policy modelling purposes, and for scientific and explorative reasons. Combined with the accessibility, the ETM could develop to become a 'golden standard' model for bottom-up modelling approaches.

6.5. Further research

Ideas for further research have been presented already. This section provides an overview of the further research propositions. The following topics could be studied further:

- Besides addressing the technological feasibility of this scenario, the socio-economic feasibility should also be investigated[26]. The energy transition will gain more support by Dutch inhabitants if costs are decreased as much as possible and the spatial planning is known and discussed by regional parties.
- The effects of the future industrial infrastructure should be studied further. The energy demand and feedstock demand will most likely change, and this will impact the feasibility of the total energy system. Besides, through sector coupling and demand-response measures, industry can become an energy supply or storage sector as well.
- This study has presented a scenario for 2050, which can be regarded as a vision for the energy system. The transition pathways towards this scenario has not been studied. However, the balance between supply and demand should be maintained throughout the period of the energy transition and not just in 2050. Therefore, it is important to study transition pathways, and get an idea on, for example, the capacity of wind and solar energy to be installed per year and the number of houses to be renovated every year. In addition, a detailed analysis into the flexibility needs at every point in time should be conducted.
- It is expected that a (north-west) European energy system might be more cost-effective than the country-based approach. Further research could be conducted into a shared vision for the future energy system for a larger region (the Netherlands, Belgium, Denmark, France, Germany, and the UK). This will be increasingly important considering the high share of intermittent energy sources and interconnection of the (north-west) European energy system.
- Another research topic is the flexibility innovations and their implementation in the ETM. Being able to explore effects of innovations on the energy system might give valuable information for the R&D trajectory of the innovative technology/policy. Besides, it could give new insights in the flexibility requirements and options of modelled scenarios.



Conclusion and recommendations

This energy system study presented a scenario for the Dutch energy system in 2050 that can be regarded as fully renewable. The energy system is able to accommodate different rates of industrial growth, and is therefore very flexible. Although the industrial size influences the final energy demand, the total energy demand decreases in both a maintenance and growth of industrial size. This was not set as a condition for the future energy system, but a result of the energy efficiency improvements and electrification introduced in the scenario. Therefore, it is concluded that a reduction in industrial size is not mandatory in a fully renewable energy system.

Flexibility was found to be the largest innovation task in such a highly renewable system. Apart from the upscaling of current technologies, flexible energy sources were installed to balance energy supply and demand. The main innovations needed are:

- Installment of wind parks offshore and onshore
- Installment of solar PV and solar thermal on roofs and fields
- Large capacities for green hydrogen production
- Large-scale deployment of batteries and power-to-heat/H_2 technologies

Although the capacities of current technologies are in agreement with the estimated potentials found in literature, socio-economic feasibility of the installment of such large quantities of volatile sources should be investigated. This feasibility is also important for the flexibility options deployed in the scenario. Other options, such as enlarged capacities of electricity import, might be more economically feasible. The commercial nature of the Netherlands and its high interconnection with neighboring countries makes it hard to model the future national energy system on itself without considering the changes in connected neighboring countries' energy systems. Therefore, it is recommended to conduct further research on the potential interconnection between north-west European countries.

In addition, the implementation of the industrial sector in the ETM and in the future energy system should be studied further. The industry remains the largest energy demand sector, and its share in the final demand increases to 49% (2050a) and 54% (2050b). Since the industry plays such an important role in the 2050 energy system, the decarbonization routes and their interaction with the entire system determine the possibilities for the energy system significantly.

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Appendices

A. Interview guides

Interview 1: Interview guide energy system and scenario expert
October 10th of 2020, 11.00-12.30

Introduction
Dank voor de tijd die u hiervoor heeft vrijgemaakt. Ik zou het gesprek graag gebruiken als interview voor mijn studie, dus daarom zou ik het graag opnemen. Vind u dat oké?

- Afstudeerder Science, Management & Innovation aan de Radboud universiteit, met een focus op klimaatverandering en de energietransitie.
- Onderzoek bij NVDE naar de mogelijkheid van een volledig duurzaam energiesysteem in 2050 met behulp van het ETM om de scenario's te construeren.
- Omdat u heeft meegewerkt aan het II3050 traject en vier scenario's heeft ontwikkeld met het ETM voor de Nederlandse energievoorziening in 2050, wilde ik u graag vragen stellen over deze scenario studie.

Interview guide
1) U bent onderdeel van het team dat de scenariostudie als onderdeel van het II3050 traject heeft uitgevoerd. Wat waren uw taken tijdens de studie?
2) Een scenario studie is heel divers en is gebaseerd op natuurwetenschappelijk en sociaal onderzoek, zoals een energiemodel, maar ook literatuurstudies, interviews en focusgroepen. Wat zijn de grootste uitdagingen die u tijdens de studie bent tegengekomen?
3) Het energiemodel dat gebruikt is in de II3050 scenario studie is het Energy Transition Model (ETM). Wat is uw ervaring met het gebruiken van het ETM-model voor een scenario studie zoals deel van het II3050 traject?
4) In het rapport *Klimaatneutrale energiescenario's 2050* worden de vier mogelijke toekomstscenario's de 'hoekstenen van het speelveld' genoemd. Er staat ook in het rapport dat een combinatie van de scenario's mogelijk is, maar dat het extremen zijn die niet per se realistisch zijn. Hoe is bepaald dat de vier scenario's de uiterste toekomstbeelden zijn?
5) Voor mijn studie probeer ik een of meerdere scenario's te maken met een volledig duurzaam energiesysteem. Een van de aannames waar de NVDE graag mee wil werken is het behoud van de Nederlandse industrie. Dit komt het dichtst bij het 'nationale scenario' in de buurt. Waarom is dit scenario een extreme en niet haalbaar?
6) Dan nog meer in het algemeen over een volledig duurzaam energiesysteem. Wat ziet u als de beperkingen voor volledig hernieuwbare scenario's?
7) Zoals ik het nu zie is de industrie de sector waar de grootste knelpunten liggen wat betreft verduurzaming. Wat zijn uw gedachten daarover?
8) Import van duurzame energie zou altijd een optie kunnen zijn om op een volledig duurzaam systeem uit te komen. Denkt u dat het haalbaar is dat Nederland zelfvoorzienend wordt, dus 100% duurzame energievoorziening zonder import van duurzame energie?
9) Dan heb ik nog een specifiekere vraag over de scenario's. Er zijn voor ieder scenario veel aannames gemaakt, die per scenario verschillen. Bijvoorbeeld voor de gebouwde omgeving is de mate van isolatie verschillend in de scenario's. Wat zijn de argumenten om niet in alle scenario's voor label A te kiezen?
10) Iets anders dat bij is opgevallen is dat er in het rapport staat dat de opslag in wijk- en thuisbatterijen niet is meegenomen, omdat het voor onrealistische effecten in kosten en netwerk zou leiden. Zou u mij iets meer kunnen vertellen over deze genoemde onrealistische effecten?
11) Dan heb ik nog een paar vragen die wat meer ingaan op de mogelijkheden van toekomstige innovaties in de sectoren. Deze zou ik voor zover het kan mee willen nemen in mijn scenario's.

Innovaties zouden een grote rol kunnen spelen in de energietransitie. Hoe is er met innovatie omgegaan in de scenario studie van II3050?

12) Wat voor invloed hebben de mogelijkheden en beperkingen van het ETM gehad op het meenemen van innovatie in de scenario's?
13) Welke innovatie technologieën of beleidskeuzes bent u tegengekomen tijdens het onderzoek, die niet meegenomen konden worden in deze scenariostudie?
14) We hebben het al gehad over de vier scenario's als 'hoekstenen van het speelveld'. Hoe denkt u dat innovaties de positie van de scenario's op het speelveld zouden kunnen beïnvloeden?

Conclusion:
Heel erg bedankt voor het uitgebreide interview. Ik heb er veel van geleerd en het was erg waardevol voor mijn onderzoek.

- Er staat in het rapport dat er een apart verslag is bijgehouden van alle aanpassingen aan de scenario's die buiten het ETM om zijn verwerkt, en dat deze bij Berenschot aangevraagd kan worden. Dit verslag zou ik graag inzien, omdat ik zelf ook met het ETM ga werken. Weet u bij wie ik het verslag op kan vragen?
- Zou ik u later per email nog vragen mogen sturen als er nog iets opkomt?
- Zou u het transcript van dit interview opgestuurd willen krijgen?

Interview 2: Interview guide TKI energy and industry expert

December 1st of 2020, 11.00 – 12.00

Introduction
Dank voor de tijd die u hiervoor heeft vrijgemaakt. Ik zou het gesprek graag gebruiken als interview voor mijn studie, dus daarom zou ik het graag opnemen. Vind u dat oké?

- Afstudeerder Science, Management & Innovation aan de Radboud universiteit, met een focus op klimaatverandering en de energietransitie.
- Onderzoek bij NVDE naar de mogelijkheid van een volledig duurzaam energiesysteem in 2050 met behulp van het ETM om de scenario's te construeren.
- Omdat u veel kennis heeft op het gebied van innovaties in het gehele energiesysteem en met name in de industrie, wilde ik u graag vragen stellen over uw inzichten in de verduurzaming van de industrie en over welke rol de industrie kan spelen in een hernieuwbaar energiesysteem.

Interview guide

1) Mijn studie focust op het modelleren van volledig hernieuwbare scenario's. Wat ziet u als de grootste uitdagingen of knelpunten in een volledig hernieuwbaar energiesysteem?
2) Wat voor invloed denkt u dat innovaties op die knelpunten kunnen hebben?
3) Hoe bent u zelf bij innovatie betrokken?
4) (Vooral met innovaties in industrie: Wat zijn de grootste knelpunten in de energietransitie specifiek voor de industrie?)
5) Wat ziet u als de grootste mogelijkheden voor de industrie?
6) Een van de opties voor verduurzaming van de industrie is circulariteit. Hoe kijkt u aan tegen circulariteit in de energietransitie van de industrie?
7) Er is net een nieuw rapport uitgekomen van EBN, Berenschot en TNO over het potentieel van geothermie in de industrie. Uit die studie blijkt dat aardwarmte tot 100 graden een potentie heeft van 147 PJ voor de industrie (gelijk aan 28% van de totale warmtevraag van de industrie). Hoe kijkt u aan tegen geothermie als base load in de industrie?
8) Een andere innovatie die een base load aan de industrie kan geven is getijden of golfenergie. Binnenkort zal TNO een routekaart energie op zee uitbrengen. Wat is uw inzicht in water energie in Nederland?

9) Welke innovaties zijn er nog meer bij u bekend die ik mee zou kunnen nemen in mijn studie?
10) Wat is volgens u de beste aanpak om tot een volledig hernieuwbare industrie te komen?

Conclusion:
Heel erg bedankt voor het uitgebreide interview. Ik heb er veel van geleerd en het was erg waardevol voor mijn onderzoek.

- Zou ik u later per email nog vragen mogen sturen als er nog iets opkomt?
- Zou u het transcript van dit interview opgestuurd willen krijgen?

The interview transcript are stored in personal records of the author. If you would like to review the transcripts, please contact the author.

B. Link to scenarios

The modelled scenarios are saved in the ETM and can be accessed through clicking on the links below. As soon as the ETM is updated, small changes in the scenario outcomes can occur due to the addition of new technologies or interactions.

- An explorative scenario study into a 100% renewable energy system in the Netherlands in 2050: 2050a - https://pro.energytransitionmodel.com/saved_scenarios/10099

- An explorative scenario study into a 100% renewable energy system in the Netherlands in 2050: 2050b - https://pro.energytransitionmodel.com/saved_scenarios/10104