Radarweg 60
1043 NT Amsterdam
The Netherlands

www.tno.nl

T +31 88 866 50 10

TNO report

TNO 2020 P10338 | Final report

Towards a sustainable energy system for the Netherlands in 2050

Date May 2020

Author(s) Martin Scheepers, Silvana Gamboa Palacios, Elodie Jegu, Larissa Pupo Nogueira De Oliveira, Loes Rutten, Joost van Stralen, Koen Smekens, Kira West

Number of pages 63

Sponsor Ministry of Economic Affairs and Climate Policy
Project name Sustainable Energy Scenario for the Netherlands
Project number 060.38214

Acknowledgement

This study was carried out as a knowledge innovation project within the TNO roadmap Embedding & Integration, the research program for socio-economic research into the energy transition. TNO receives funding from the Ministry of Economic Affairs and Climate Policy to conduct research in this program.

The project was supervised by a TNO sounding board group that consisted of Ruud van den Brink, André Faaij, Peter Eecen, Ronald van den Berg, Sjaak van Loo, Frits Verheij, Richard Smokers, Jaap Kiel en Willem ter Horst. The authors are grateful to the sounding board group for their constructive comments on the approach and results of the study.

Summary

According to the Dutch Climate Act, the Netherlands must have an almost complete climate-neutral energy system by 2050. But how can we achieve that goal? What are the consequences of our choices for our energy system? Are we going to achieve the goals by radically reforming the economy, or are we going to continue as normal, but without emitting CO_2? It is impossible to predict what the future will look like. An energy system without CO_2 emissions is certainly conceivable, but there are differing opinions about what this should look like. Many of the scenario studies published in recent years indicate a wide variety of possible future energy systems for the Netherlands, but what determines these results is often unclear. Why do multiple renewable energy options appear in most scenarios, while there are fewer options in others? And how do the choices for, or the limitation of, certain options affect the costs of the energy system? Parties involved in the energy transition, such as policy makers, energy companies, network operators, technology developers, non-governmental organisations and energy users need insights into these options and how they can be influenced.

Exploring the future with two scenarios
In this study two scenarios (ADAPT and TRANSFORM) are used to explore the major changes in the Dutch energy system that may take place up to 2050. For both scenarios, the aim of the Dutch Climate Act has been taken as a starting point: a step-by-step reduction of GHG emissions in the Netherlands to a level that is 95% lower in 2050 than in 1990, which helps to implement the Paris Agreement to keep global warming below 1.5 degrees. The two scenarios are also designed to achieve the objective of the Dutch Climate Agreement: a reduction of GHG emissions by 49% in 2030. The scenarios differ in the way the goals are achieved, in particular the difference in intrinsic motivation of citizens and companies. In the ADAPT scenario, the Dutch economy builds on current strengths, chooses security and preserves the current lifestyle, but with a strong limitation of CO_2 emissions. In the TRANSFORM scenario, the Dutch society is prepared to change behaviour and opts for a structural change to a more sustainable economy. This makes the Netherlands less energy intensive. The two scenarios are not meant to be compared with each other, but as to study the impact of certain choices in two different plausible futures for the Netherlands.

Analysing the two scenarios with an energy model
Quantitative projections of both scenarios have been made using a techno-economic optimization model to analyse the entire Dutch energy system as an integrated system. It is highly probable that the technological developments will proceed differently than assumed in the scenarios. For all technologies cost estimates were made for 2030 and 2050. However, the costs of some technology options may fall faster than others. In a cost-optimized system, this leads to shifts in the energy mix, both in energy production and consumption. Accelerated cost reductions can be the result of (global) market developments, but targeted Dutch government policy can accelerate the cost reductions of certain technologies, both with regard to technology development and implementation. In recent years, we have been able to see this in technologies such as solar panels, wind turbines and Li-ion batteries.

Societal views on the energy system may also differ from those assumed in the scenarios. Objections may arise against the development of certain options, but there may also be options that enjoy broad societal support, sometimes despite higher costs. Limiting or expanding the use of certain options are often policy choices. For instance, agreements about the use of the North Sea (including for offshore wind energy), permits for underground storage of CO_2, sustainability criteria for the import of biomass, etc.

These various possible developments have been further investigated for the scenarios using the optimization model. For this we “turned the dials” of the model, i.e. we changed the assumptions (‘parameters’) of the model scenarios. In addition to providing an idea of the degree of sensitivity of the outcomes to changes in the assumptions and preconditions (and thus the robustness of the insights obtained), this type of analysis also provides insight into the competition between energy technologies and energy carriers in fulfilling the energy demand which determines the outcomes in a cost-optimized scenario. These insights can help policy makers, technology developers and non-governmental organizations better understand what the role of certain technological innovations may be in the future energy system, and shows the impact of promoting or limiting certain solutions.

Results of the scenario analyses
The GHG reduction targets are achieved for both energy scenarios. The costs of the energy system are lower in both scenarios than for a scenario that does not aim for a climate-neutral energy system, and are lowest for the TRANSFORM scenario.

The two scenarios show a number of comparable results, which seem robust elements of a future Dutch energy system up to 2050. The scope with which energy options are used differs per scenario, but when assumptions are changed, such as technology costs, the changes are limited:

- The share of electricity in the primary energy supply increases from 19% today to 41% by 2050 in the ADAPT scenario and 71% in the TRANSFORM scenario. In 2050, more than 99% of electricity will be generated by wind turbines and solar panels. The increase in electricity use in the Dutch energy system is caused by the electrification of energy functions in all sectors: electric vehicles in the transport sector, electric heat pumps in heat supply for industry, the built environment and the agricultural sector, production of hydrogen with electrolysers and electrification of industrial processes. Only in international aviation and shipping electricity is not directly used, but applied indirectly for the production of synthetic fuels.
- Biomass is mainly used in industry (27% to 48% of the biomass) and for the production of fuels for international aviation and shipping (32% to 48% of the biomass).
- Electrification (approx. 30% of the energy demand) and CO_2 neutral residual heat from industry and waste incineration (approx. 50% of energy demand) play an important role in making the built environment free of natural gas.
- The agricultural sector will become natural gas-free by residual heat from industry (27% to 42% of energy demand), geothermal (17% to 19% of energy demand) and biomass (28% to 44% of energy supply).
- The GHG emission reduction in industry is achieved by using electricity (22% to 55% of energy demand) and biomass (28% to 42% of energy demand).
- Electricity (31% to 44% of energy demand) and hydrogen (32% to 44% of energy demand) are the main energy carriers in the transport sector.

The scenario analyses have also shown that the role of a number of energy options is less straightforward. Their use depends on the scenario or change significantly when the cost or the potential availability of key technology options changes:

- Hydrogen production in the Netherlands will have to compete internationally. If international trade prices are lower than the costs of domestic production, domestic production will be low and hydrogen will be imported. But the reverse also applies: at high international trade prices, the Netherlands will not only produce hydrogen for the domestic market, but also for foreign countries.
- If there is a possibility of CO_2 storage, the production of hydrogen from natural gas with CO_2 capture and storage is the most commonly used technology to produce hydrogen. If CO_2 storage is not possible, hydrogen will be produced with electrolysers.
- CO_2 capture and storage, if allowed, plays an important role in reducing industry emissions, also in combination with the use of biomass resulting in negative emissions.
- The potential for geothermal energy is in 2050 not fully utilized in both scenarios. When investment costs decrease, the use of geothermal energy strongly increases and becomes an important source for heat supply in the built environment.
- In the domestic transport sector, hydrogen, electricity and biofuels are used side by side. In passenger cars electricity competes with hydrogen, and in trucks hydrogen competes with biofuels. What will become the preferred energy carrier is highly dependent on the costs of the fuels and the costs of the propulsion technology of the vehicles.

If certain adjustments to the energy system are more difficult to realize or if certain technology solutions are less socially desirable, the goal of a climate-neutral energy system will remain achievable. However, limiting sustainable energy options does lead to higher system costs. If several options are limited at the same time, or even not allowed at all, it will no longer be possible to cover energy demand in a sustainable manner. Faster technology development through innovation and implementation policies has a positive effect on the accelerated decrease in technology costs, which means that the future costs for the energy system may be significantly lower. Further research and development is of course necessary, not only for technology development, but certainly also to facilitate further implementation. The scenario analyses help to understand how the energy transition can be influenced to make the future Dutch energy system affordable and sustainable.

Contents

1 Introduction

In the 2015 Paris Agreement on Climate Change (UNFCCC, 2016), 195 states agreed on a long-term goal to keep the increase in global average temperature well below 2 °C above pre-industrial levels, and to pursue efforts to limit the increase to 1.5 °C. This requires a far-reaching reduction of greenhouse gas (GHG) emissions and a transition to a CO_2 neutral energy system in 2050. To help achieve this, countries in the European Union have agreed to reduce GHG emissions in 2030 by 40% compared to 1990 levels (European Commission, n.d.). The European Commission has presented an European Green Deal, an ambitious plan and roadmap toward a sustainable climate neutral Europe with a package of measures and proposals for financing this plan (European Commission, The European Green Deal, 2019). In 2017, the Dutch government set a reduction goal of 49% in 2030 (VVD, 2017) also compared to 1990 levels. With the adoption of the Climate Act in 2019 (Rijksoverheid, 2019), the Dutch government decided that GHG emission in 2050 should be reduced with 95%. Subsequently, in 2019 more than 100 public and private parties agreed in the Climate Agreement on measures to achieve the 2030 goal (Klimaatakkoord Industrie, 2019).

A sustainable energy system can have many different forms
Achieving a sustainable energy system depends on choices made by the government, citizens and companies. The Climate Agreement includes measures that stimulate sustainable choices. In principle, citizens and companies have a great deal of freedom in making their choices. Choices can be influenced by many factors, not just by incentives from policy measures. They depend also on which renewable energy technologies are available on the market and which are the most economically attractive In the coming decades many innovations will take place, new technologies become available and major technological improvements and cost reductions will take place. Apart from technological developments, also societal aspects influence the deployment of certain options to reach the climate targets. Some options are considered more attractive, despite higher costs, or are less desirable, despite lower costs. Choices also influence each other: e.g. in the same region the use of geothermal energy for greenhouse horticulture limits or excludes the use of this sustainable energy source for the built environment. Once a choice has been made, it has consequences for choices that can be made afterwards e.g. switching off a gas distribution network excludes the use of green gas or hydrogen. Furthermore, there are many other trends: economic, demographic, non-energy technological and social trends will influence the demand for energy and the choices citizens and companies are willing or able to make. Because of the large number of factors that influence energy demand and the choices to be made, it is difficult to predict how such a future energy system will look like. Nevertheless, we know that a future sustainable energy system that meets the greenhouse emission reduction target in 2050 may take different forms.

Why is it important to know what a future sustainable energy system might look like?
First of all, due to the dependence of successive choices and mutual influences of choices that are being made, it is important to know whether the sum of all

individual choices and decisions ultimately leads to an environment in which the energy demand is covered and policy targets can be achieved. Secondly, better insights into the consequences of certain choices are also desirable. Do those choices lead to a sustainable energy system that is socially acceptable, and are the costs of such a system affordable? Or do the choices lead to solutions for which there is no societal support? These insights are useful in determining options that are most promising, and to understand which conditions and circumstances make options attractive. These insights are important for energy policy. Energy policy goes beyond setting of policy targets. Energy policy can ensure that necessary changes are made in a coordinated manner, that they are fair and affordable for different stakeholder groups, and that negative effects are limited as much as possible. Furthermore, the insights can provide direction for energy innovation policy, and for designing policy that supports the implementation of sustainable energy solutions.

How can we get an idea of what a future sustainable energy system looks like?
In order to get an idea of how a future sustainable energy system may look like, these possible developments and consequences can be identified, and where possible also the mutual influence of developments, decisions and events. A well tested and accepted method is to create a future scenario in which various developments, decisions and events are described in a logically coherent manner. Because the uncertainties about the possible developments are large, different future scenarios can be made based on different coherent assumptions about which developments and events can take place, and how decisions will be made.

Future scenarios for an energy system can be explored in quantitative terms. The result is a description of a possible future energy system in physical parameters, such as energy production and use, capacity of energy infrastructure components, CO_2 emissions, etc. and economic parameters such as investment and annual costs. These quantified projections can be made with quantitative models in which algorithms describe the coherence the system and how it is influenced by technology choices.

Future scenarios of a sustainable energy system for the Netherlands
In anticipation to, and in support of, negotiations on the Climate Agreement, various parties presented scenarios for a sustainable energy system for the Netherlands. This concerns both integrated scenarios for the entire energy system as well as scenarios and projections that describe a part of the energy system. (Sijm, 2020) provides an overview and analysis of a large number of these scenario studies. These scenario studies indicate a wide variety of possible future energy systems for the Netherlands. What determines these results, however, is often insufficiently clear. In the II3050 study (Den Ouden et al., 2020) four energy futures for the Netherlands are explored. The deployment of energy technology options were input for an energy system simulation model, that calculated the consequences for infrastructure requirements. In the present study, we use an energy system optimization model, which means that the model calculates a cost optimal energy system within certain boundary conditions and greenhouse gas emission targets. This answers question such as: Why do a number of renewable energy technologies occur in many scenarios and are other

technological options only applied in a limited number of scenarios? And how do the preferences or limitations of certain options affect the cost of the energy system?

This study presents two scenarios of a possible sustainable energy system for the Netherlands. In particular, it provides insights about the period between 2030, the target year of the Climate Agreement, and 2050 when GHG emissions must be reduced by 95%. The study complements the Climate and Energy Outlook (KEV 2019) (PBL et al., Klimaat- en energieverkenning 2019, 2019), which makes a projection up to 2030.

Uncertainty about future developments can be represented with different scenarios. This can be done in various ways. Two well-known approaches are:

- *Reference and alternative scenarios*: One scenario is used as a reference to compare the results of one or more alternative scenarios. The reference scenario is often called the business as usual (BAU) scenario.
- *Exploration of the playing field*: Multiple scenarios (4 scenarios are common) are made that covers the area of possible futures. It is often decided to vary two important, but independent, uncertainties. Although this approach presents a broad spectrum of possible futures, there is a risk that each scenario gives a somewhat extreme, less realistic picture. To arrive at a more realistic future, i.e. somewhere in the middle, interpolation between the different scenarios is required.

This study takes a different approach. Two scenarios have been created, none of which is a reference scenario. This choice is made because the energy transition is a major disruption from the current situation. With the two scenarios, two plausible and not too extreme images of the future are created. The two scenarios show that the long-term objective of a sustainable energy system for the Netherlands can be achieved in different ways. However, because the uncertainties are substantial, it is almost certain that the future reality will differ from these two scenarios.

For the two scenarios storylines are developed that describe the scenario in a logical, realistic, coherent way, and in connection with social developments. A distinction is made between two types of developments: developments outside the energy system that cannot be influenced by stakeholders, such as demographic growth, economic growth, world energy prices, etc., and developments within the energy system that can be influenced, to a certain extent, by stakeholders. From these storylines parameters are derived that are used as boundary conditions in the quantification of the scenarios.

There are different ways to quantify future scenarios for an energy system. A distinction can be made between four approaches:

- *Creating a future energy balance:* A future energy balance is constructed in which the expected energy demand (divided into energy demand sectors) is met by different energy carriers. These energy carriers are produced from energy sources or obtained by conversion of other energy carriers. This allows to determine the energy supply mix. Energy losses in energy transport and conversion are taken into account.

- *Backcasting:* A desired future energy system is determined. The changes required to realise the future energy system compared to the current system are examined.
- *Simulation:* Starting from the existing energy system, developments and choices are simulated with quantitative models. This method can be applied to describe developments year after year, and is in particular suitable for analysing the effects of policy and policy instruments.
- *Optimization:* An optimization model can be used to calculate a future energy system that meets a set of criteria, for example an energy system with a certain maximum CO_2 emission at minimum annual costs. This method is particularly suitable for projections in the longer term. The method describes an energy system in a specific future year. The development of an optimal energy system over a certain period can be determined by combining calculations of a couple of future years i.e. creating a projection of a transition path.

This study uses ***the OPERA optimization model, which describes the integrated energy system in the Netherlands***. The model covers the energy system of all sectors (energy production, industry, transport, built environment, agricultural sector and bunker fuels for international aviation and shipping) and the entire GHG system (in addition to CO_2, CH_4, N_2O and F-gas emissions) of the Netherlands. The OPERA model calculates the energy system and the associated emissions, given specific goals (e.g. GHG reduction target) and preconditions, at the lowest social costs. The model optimizes between different competing technology options, energy sources and energy carriers. Technology learning is taken into account: technology improvement, and cost reductions as a result of R&D and technology deployment. For 2030, the emission target of the Climate Agreement is considered: -49% GHG emissions compared to 1990. For 2050, a reduction of greenhouse gases of -95% is assumed. In this study the OPERA model calculates the transition path of the Dutch energy system for the two scenarios by making projections for 2030, 2040 and 2050.

Gaining insight into factors that determine the scenario
A cost-optimized scenario corresponds to the policy goal of implementing the energy transition cost-effectively. However, it is possible that the technological developments proceed differently than assumed in the scenarios. For all technologies cost estimates were made for 2030 and 2050. However, the costs of some technology options may fall faster than others. In a cost-optimized system, this leads to shifts in the energy mix, both in production and consumption. Accelerated cost reductions can be the result of (global) market developments, but targeted Dutch government policy can accelerate the cost reductions of certain technologies, both with regard to technology development and implementation. In recent years we have been able to see this in solar panels, wind turbines, and Li-ion batteries, among others.

Society may also develop a different view on the energy system than assumed for the scenarios. Objections may arise against the development of certain technology options, but there may also be options that enjoy broad social support, sometimes despite higher costs. Limiting or expanding the use of options are often political or policy choices. Examples include: agreements about the use of the North Sea (including for offshore wind energy), permits for underground storage of CO_2, sustainability criteria for the import of biomass, etc.

These different possible developments have been further investigated for the scenarios using the optimization model. In addition to providing an idea of the degree of sensitivity of the outcomes to changes in the assumptions and preconditions (and thus the robustness of the insights obtained), this type of analysis also provides insight into the competition between energy technologies and energy carriers in fulfilling the energy demand which determines the outcomes in a cost-optimized scenario This shows policy makers, technology developers and civil society organizations what the role of certain technological innovations may be in the future energy system and shows the effects of promoting or limiting certain solutions.

Reading guide

This report presents results of the scenario study and provides background information on the two scenarios and the OPERA model. The report is structured as follows:

- Chapter 2 describes the two scenarios used for the study and how they were constructed.
- Chapter 3 explains the techno-economic optimization model OPERA and provides information about the input parameters used in the quantification of the scenarios.
- Chapter 4 presents the results of the two scenarios.
- Chapter 5 discusses the insights gained about the underlying factors that determine the outcomes of the two cost-optimized scenarios.
- Chapter 6 lists the main conclusions and provides recommendations for energy policy and further research.

2 Two scenarios for a sustainable energy system in the Netherlands

This chapter describes two scenarios for the development of the Dutch energy system between 2030 and 2050:

- ADAPT scenario
- TRANSFORM scenario.

The principles of the applied scenario methodology is described in Section 2.1. Section 2.2 introduces the ADAPT and TRANSFORM scenarios with common and distinctive scenario drivers. Section 2.3 discusses the parameterisation of the two scenarios.

2.1 Scenario methodology: Multi-Level Framework Analysis

Identifying specific scenarios for the Dutch energy system is a challenging task. Future developments are shaped by many possible interactions and uncertainties. These make it difficult to forecast specific development paths and the state of the system at any given year. As described by Timpe and Scheepers (Scheepers, 2003), the range of possible future developments for complex systems can be simplified utilising a scenario funnel (see Figure 2.1). The circles in the funnel represent the possible realistic futures in a given future year. The dotted line represents the development path of a specific scenario. The picture illustrates that the range of possible futures is much larger than a limited number of scenarios.

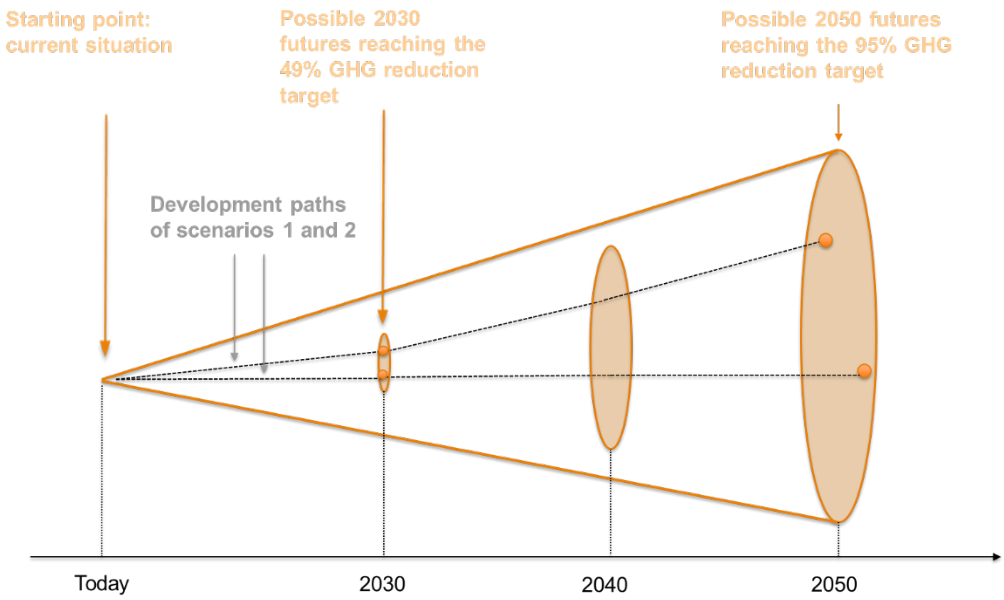


Figure 2.1 Scenario funnel

Differences across scenarios arise from an array of differing characteristics, factors and trends. Amongst these however, few 'scenario drivers' can be identified as key drivers of differences between scenarios and the systems they describe. Identifying such scenario drivers will narrow the development path possibilities for a given scenario.

As suggested by Timpe and Scheepers, once scenario drivers are identified, a scenario can be designed utilising ‘scenario descriptors’. These include more specific characteristics of the scenario that are consistent with the scenario driver. In this study, scenario descriptors were found utilising a Multi-Level Framework of Analysis described by Geels (Geels, 2011). This method consists of finding scenario descriptors for three socio-technical levels: The Landscape level, the Regime level and the Niche level. This is illustrated in Figure 2.2.

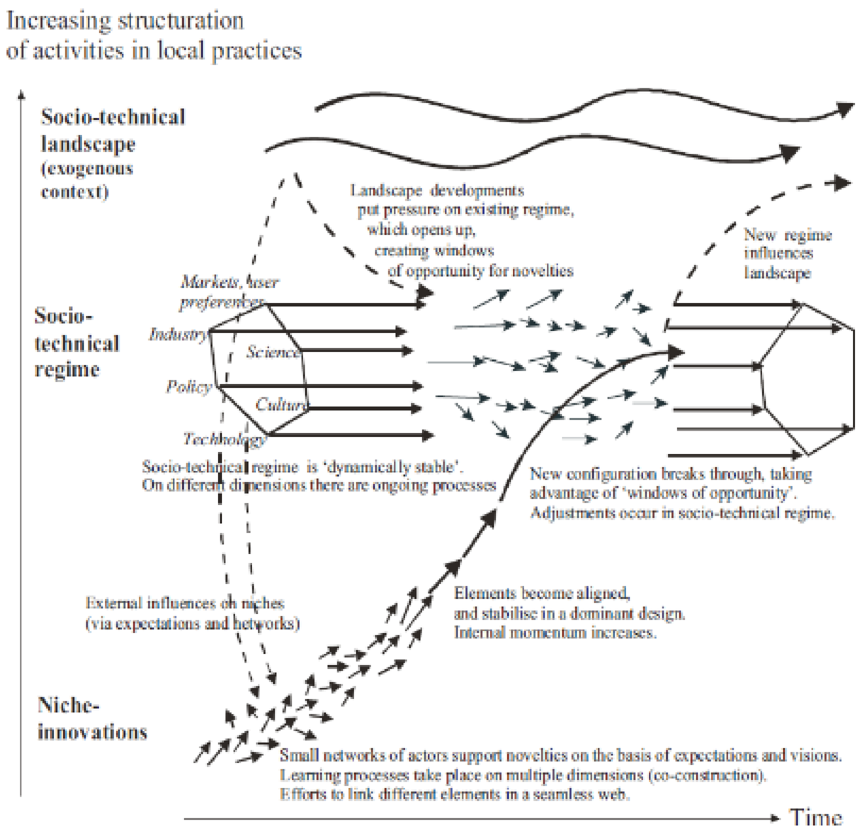


Figure 2.2 Multi-level perspective on transitions (from Geels)

The *Landscape level* consists of the overarching set of trends and developments that put pressure on the existing regime. Landscape characteristics should be seen as external drivers that can have a considerable impact on the regime and niche levels, but which cannot be changed by the actors that are involved at these levels. These drivers can be of varying nature (i.e. environmental, international, social, economic, political).

The *Regime level* includes factors that provide a framework and guidelines for the decision-making and actions of actors within those levels that the actors can influence. These factors include status quos such as stabilized or dominant technologies, structures, mindsets, and other rules of the game. In general regime characteristics may be difficult to change due to their stability. On the contrary, a transition is characterized in particular by adjustment of the regime level.

The *Niche level* consists of controlled environments or protected sub-systems where innovations are nurtured and enabled to thrive. Niches provide shelters against established technologies and frameworks, which the development of new technologies, behaviours and structures may not be able to compete against. In a transition, a complex interaction arises between regime adjustments that accelerate the uptake of innovations from the niche level, and innovations that themselves lead to socio-economic changes at the regime level. Since, the scenario study mainly looks at the broad introduction of sustainable technology, no specific assumptions at niche level are included in the scenarios.

2.2 Storylines for the ADAPT and TRANSFORM scenarios

This study examines two different plausible visions of the future for the Dutch energy system in the period 2030-2050: the ADAPT scenario and the TRANSFORM scenario. The *common scenario driver* for both scenarios is the ambition to reduce 95% of Dutch GHG emissions by 2050 compared to 1990. But the way in which this goal is achieved is different. The difference between the two scenarios (i.e. *distinctive scenario driver*) lies in the difference in intrinsic motivation and support for change among citizens and companies. Other dimensions, such as differences in coordination of the government, and differences in international cooperation, are included in this scenario driver.

The two scenarios can be elaborated using scenario descriptors. These include: growth in energy demand, industrial production and mobility, role of government, international cooperation, use of energy resources and technologies or limitations therein. The scenarios are described below with two storylines. Table 2.1 summarizes both the ADAPT and TRANSFORM scenarios, the scenario drivers and scenario descriptors.

- *ADAPT*
  In the ADAPT scenario, the Netherlands builds on its current strengths, but ensures that CO_2 emissions decrease by 95%. In recent decades, oil, coal and gas have created a strong industrial sector, a strong transport and logistics industry, a reliable electricity supply and comfortably heated buildings. In this scenario, Dutch society opts for security: retain employment and the current comfortable lifestyle. Sustainability is considered less important by citizens and companies. This requires energy carriers that resemble what we have now, but are CO_2 neutral. The current system is being adapted and optimized, while the impact on energy-using sectors is limited. Other European countries are also trying to achieve their 2050 reduction targets while preserving their competitive advantages and minimizing disruptions to their current established systems. In this context, centralized environmental restrictions from Europe, except GHG targets, are not becoming much stricter than they are today, giving European countries more freedom to manoeuvre their energy transition, but also with less European collaboration. In the Netherlands, national and local governments take the lead and guide citizens and companies in making choices regarding the energy transition with concrete policy measures. Mobility demand and industrial production continue to grow. For international aviation and shipping, whose GHG emissions are outside the national target, the aim is a GHG emission reduction of 50% by 2050. In this scenario, there are no major social

objections to the use of fossil fuels in combination with CO_2 capture and storage (CCS). A large import of biomass is also accepted.

- *TRANSFORM*
  In the TRANSFORM scenario, the Netherlands together with the other EU members are at the forefront of the fight against climate change and for sustainability. With its strong knowledge infrastructure and innovative business community, the Netherlands is ideally positioned to build a new clean, energy-efficient economy. People's awareness of their energy consumption and their carbon footprint leads to a change in behaviour and many different types of sustainable initiatives. New technologies are enthusiastically embraced. EU member states are committed to collaborate in realizing the transition and to harmonize policies within the EU. The Dutch government has a stimulating and enabling role. As citizens are more environmentally aware and act accordingly, energy demand as well as mobility demand and demand for environmentally harmful industrial and agricultural products decrease. Companies are also taking initiatives for an ambitious transformation by replacing existing processes with sustainable alternatives. Industry is becoming less energy intensive and part of the economic activity is shifting to the growing, but less energy-intensive services sector. Social change is also leading to adjustments in the agricultural sector, such as more sustainable agriculture and less livestock farming. International aviation and shipping, whose GHG emissions are outside the national target, also have a 95% reduction target. There is no public support for CO_2 capture and storage (CCS), and the import of biomass remains limited.

Table 2.1 Characteristics of the ADAPT and TRANSFORM scenario

	ADAPT	TRANSFORM
Landscape	• Netherlands and EU will meet 2030 and 2050 GHG reduction targets. • Society values current living standards. • EU countries have their own policies in achieving GHG reduction. • Industrial production and economic structure remain basically the same.	• Netherlands and EU will meet 2030 and 2050 GHG reduction targets. • Strong environmental awareness and sense of urgency in society. • EU and Netherlands want to become innovative power house. • Individual and collective action by civilians.
Regime	• National and local government take the lead. • Adapting and optimizing the energy system and industrial processes. • Keep options open and structural change post 2020. • Fossil fuels are expected to be utilized in combination with carbon capture and storage (CCS) to abate CO_2 emissions. • Imports of biomass and biofuels.	• Government has a stimulating and enabling role. • Ambitious transformation of energy system, replacement of energy intensive industry, resulting in lower industrial production and energy use, increase of service sector. • Reduction of other GHG intensive activities (cattle, international travel, etc.). • No carbon capture and storage (CCS), and limited biomass use.

2.3 Scenario parameterization

On a *landscape level*, the ADAPT and TRANSFORM scenarios share similarities:

- *Economic development:* In both cases it is assumed that national and international economic development is similar, and recessions are not taken into account within the studied time-frame. The scenarios use an economic growth path from a CPB and PBL study (PBL et al., 2015) on the macro-economic developments of the Netherlands. In both scenarios the Dutch economy will grow by approximately 1.5% per year on average between 2030 and 2050.
- *Demographics:* The demographic development of the Dutch population is the same in both scenarios, and based on the aforementioned CPB and PBL study.
- *Abatement targets:* Besides the 2050 95% reduction target, the 49% reduction target for the Netherlands for 2030 is considered to be a fixed goal.
- *International trends:* In both scenarios, countries in Asia, Africa and South-America are developing fast and positioning themselves as leaders within innovative markets. European trends however differ in the two scenarios, see Table 2.1.
- *Technology development:* Development and deployment of sustainable technology takes place in many countries in the World. The Dutch energy system is benefiting from this global technology development. As starting point for both scenarios, technology development and the costs of technology are the same. Differences in cost development between technologies are analysed and discussed in Chapter 5.

At the *regime level*, some intended measures from the Climate Agreement are taken into account. The specific measures should be seen as constraints for the scenarios:

- Closing all coal-fired power plants within the country by 2030.
- Drastically decreasing natural gas extraction in the Netherlands, and ending the Groningen gas extraction in 2022.
- Closing of the Borssele nuclear power plant in 2033.

Table 2.2 provides an overview of the main and distinctive parameters for the ADAPT and TRANSFORM scenario.

Table 2.2 Main and distinctive parameters in the ADAPT and TRANSFORM scenario

	ADAPT	TRANSFORM
National GHG reduction target	2030: -49% 2050: 95%	2030: 49% 2050: 95%
GHG reduction target international aviation and shipping	-50%	-95%
Fossil fuel prices	Constant after 2030	Constant after 2030
Industry		
• Energy demand	↑	↓
• Production	↑	↓
Energy demand service sector	↑	↑↑
Energy demand agriculture sector	↑	↓
Mobility demand		
• Domestic	↑	↓
• International	↑	↓
Biomass availability		
• Domestic	ooo	o
• Imports	ooo	o
Use CO_2 capture and storage (CCS)	Yes	No
Use coal-fired power plants	No	No

↑ means growth, ↓ shrinkage and ↑↑ extra growth, ooo means ample and o limited availability

3 Modelling of the scenarios

The ADAPT and TRANSFORM scenarios described qualitatively in the previous chapter have been quantified using the OPERA numerical model. This chapter describes how the model works (Section 3.1) and which input data are used to quantify and optimize the energy system for the two scenarios (Section 3.2). The model results are presented and discussed in Chapter 4.

3.1 The OPERA model

The OPERA (Option Portfolio for Emissions Reduction Assessment) model tool for integrated energy system analysis for the Netherlands has been developed by ECN[1]. The OPERA model has been successfully applied for cross-sectoral analysis within multiple research projects during the past several years (Van Stralen J.N.P., 2019). The OPERA model covers the entire energy and GHG system of the Netherlands. OPERA optimises the energy system and corresponding GHG emissions in a cost-effective manner given certain targets and boundary conditions. It uses a least cost approach based on a national cost-benefit analysis method to determine what the optimal technology mix is that both satisfies the demand for energy and products, and adheres to the user defined constraints.

Technologies

OPERA is a technology-rich model. It uses a database with over 600 technology options that cover the entire technology chain from production, conversion and energy infrastructure to end-use demand services (including energy efficiency options). Mining of domestic energy and interconnection infrastructure are not explicitly modelled. For oil (and derived products), natural gas, biomass and biofuels, a border price is provided. All other commodity costs (energy and emissions) are determined endogenously by the model. To enable import or export of hydrogen border prices are required. The model represents all technologies that convert primary into secondary sources, such as power plants for electricity, boilers for heat and refineries in the case of crude oil. Also infrastructure for the transport of electricity (see Figure 3.1), heat, natural gas and hydrogen is explicitly modelled. It has to be noted that heat infrastructure, in contrast to the other infrastructures which have more disaggregated levels, is represented more simply in the model. Exchange over network infrastructure between sectors and between regions in the country is allowed, but can be restricted.

[1] In 2018 when ECN merged with TNO, PBL became the official owner of the model. The model has since then been further developed by TNO in close cooperation with PBL.

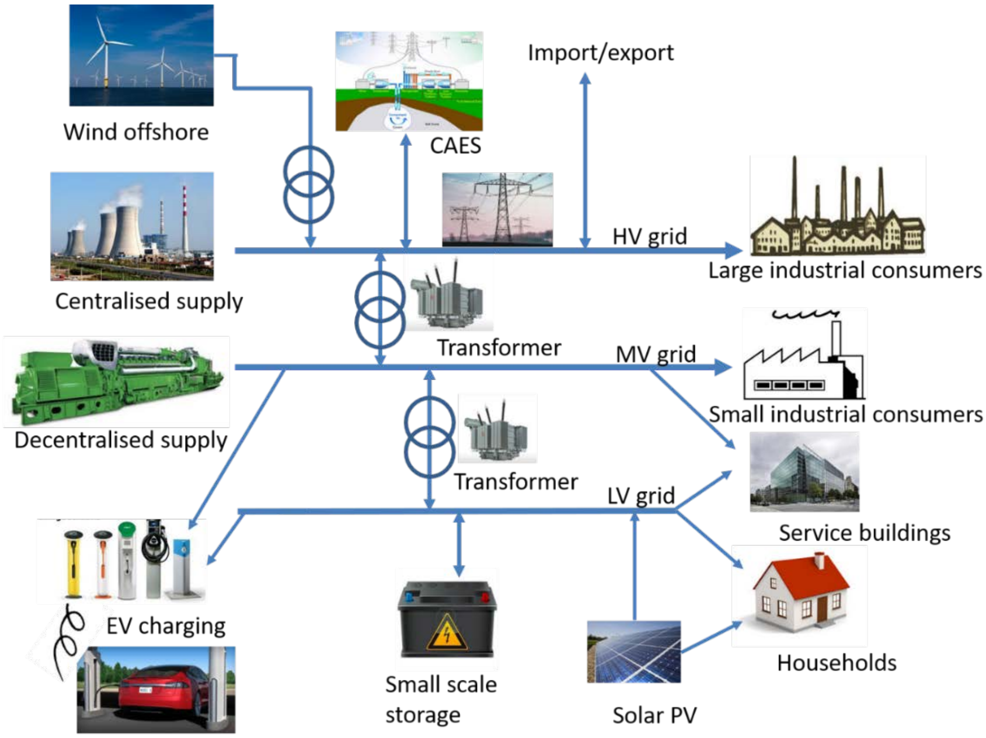


Figure 3.1 Schematic representation of the electricity infrastructure contained in OPERA

The technologies and processes considered in the applied version of OPERA[2] are those that directly contribute to the national GHG accounting of the Netherlands. This includes primarily energy technologies, but also non-CO_2 abatement options in agriculture and other sectors. The applied model considers both emissions originating from energy consumption, and process emissions from industry in the Netherlands, as well as separate CO_2-emissions from land use change and forestry and CO_2-emissions from international aviation and shipping.

Technologies are characterized by their technologic and economic data, covering at a minimum the in- and output energy flows, efficiencies, investment and operational costs, lifetime and annual availability. These data are stored in an underlying database. Data are provided for 2030, 2040 and 2050 - which are the target years for this study. If no data for 2040 is provided, the model automatically interpolates between the 2030 and 2050 values. If only 2030 data are provided, the model will assume constant values for 2040 and 2050. An update of techno-economic data for those technologies for which TNO has produced and published a factsheet[3] was performed in preparing the database for the scenario model runs and analyses. Furthermore, for those technologies which have constant costs over all years, and do not have a corresponding factsheet but that are considered to have a learning-by-doing potential, an investment cost reduction of 20% in 2050 compared to 2030 is applied[4].

[2] For this study OPERA version 2019.4 has been used.
[3] For the available factsheets, see www.energy.nl.
[4] This includes technologies such as green gas production from biomass with CCS, hydrogen production from biomass, micro CHP fuel cell and biomass fired boilers and CHP with CCS.

GHG emissions are in general linked to the energy flows, but can be specified by technology, e.g. the CO_2 capture ratio by CCS options. The current version of the model does not contain other emissions like NO_x, SO_x and particulate matter, but once emission factors become available, there is no obstruction to including them in future analyses.

Demand
A second component of the model, which is actually the driving force for obtaining a solution, is the level of energy or product demand in the entire system. The current model distinguishes final demand for heat and electricity in the end use sectors (households, service sector, agriculture and the chemical, fertiliser, steel and the rest of industry sectors) as well as demand for certain energy intensive products (tonnes of high value chemicals, fertiliser, steel) and demand for mobility (private road transport, light and heavy duty vehicle road transport, public transport, inland shipping). The model uses the demand levels from the National Energy Outlook 2016 (NEV2016)[5] (ECN, 2016) as a basis and are increased or decreased according to the scenario storyline, see Table 2.2. These data are provided for 2030, 2040 and 2050. If no data for 2040 is provided, the model automatically interpolates between the 2030 and 2050 values.

For energy demand, not only the annual volume is important, but also the time of the year it is occurring and at what level. For both final heat and electricity demand in households and the agriculture sector, hourly profiles are used. For industry, a flat profile is assumed. For the services sector, because no sectoral data are available, the profile is made up by subtracting the known sectoral profiles from the known aggregated national profile. For transport, private car transport follows a mobility profile (and a load profile for electric vehicles). For light and heavy duty road vehicles, a flat profile is assumed. The other transport forms (two-wheelers, inland shipping, off-road vehicles) also have a flat profile. For energy supply technologies, profiles of solar and wind energy are explicitly provided. Other supply technologies act and react following the demand.

In order to link OPERA with the rest of Europe, a soft link with the electricity market model COMPETES is made. Based on similar assumptions regarding electricity demand and renewable power plant capacity for the Netherlands and the other EU countries, COMPETES (Hobbs and Rijkers, 2004) calculates the hourly volumes and prices for import and export of electricity to and from the Netherlands. OPERA considers these cross-border trade results as a fixed boundary conditions and, hence, they do not change in the scenarios.

Whereas previous versions of OPERA had a single national scope, the applied model for this study has been regionalised. It distinguishes 7 land-based regions: Limburg, Mid-Netherlands (Utrecht, Gelderland, Overijssel), North Brabant, North Holland, North Netherlands (Friesland, Groningen, Drenthe), South Holland and Zeeland and 7 offshore regions, see Figure 3.2. To each region, a share of the final demand, as well as an estimation of the potential for energy supply and the interconnection capacity, has been allocated.

[5] These demand levels are slightly higher than in the Climate and Energy Outlook 2019 (KEV 2019).

Scenarios are run over consecutive target years. To keep the solution consistent over time, i.e. to avoid that for each target year the model would optimise a completely new energy system, a transfer procedure is applied so that residual capacity of technologies with a lifetime greater than 10 years is proportional to its lifetime carried over to the next decade target year. This ensures that the model does not re-invest in capacity which is still remaining from investments in the previous target year. Even if the new technology option is cheaper than an existing technology option, part of the existing capacity will continue to be used, depending on the life of the existing technology option. It does mean, however, that for 2030, being the first target year, the model builds up an energy system from scratch, and thus overestimates the required investments for that year[6].

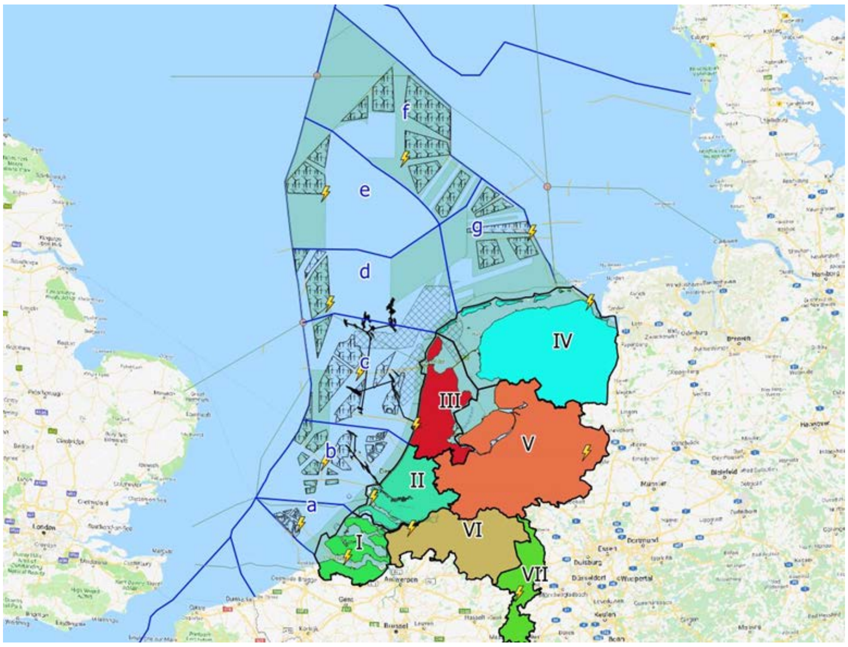


Figure 3.2 Regions distinguished in the OPERA model

Target
The third component is the user-defined conditions to which the system has to adhere. For this study, covering target years 2030, 2040 and 2050, the main assumptions were made on the allowed GHG level. For 2030, the Dutch Climate Agreement has been taken as the target (-49% GHG emissions compared to 1990) and for 2050 the EU target of -95% has been taken. 2040 is interpolated between these two targets. Separate emission constraints were set on land use and forestry and on international aviation and shipping. OPERA is capable of handling several targets simultaneously.

Based on these input elements, OPERA calculates a least-cost ('optimal') solution for each target year. To do so, it uses the annual costs for each technology. These costs contain of three elements: the annualised investment costs using the technical lifetime of each option and a national (social) discount rate of 3%, the annual operational costs, and the annual energy costs (including costs for network infrastructure). For supply technologies, the energy costs are seen as a revenue for

---

[6] On the other hand, the real energy system is likely to be less cost-optimal than the energy system being modelled, which will result in lower system costs for the modelled energy system.

suppliers, and for end users as a cost. The objective function is the lowest cumulative summed annual cost over all technologies.

Time slices: multiple energy balances
Although OPERA could run on an hourly basis, in order to save on calculation time, the model aggregates hours into time slices containing hours with similar demand and supply characteristics. These time slices vary amongst themselves in numbers of hours covered and in demand level. Baseload demand time slices are characterised by many hours, and a low to intermediate demand level. Peak time slices on the other hand only contain a few hours and have a high to very high demand level. All time slices combined cover a whole calendar year. For each time slice, the model ensures that supply and demand are in balance: to satisfy demand in a particular time slice, the model will deploy certain technologies that deliver the demand service (e.g. heat, electricity, etc.). In making the technology choices, the model does not only look at individual time slices, but over the whole year, in order to avoid non-optimal overinvestment in certain technologies. Demand in each time slice starts from the basic demand level as taken from the NEV2016, but due to the scenario characteristics demand can increase (e.g. electrification technologies will increase demand for electricity) as well as decrease as a result of applying energy saving technologies. For this study, model runs with 85 time slices are performed. In a post-processing procedure, the results can be reconstructed on an hourly basis.

3.2 Assumptions and input parameters for the scenarios

As described above, the basic assumptions for energy and product demand are taken from the NEV2016. Recent developments are also taken into account. Examples are:
- The closure of the Borssele nuclear power plant in 2033.
- The ban on coal power plants in 2030 as a result of the Climate Agreement.

For solar and wind, and electric road transport, an additional feature is introduced in the model to prevent generating an optimised solution with installed capacity that is less than the reference level from the NEV2016.

Following the parameterisation of the scenarios (see Section 2.3), for ADAPT and TRANSFORM, separate assumptions have been entered in OPERA as input data. The tables below summarise the main parameters for each of the scenarios. Table 3.1 contains the assumptions on the supply side:
- In the ADAPT scenario, CO_2 storage is allowed, increasing from the 7 Mton in the Climate Agreement to a maximum of 50 Mton in 2050. The latter figure is derived from the total available storage capacity of 1600 to 1700 Mton in the Dutch part of the North Sea (Klimaattafel, 2018). OPERA does not include a detailed CO_2 infrastructure system with transport and storage, instead a cost mark-up to CO_2 capture options has been included, set at 10 €/ton CO_2 for transport and storage costs. In the TRANSFORM scenario, no CO_2 storage is allowed, but the system may use captured CO_2 in downstream processes as feedstock, e.g. to produce synthetic fuels in combination with hydrogen.

- For renewable electricity production by wind and solar, maximum capacities have been defined, including for off-shore and on-shore wind energy. The maximum production for offshore wind is based on (Matthijsen J., 2018).
- Biomass (woody products) is available to the system from two sources: a domestic potential and a foreign potential (i.e., import). Both potentials are limited while, in addition, the border price of biomass also plays a role in affecting the amount of biomass imports (see Table 3.2). For the ADAPT scenario, it is assumed that the full domestic potential is available and a decent share of the international potential[7]. For the TRANSFORM scenario, environmental concerns and social acceptance reduce the available potentials. Besides woody biomass, other domestic biomass sources are available in both scenarios. Examples are vegetable and garden waste, sewage and waste water streams, manure, and products for co-fermentation.
- Biofuel import has been deliberately limited in this study to 10 PJ in 2030 and 25 PJ in 2050 for two reasons: firstly the potential for an international biofuel market is not yet known, and secondly, and more important, because OPERA is a cost optimisation model, the level of import and export prices are decisive in terms of modelling outcomes. If import prices are lower than cost of domestic biofuel production, the model will try to import as much as possible. On the other hand, if export prices are sufficiently high enough, the model will increase domestic production to the level at which the system profits the most from the export revenues. Given the uncertainties about the international biofuel market, both for import and export, the import amount has been limited to 10 to 25 PJ and no export is allowed.
  In addition, to avoid that the Dutch energy system is solely responsible for providing decarbonised fuels for international aviation and maritime transport, an assumption has been made that half of the required amount of zero emission bunker fuels could originate from import of biofuels. This means that for 2030 in both scenarios 1 PJ each is allowed for bio-heavy fuel oil and for bio-kerosene. These amounts can increase to a maximum of 57 PJ and 72 PJ for bio-kerosene in 2050, and 182 and 132 PJ for bio-heavy fuel oil for respectively the ADAPT and TRANSFORM scenarios.
- The geothermal potential for the ADAPT scenario is taken from the “Masterplan aardwarmte” by Energie Beheer Nederland (EBN) and the geothermal sector (EBN, 2018). In the TRANSFORM scenario the potential in 2050 is considered to be 50% larger.
- For hydrogen import and export, even more than for biofuels, the system showed to be very sensitive to the assumptions made. Thus, it has been assumed that for the base cases that no import or export of hydrogen takes place. To research the sensitivity of the energy system to hydrogen import and export, dedicated scenario variants have been created in which import and export prices vary, given a fixed maximum import (250 PJ), see Section 5.2.
- Because OPERA works with regions in the Netherlands, interconnections between these regions regarding infrastructure, and especially for electricity, are important in order to avoid extreme exchanges between supply and demand regions. To anticipate on increase in electrification, it is assumed that the capacity of the high voltage network between regions will be 2.5 times the current capacity by 2050.

---

[7] https://www.pbl.nl/en/publications/biomass-wishes-and-limitations.

Table 3.1: Maximum supply volumes and capacities used in the base scenarios

		ADAPT			TRANSFORM		
	Unit	2030	2040	2050	2030	2040	2050
CO_2 storage potential	Mton	7.5	19	50	No CO_2 storage allowed, CCU is possible		
Wind offshore capacity	GW	12	36	40	14	45	60
Wind on land capacity	GW	8	8	8	8	10	12
PV capacity	GW	31	60	101	39	75	127
Biomass domestic	PJ	220	220	220	147	147	147
Biomass import	PJ	187	351	515	70	100	129
Biofuels import for domestic transport	PJ	10	18	25	10	18	25
Biofuels import for bunker fuels	PJ	2	121	239	2	103	204
Geothermal potential (> 500 m depth)	PJ	50	125	200	50-	175	300
H_2 import and export		Not allowed			Not allowed		
Increase of electricity interconnection capacity between regions compared to current capacity		250%	250%	250%	250%	250%	250%
Maximum of total heat demand that can be supplied via heat network to the built environment (households and service sectors) and agriculture sector	Zeeland	29%			29%		
	South Holland	100%			100%		
	North Holland	63%			63%		
	North NL	16%			16%		
	Mid NL	28%			28%		
	North Brabant	40%			40%		
	Limburg	28%			28%		

- Based on information from the Warmteatlas (RVO) an estimation has been made about the maximum potential amount of heat delivery through a (district) heating network for each region, see Table 3.1. Household, service buildings and horticulture greenhouse geographic density on the demand side, and geothermal and industrial waste heat potential on the supply side, have been used to determine the maximum share of heat delivery through networks for each region. Exchange of heat between regions is not allowed.

On the demand side, several assumptions have been quantified aligned with the storylines. Whereas the ADAPT scenario hardly assumes any change compared to the reference case (NEV2016), this is not the case for the TRANSFORM scenario. The main point is that volumes of energy intensive activities, such as steel and ammonia production, private road transport, international transport, etc. are lower in TRANSFORM compared to ADAPT. Table 3.3 contains the overview of the important parameters that are driving demand.

Table 3.4 shows the GHG reduction targets used in the scenarios: for 2030 a 49% GHG emission reduction compared to 1990 levels in line with the Dutch Climate Agreement and for 2050 the a reduction target of -95% GHG emissions in line with the Dutch Climate Act. For the emissions for international aviation and shipping (bunker fuels), not included in the national target, additional assumptions have been made: for the ADAPT scenario it concerns a -50% reduction compared to 1990 levels and for the TRANSFORM scenario a -95% reduction. Besides the GHG and bunker targets, additional GHG constraints have been added to the model. For CH_4, N_2O, F-gases and LULUCF, the maximal allowed emission levels have been defined per scenario (see Table 3.5), in line with the underlying storylines. From these CH_4, N_2O and F-gases levels, OPERA can chose to implement further emission reduction options to meet the overall GHG target when these prove to be a cost-efficient contribution in reaching the overall GHG target. A similar approach is possible for LULUCF once it has been decided to include LULUCF emissions in the national target. For the time being, LULUCF emissions are not included in the GHG reduction target.

Table 3.2: Commodity border prices[8]

		ADAPT			TRANSFORM		
	Unit	2030	2040	2050	2030	2040	2050
Natural gas	€2015/GJ	7.5	7.5	7.5	7.5	7.5	7.5
Oil	€2015/GJ	14.6	14.6	14.6	14.6	14.6	14.6
Coal	€2015/GJ	2.9	2.9	2.9	2.9	2.9	2.9
Biomass (woody)	€2015/GJ	8.0	8.0	8.0	8.0	8.0	8.0
Biofuel	€2015/GJ	23.7	46.5	69.4	23.7	46.5	69.4

[8] Fossil energy prices and biomass border prices are taken from Climate and Energy Outlook (KEV) 2019; biofuel border prices are derived from the AdvanceFuel project (http://www.advancefuel.eu/en/publications)

Table 3.3: Demand values used in the base scenarios (2040 values are interpolated)

	Unit	ADAPT		TRANSFORM	
		2030	2050	2030	2050
Steel production	Mton	8.50	9.00	7.65	6.80
Ammonia production	Mton	3.43	3.81	2.88	1.60
High value chemicals production	Mton	4.15	4.65	3.86	3.00
Feedstock demand relative to the NEV2016		100%	100%	82%	64%
Passenger road traffic	Billion vehicle kilometre	125.21	149.85	101.57	84.65
Light freight road traffic	Billion vehicle kilometre	19.47	22.03	19.47	22.03
Heavy freight road traffic	Billion vehicle kilometre	7.65	8.25	7.65	8.25
Public transport relative to the NEV2016	%	No change	No change	+3%	+8%
International aviation	PJ	198	213	188	149
International navigation	PJ	572	649	486	286
Heat demand					
Households	PJ	278	242	278	242
Service sector	PJ	119	95	125	105
Agriculture	PJ	94	83	75	50
Steel industry	PJ	32	36	29	29
Fertilizer industry	PJ	22	19	19	10
Chemical industry	PJ	204	221	183	155
Other industries	PJ	153	145	160	160
Electricity demand					
Households	PJ	74	82	74	82
Service sector	PJ	128	133	141	160
Agriculture	PJ	29	31	38	47
Steel industry	PJ	18	17	20	21
Fertilizer industry	PJ	3	3	3	2
Chemical industry	PJ	42	43	47	56
Other industries	PJ	76	78	83	94

Table 3.4: GHG targets used in the base scenarios (2040 values are interpolated)

	Unit	ADAPT			TRANSFORM		
		2030	2040	2050	2030	2040	2050
GHG reduction target		-49%	-72%	-95%	-49%	-72%	-95%
GHG emission target	Mton	113.3	62.2	11.1	113.3	62.2	11.1
International aviation CO_2 emission target	Mton	14.2	12.7	7.1	14.2	11.3	0.2
International shipping CO_2 emission target	Mton	44.2	39.8	22.1	44.2	35.4	1.7

Table 3.5 Additional GHG constraints used in the base scenarios (2040 values are interpolated)

	Unit	**ADAPT**			**TRANSFORM**		
		2030	**2040**	**2050**	**2030**	**2040**	**2050**
CH_4 from agriculture	Mton CO_2-eq	16.8	16.0	15.1	14.3	12.5	10.7
N_2O from agriculture	Mton CO_2-eq	7.5	7.4	7.3	6.1	5.4	4.6
F-gases	Mton CO_2-eq	1	1	1	1	1	1
LULUCF CO_2 emissions	Mton	5.5	5.0	4.2	5.5	4.4	3.0

4 Results for ADAPT and TRANSFORM scenarios

This chapter presents the results of the quantitative modelling of the two scenarios. In this modelling a solution is looked for with an energy and technology mix for each sector that has overall the lowest possible costs. This means that technology options and energy carriers compete with each other in every sector and for every energy function and that the technology-energy carrier combination is chosen with the lowest costs. This applies to both the energy demand and the energy supply, where the energy demand determines the energy carrier, and thus the type of energy supply. Note that fluctuations in energy supply and demand, potentials of energy sources, transport limitations, etc. also influence the energy and technology mix. These quantified scenarios form the basis for further analyses into the factors that influence competition between energy technologies and energy carriers and determine the modelling results. The results of these so-called insight analyses are presented in Chapter 5.

The quantitative presentation of the scenarios in this chapter takes place on the basis of graphs and an explanation. The values determined by the OPERA model are shown for both scenarios for 2030, 2040 and 2050. For comparison, the same values are shown for recent years (2018 or 2017) derived from statistical data. This quantitative presentation of the scenarios is divided into 6 sections: total primary energy supply (Section 4.1), energy production (Section 4.2), energy consumption (Section 4.3), remaining GHG emissions (Section 4.4), energy infrastructure (Section 4.5), total energy system (Section 4.6) and energy system costs (Section 4.7).

4.1 Total primary energy supply

To get a good picture of the transition of the Dutch energy system in both scenarios, Figure 4.1 shows the total primary energy supply, excluding the energy demand for international aviation and shipping and the non-energy demand of hydrocarbons that are used in industry as feedstock. The latter two uses of energy and hydrocarbons are discussed in Section 4.3. The primary energy supply consists of fossil (oil, natural gas, coal) and non-fossil energy (nuclear, wind, solar, biomass, geothermal and ambient energy) sources supplemented with energy carriers that are imported from abroad (i.e. electricity and biofuels).

The total primary energy supply falls from 2500 PJ in 2018 to almost 1837 PJ in the ADAPT scenario and 1927 PJ in the TRANSFORM scenario in 2030. Note that the primary energy supply in 2030 for both scenarios is the result of a cost-optimal energy system that meets the 49% GHG reduction target, but does not necessarily correspond to the energy supply as a result of implementation of the Climate Agreement measures. The observed reduction in energy supply in the scenarios is the result of energy savings and reduced energy conversion losses in, among others, electricity production (i.e. wind and solar substitute less efficient thermal power plants) and the transport sector (i.e. electric vehicles substitutes vehicles with combustion engines). After 2030, the energy supply in ADAPT increases again to 2249 PJ in 2050, due to energy demand increase caused by economic growth and higher energy conversion losses (e.g. hydrogen production). Despite economic growth and an even a higher energy conversion loss due to production of green hydrogen, the energy supply decreases in the TRANSFORM scenario further to 1698 PJ in 2050. This is caused by the scenarios assumptions regarding decreasing energy demand in industry and the transport and agriculture sector.

The supply mix in Figure 4.1 clearly shows the shift from fossil primary energy to renewable energy. Compared to TRANSFORM, more fossil fuels remain in the ADAPT scenario due to the use of carbon capture and storage (CCS), see Section 4.4. In the ADAPT scenario more biomass is used compared to the TRANSFORM scenario. In both scenarios biomass is partially imported. In the TRANSFORM scenario, some natural gas will still be used in 2050. This is further explained in Section 4.4.

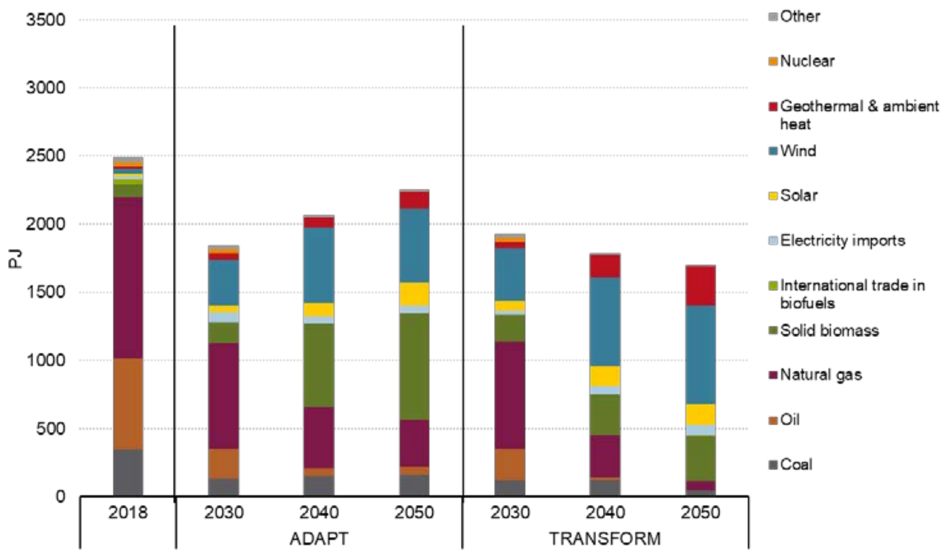


Figure 4.1 Total primary energy supply in 2018 and 2030-2050 (ADAPT and TRANSFORM scenarios), excluding energy for international aviation and shipping and feedstock use

4.2 Energy production

Electricity generation
In the ADAPT scenario the electricity production triples in 2050, and in the TRANSFORM scenario the electricity production in 2050 is more than four times that of 2018, see Figure 4.2. In both scenarios in 2030, approximately 80% of the electricity will be generated from wind and solar energy. By expanding the generation capacity of wind and solar energy (see Figure 4.3), electricity production will be almost completely from sustainable energy sources by 2050. The potential for on-shore and off-shore wind energy is then fully utilized.

In addition to large-scale electricity generation, electricity production also takes place in the end-user sectors, in particular in the built environment and agriculture sector with solar panels (PV). In 2018, the agriculture sector is a net supplier to other sectors using natural gas-fired combined heat and power installations. However, due to an increase in electricity demand in the agriculture sector, the growing electricity production with PV in later years will be consumed entirely within this sector.

Figure 4.2 shows that a small part of the electricity supply is import in all years for both scenarios. During a year there are periods with import and export of electricity (total exports are not shown in the figure). In 2018 the total import is still larger than the total export (i.e. resulting in a net import), but from 2030 in the TRANSFORM scenario and from 2040 in the ADAPT scenario, the total export of electricity exceeds the total import of electricity resulting in a net export. The exchange of electricity with neighbouring countries is limited by the interconnection capacity which is expanded in both scenarios[9].The net export increases in 2050 to 56 TWh in the ADAPT scenario and 44 TWh in the TRANSFORM scenario. This is 13% of the total electricity generation in the ADAPT scenario and 8% in the TRANSFORM scenario.

More wind and solar energy in the electricity system increases the need for flexibility in order to keep electricity supply and demand in balance. This flexibility requirement is met with power trade with neighbouring countries, peak power generation (natural gas), demand response (EV's, electrolysers), curtailment of wind and solar energy, and with energy storage (batteries and compressed air).

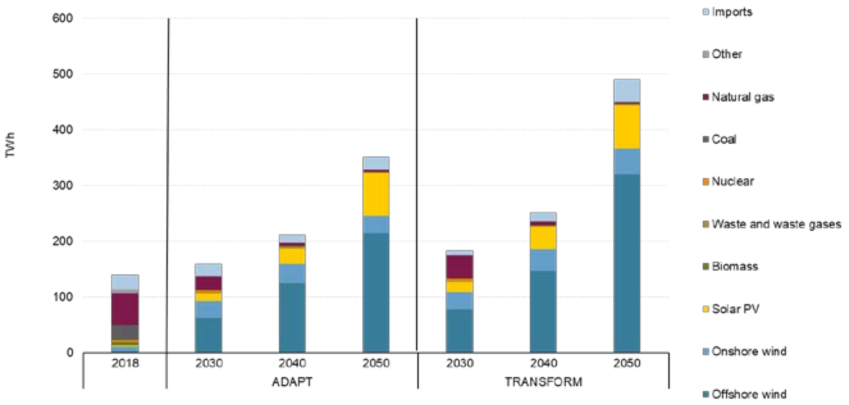


Figure 4.2 Electricity supply to the Dutch energy system in 2018 and in the ADAPT and TRANSFORM scenarios. From 2030 in the TRANSFORM scenario and from 2040 in the ADAPT scenario, the total electricity generation exceeds the domestic supply resulting in a net export.

9 It is assumed that, as a result of intensive European coordination, the interconnections with neighbouring countries, including countries around the North Sea, will be expanded from about 11-12 GW in 2030 (both scenarios) to some 53 GW by 2050 in ADAPT and even to approximately 71 GW in TRANSFORM.

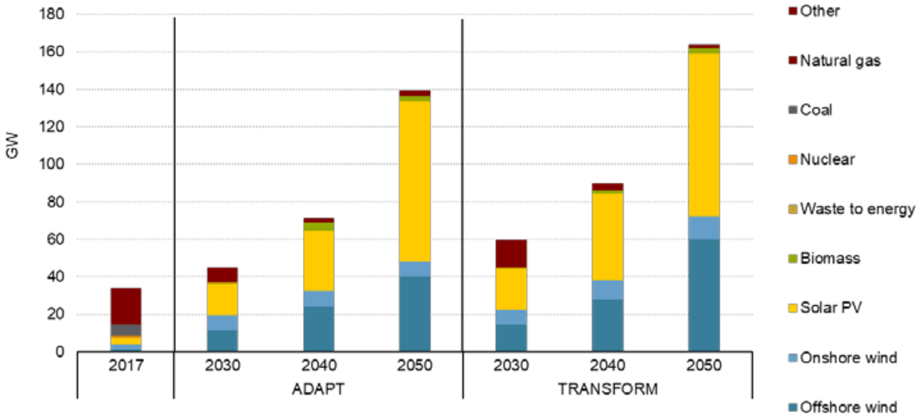


Figure 4.3 Electricity generation capacity in 2017 and in the ADAPT and TRANSFORM scenarios

Hydrogen production
In 2018 hydrogen is produced from fossil fuels and chlorine production and consumed in industry. Most hydrogen is produced from natural gas, estimated at 100 PJ. In the scenario results, a distinction is made between hydrogen from hydrogen plants and hydrogen produced within industrial processes. Hydrogen produced within industrial processes (e.g. methanol, ammonia, other chemicals) increases in both scenarios between 2030 and 2050: from 75 to 113 PJ in the ADAPT scenario, and from 68 to 101 PJ in the TRANSFORM scenario. There is a shift from hydrogen produced within the industrial processes, to hydrogen supply by hydrogen plants. In addition, in 2050 in both scenarios a substantial amount of hydrogen is produced in power-to-liquid processes.

The hydrogen produced by hydrogen plants is shown in Figure 4.4. In the ADAPT scenario the production takes place with so-called blue hydrogen: hydrogen produced from natural gas and CO_2 stored in empty gas fields in the North Sea. In 2050, this will be supplemented with hydrogen production with large-scale electrolysers. The hydrogen production in the ADAPT scenario decrease slightly in 2040. This is caused by a lower demand for hydrogen in the transport sector, see 4.3. In the TRANSFORM scenario in 2030, natural gas will also be used for hydrogen production, but without CO_2 storage. From 2040 the hydrogen will be produced with electrolysers (both large and small-scale types).

In 2050, the production capacity of the green hydrogen plants is 0.7 GW in the ADAPT scenario and 7.3 GW in TRANSFORM.

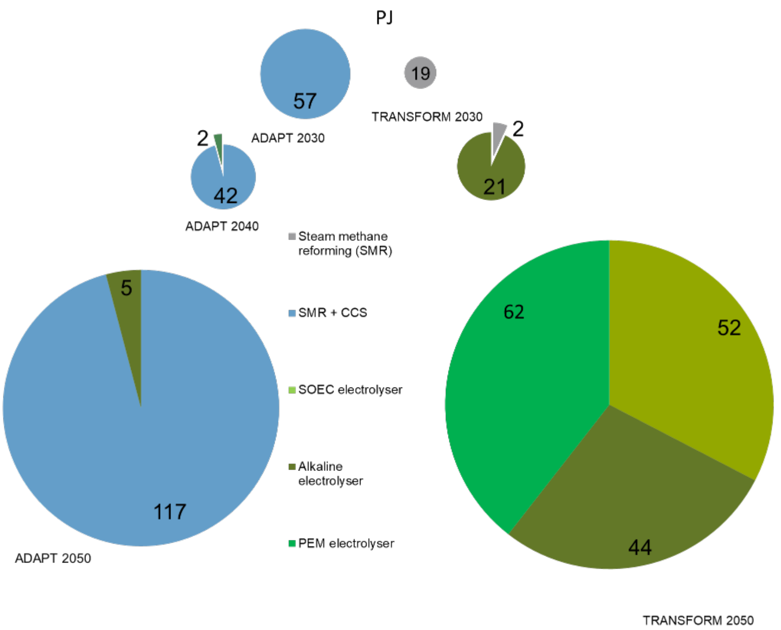


Figure 4.4 Hydrogen production plants in ADAPT and TRANSFORM scenarios. In addition hydrogen is produced within industrial processes: in 2050 113 PJ in the ADAPT scenario and 101 PJ in the TRANSFORM scenario.

Heat supply
Figure 4.5 shows how the energy system is supplied with heat for industry, built environment and the agriculture sector. As the demand for heat in all sectors decreases due to energy saving and lower production in the TRANSFORM scenario, total heat production in both scenarios also decreases compared to 2018: a 13% reduction in 2050 for the ADAPT scenario and a 25% reduction for the TRANSFORM scenario. In 2018, the heat supply consists mainly of natural gas, waste heat and residual gases. In both scenarios, the share of natural gas in the heat supply will decrease sharply from 2030 onwards. The fall in natural gas is mainly taken over by biomass, biogas, geothermal energy and electricity (heat pumps and electric boilers). Heat is supplied from industry to the built environment and the agricultural sector by heat networks. Other sustainable heat production installations can also be connected to these heat networks, such as geothermal sources and biomass boilers.

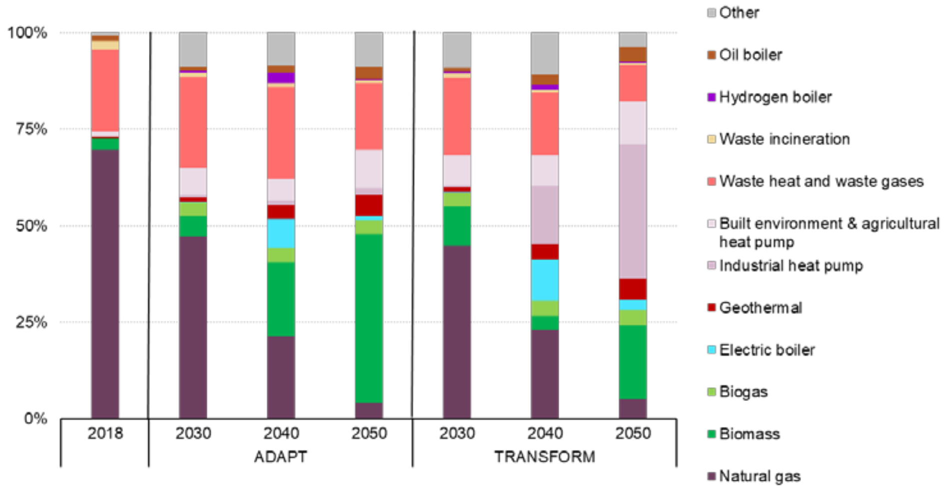


Figure 4.5 Energy mix in heat supply to industry, built environment and agriculture sector in 2018 and the ADAPT and TRANSFORM scenarios

Fuel supply

The industry supplies some hydrogen to the built environment and hydrogen and liquid fuels to the domestic transport sector and international aviation and shipping (see Figure 4.6). In the ADAPT scenario, the fuel supply from industry increases. Fossil oil products are being replaced by biofuels and hydrogen. In the TRANSFORM scenario, the fuel supply decreases, due to a lower mobility demand, both in domestic and international transport. In addition to the substitution of fossil oil products by biofuels and hydrogen, synthetic fuels are produced in 2050 in both scenarios.

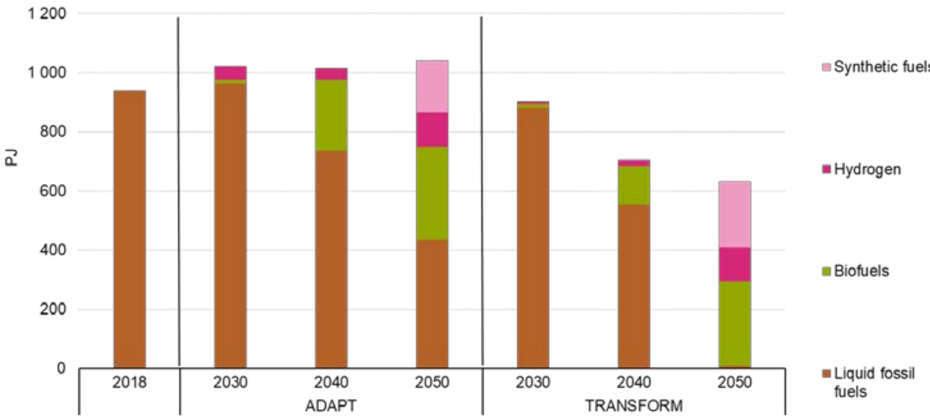


Figure 4.6 Fuel supply from industry to other sectors in 2018 and in the ADAPT and TRANSFORM scenarios

Biomass

Biomass is used in industry for heat production, as feedstock and for the production of biofuels. The built environment and agriculture sector also use biomass for heat production. Figure 4.7 shows the input-output flows of biomass. Most of the biofuels are used by international aviation and shipping. It is assumed that half of the biofuels for international aviation and shipping are imported (see Chapter 3). Biogas is produced in industry and by the agriculture sector, and almost all biogas is used within these sectors.

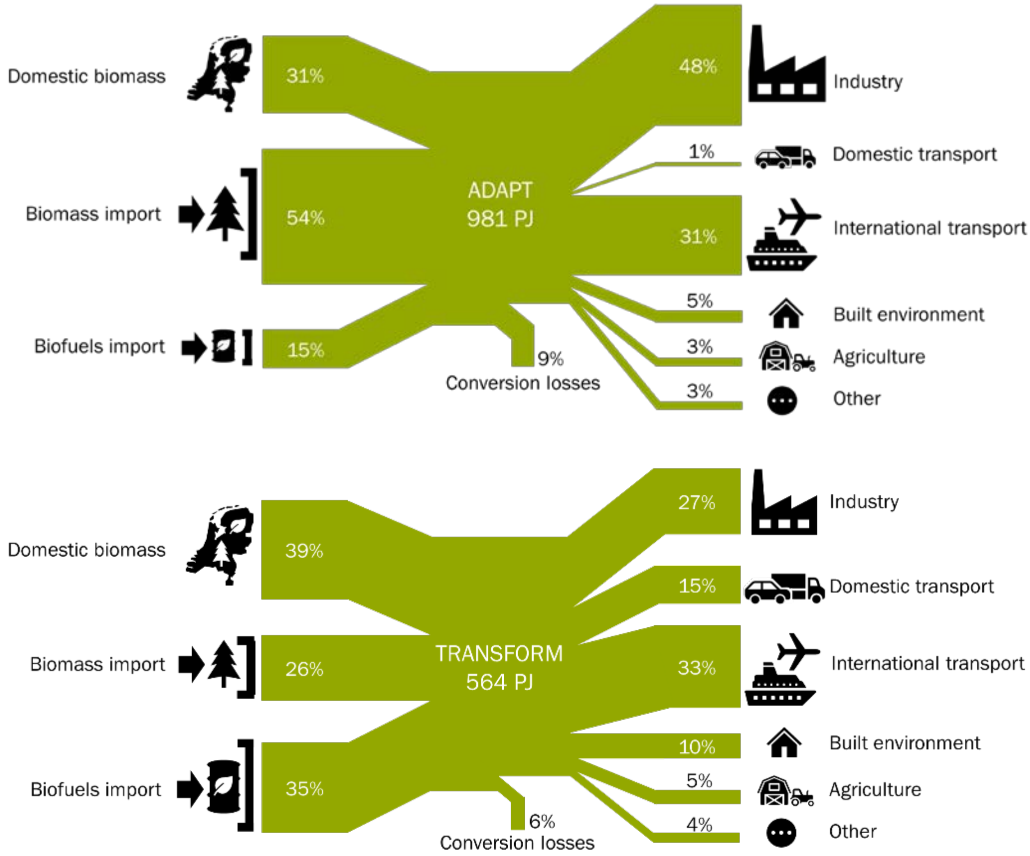


Figure 4.7 Biomass flows in ADAPT and TRANSFORM scenarios

4.3 Energy consumption

Industry

The demand for energy (including fuel production for international aviation and shipping) and hydrocarbons for feedstock is increasing in the ADAPT scenario in 2050 by 39% in comparison with 2018 due to economic growth. In the TRANSFORM scenario the energy demand remains about the same as in 2018 due to the industrial transformation and changes in the economic structure, also outside the industrial sector (according to the storyline for this scenario, a decline in industrial production is compensated by a growth in the services sector, see Section 2.3). The energy mix is shown in Figure 4.8. Heat is produced from biomass, electricity (heat pumps and electric boilers and geothermal energy. Non-energy use of hydrocarbons that end up in chemicals and other products do not contribute to GHG emissions (or only at the end of the lifecycle in which case they are counted as emissions from waste incineration). In both scenarios, the model opts for fossil oil for this hydrocarbon demand. The use of fossil as a raw material is conceivable for the ADAPT scenario, but for the TRANSFORM scenario, which presumes the introduction of new production processes and a circular economy, it is more likely that oil will be replaced by biomass[10]. Electrification of energy appliances and use of geothermal energy takes place in both scenarios, more in the TRANSFORM scenario than in the ADAPT scenario.

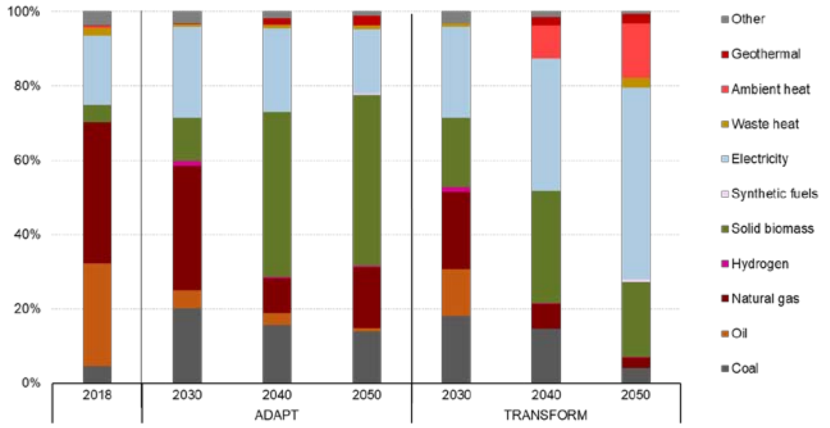


Figure 4.8 Energy consumption mix in industry

Built environment
In the built environment, energy consumption is gradually decreasing in both scenarios, by somewhat more in the ADAPT scenario (-25% in 2050) than in TRANSFORM (-19% in 2050). The lower demand reduction in the TRANSFORM scenario is related to the growth assumed for the service sector that is part of the built environment. Both scenarios hardly differ from each other with regards to the consumption mix, see Figure 4.9. Natural gas consumption in the built environment is gradually being replaced in both scenarios by heat pumps, heat from heat networks, biomass, and to some extent hydrogen and biogas. In contrast to industry and the agricultural sector, geothermal energy is not used in the built environment. Peak supply in heat demand is covered by biomass, electricity, natural gas and hydrogen. While electricity consumption in the built environment is increasing, a larger proportion within the sector is being generated with PV. This share will increase from 4% in 2018 to well above 50% in both scenarios.

[10] The use of biomass is probably somewhat underestimated in the TRANSFORM scenario. The total feedstock usage in the TRANSFORM scenario is approx. 330 PJ. In new industrial processes, biomass will probably be used in combination for feedstock and heat production.

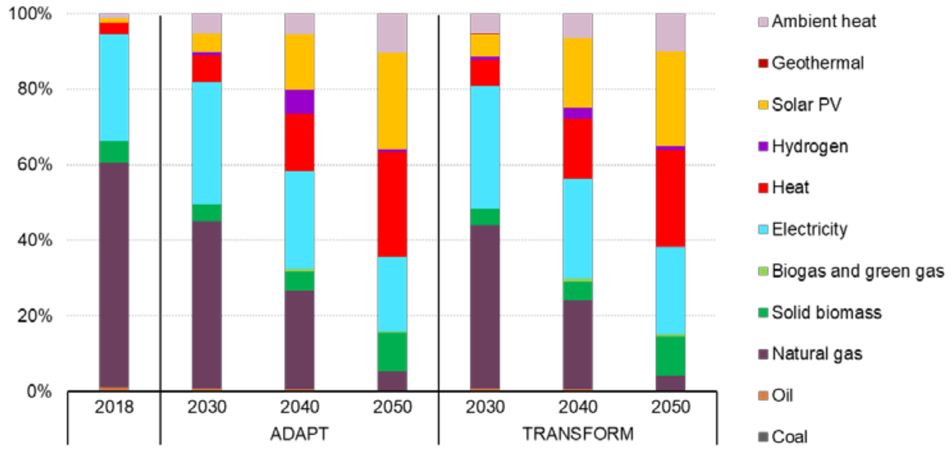


Figure 4.9 Energy consumption mix in the built environment

Agriculture sector

In the agricultural sector, energy consumption is gradually declining: in the ADAPT scenario by 17% in 2050 and in the TRANSFORM scenario by 35%. In both scenarios, natural gas is being replaced by biomass, electricity (electric boilers and heat pumps) and geothermal energy, see Figure 4.10. In addition, residual heat is supplied by industry, more in the ADAPT scenario than in the TRANSFORM scenario. Electricity is generated within the agricultural sector with PV, more so in the TRANSFORM scenario than in the ADAPT scenario. A declining share of PV generation in 2040 in TRANSFORM does not mean that PV systems are being removed, but that there is lower production due to curtailment (a flexibility option to balance the electricity system).

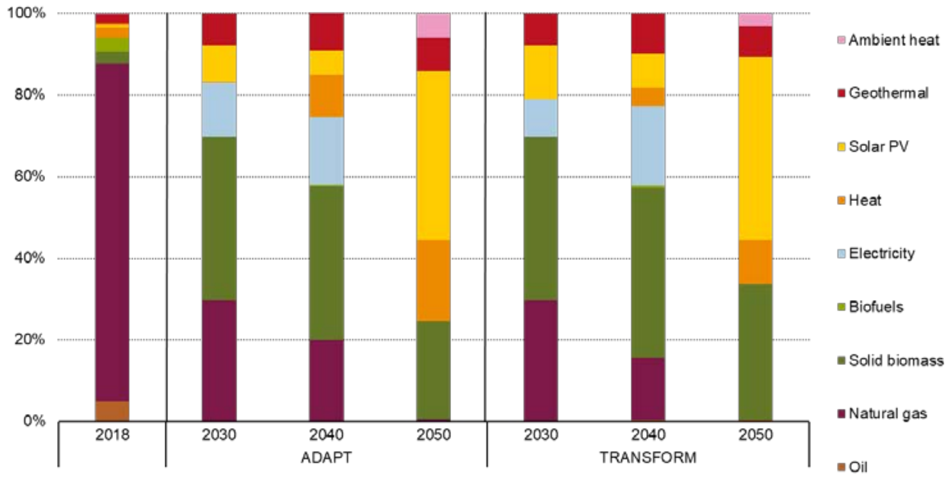


Figure 4.10 Energy consumption mix in the agriculture sector

Transport sector

The energy consumption for domestic transport will decrease in 2030 compared to 2018. This is mainly caused by a growing share of electric vehicles, which are more energy efficient than vehicles with internal combustion engines. In the TRANSFORM scenario energy consumption falls further due to a decrease in mobility demand, while in the ADAPT scenario, energy consumption subsequently increases due to growth in mobility demand. Figure 4.11 shows the energy mix for the transport sector. The use of gasoline and diesel is declining in both scenarios and is being replaced by electricity, natural gas (CNG), biofuels and hydrogen. This substitution differs per scenario. In the ADAPT scenario in 2030, passenger cars will switch to both electric and fuel cell cars using hydrogen. The use of electric cars continues to increase and eventually the fuel cell cars disappear. In the TRANSFORM scenario, passenger cars switch from gasoline and diesel to electric cars and not to hydrogen. In both scenarios heavy duty vehicles (e.g. trucks) switch first from diesel to natural gas and biofuels, reducing the use of diesel oil. In 2050 fuel-cell-driven trucks appear, reducing the use of natural gas and biofuels.

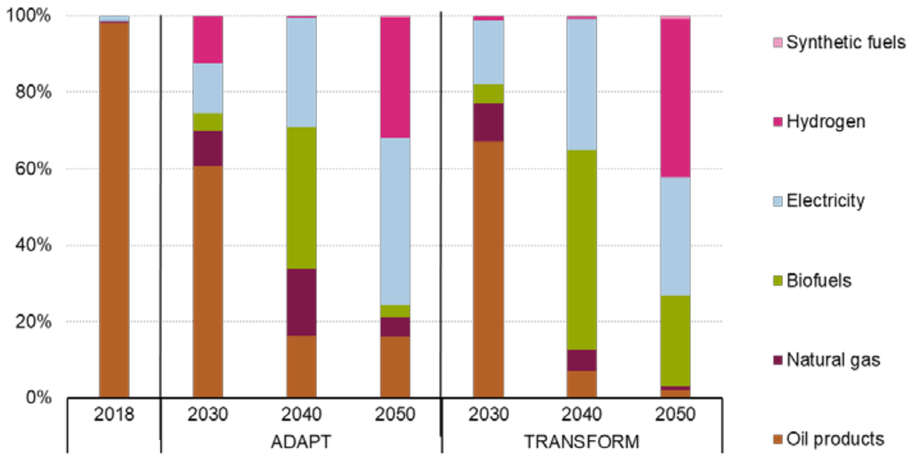


Figure 4.11 Energy consumption mix in the transport sector

International aviation and shipping (bunker fuels)
Compared to 2018, the demand for fuels for international aviation and shipping (bunker fuels) increases in both scenarios in 2030: an increase of approximately 5% in the TRANSFROM scenario and more than 20% in the ADAPT scenario. In the TRANSFORM scenario, the demand for international transport is subsequently decreasing, which reduces the demand for bunker fuels (more than 30% lower in 2050 compared to 2018). Initially in this scenario the demand reduction is enough to meet the CO_2-reduction targets assumed. In the ADAPT scenario, the demand for international transport continues to rise and so does the demand for bunker fuels: 35% growth in 2050 compared to 2018. Figure 4.12 shows the energy mix for international aviation and shipping (bunkers fuels). Fossil-based heavy fuel oil used by shipping and kerosene by aviation will continue to be used in both scenarios in 2030 and 2040. Only in 2050, when more stringent CO_2-reduction targets are assumed to be in place, will these fuels be partially replaced by sustainable alternatives: in both scenarios by biofuels and synthetic fuels. In contrast with the TRANSFORM scenario, the biofuel substitution starts already in 2040 in the ADAPT scenario, due to the larger demand for bunker fuels in this scenario. In the TRANSFORM scenario fossil bunker fuels will be completely replaced by CO_2-neutral biofuels and synthetic fuels in 2050, whereas in the ADAPT scenario more than 50% will be CO_2-neutral. The fuels for international aviation and shipping are partly produced in the Netherlands and partly sourced from the international market, see Section 4.2.

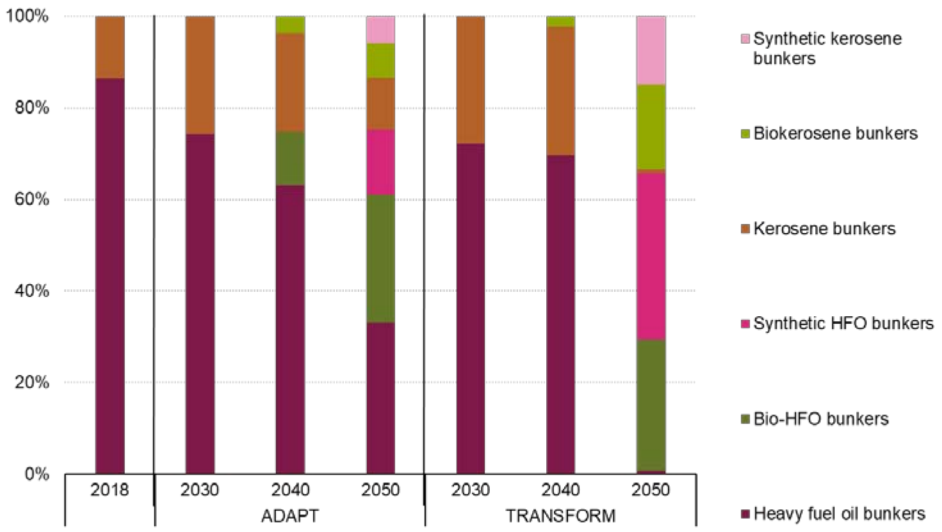


Figure 4.12 Energy consumption mix for international aviation and shipping (bunker fuels)

Total energy demand

The energy consumption for industry (excluding non-energy use), built environment, agriculture sector and transport sector are summarized in Figure 4.13. As the energy system becomes more sustainable, the exchange of energy between sectors increases (e.g. residual heat from industry to the built environment and the agricultural sector and hydrogen and biofuels from industry to the transport sector), as a result of which the sum of final energy consumption of individual sectors exceeds the total primary energy supply as shown in Figure 4.1. This is also illustrated in Section 4.6.

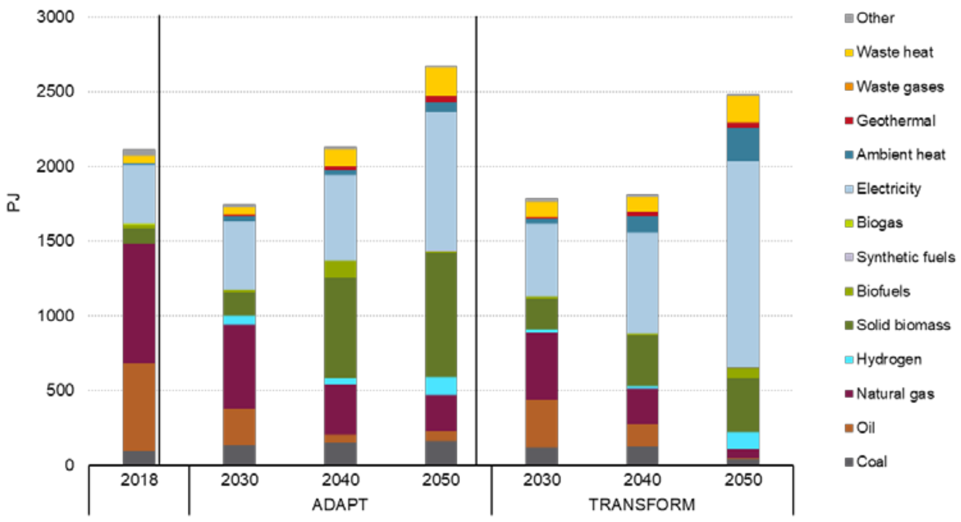


Figure 4.13 Total energy demand for industry (without non-energy use), built environment, agriculture sector and transport sector.

4.4 Carbon dioxide and GHG emissions

Carbon capture

Carbon capture and storage (CCS) is only applied in the ADAPT scenario. For the TRANSFORM scenario this option is excluded, see Chapter 2. Nevertheless, in the

TRANSFORM scenario carbon capture from biobased processes is used in 2050 (6.5 Mton), but the carbon thus obtained is used for the production of (a limited amount of) synthetic fuels (i.e. carbon capture and utilization, CCU). Also in the ADAPT scenario in 2050 15 Mton CCU is applied for production of synthetic fuels.

For CCS in the ADAPT scenario 86% of the available storage capacity is used in 2030, and in 2040 and 2050 the full available capacity for CO_2 storage of 19 and 50 Mton respectively is used. Figure 4.14 shows both the increase of the CO_2 captured and the processes involved. In 2030, CO_2 capture will be applied to waste incineration plants and hydrogen production from natural gas ('blue hydrogen'). CO_2 capture from the steel and chemical industry will be added in 2040. In 2050, CO_2 capture in the hydrogen production and steel industry will increase, and CO_2 capture will also take place in other industries.

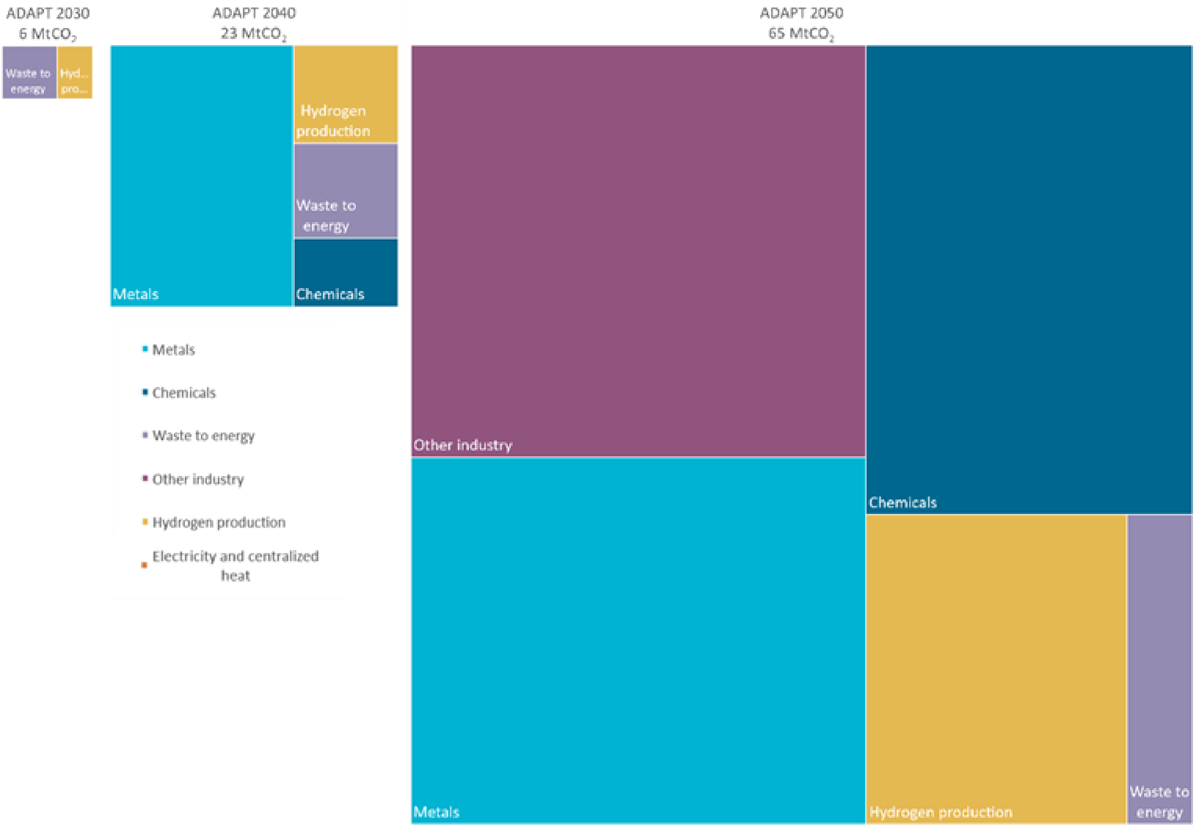


Figure 4.14 Carbon captured in the ADAPT scenario

GHG emissions

In both scenarios, GHG emissions are reduced compared to 1990 by 49% in 2030 and by 95% in 2050. This means that in 2030 an emission of 113.3 Mton GHG is allowed, and in 2050 only 11.1 Mton. The emissions and international aviation and shipping fall outside these objectives. We include separate objectives for this sector (see Table 3.4) in order to analyse the effect of fuel supply and related GHG emissions for the Dutch energy system. Emissions from land use, land use change and forestry (LULUCF) also fall outside the GHG reduction target. In 2030 these emissions will be 5.5 Mton for both scenarios and in 2050 4.2 Mton in the ADAPT scenario and 3 Mton in the TRANSFORM scenario. To get a complete picture of the remaining greenhouse gas emissions, the LULUCF emissions are also included in the graphs below.

In both scenarios for 2040 the target is interpolated (62.2 Mton). Figure 4.15 shows the distribution of the remaining GHG emissions among the various sectors. Initially, in 2030 the reduction in GHG emissions mainly takes place by making the electricity production more sustainable. GHG reduction in the transport sector (through electrification of passenger cars and introducing biofuels), the built environment and the agricultural sector also contributes to achieving the reduction target. Whereas GHG reduction in industry is limited in 2030, from 2040 onwards substantial reductions take place in this sector. In the ADAPT scenario in 2050 industry realizes larger negative emissions. The waterfall graph of Figure 4.16 illustrates that the use of CCS and CCS applied to biomass processes (Bio-energy CO_2 capture and storage; BECCS) results in negative emissions for the industry sector that compensate for remaining GHG emissions from other sectors.

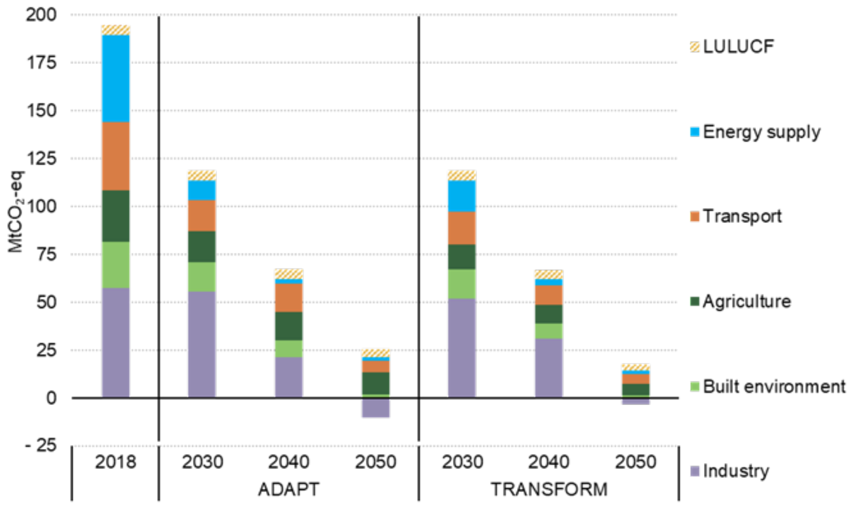


Figure 4.15 GHG emissions in the ADAPT and TRANSFORM scenarios, excluding emissions from international aviation and shipping

Figure 4.16 Waterfall graph for the ADAPT scenario that shows how CCS is used to meet the target for 2050

4.5 Energy infrastructure

Energy networks are available for the transport of energy from production locations to consumption centres, in particular electricity, gas and heat networks. Due to changes in energy production, both in terms of energy source and place of production, existing energy networks must be expanded and/or adapted.

Electricity
The growing demand for electricity, and the increase in sustainable electricity generation - in particular offshore wind - have major consequences for electricity infrastructure. Different regions are distinguished in the model, both on land and at sea. Figure 4.17 illustrates the electricity transport flows between the regions for the ADAPT and TRANSFORM scenarios in 2050. The expansion of the transmission network may encounter technical limitations and/or social objections, due to new high-voltage lines and transformer stations. Therefore, the transport between the on-land regions is limited to 2.5 times the current capacity. This maximum capacity is not fully used in both scenarios. Fluctuations in electricity production and demand are absorbed by energy trade with neighbouring countries, electricity storage, demand response with EVs and electrolysers and curtailment of wind and solar energy. In both scenarios, large-scale electricity storage (compressed air) and small-scale electricity storage (batteries) is used. The Netherlands exports electricity via different connections, both by land and by sea. The figure shows this total net export, and the region from which this export takes place is not further specified.

Gas
The transport of natural gas will gradually be replaced by hydrogen. This will take place by converting the existing natural gas network. Although hydrogen has less energy per cubic meter, the capacity of the existing gas network will probably be large enough due to lower gas demand. No limitation of gas transport is assumed for the two scenarios. The production of hydrogen can take place both on a large scale (for industry and gas distribution) and on small scale (e.g. hydrogen filling

stations for cars, vans and trucks). Installations for large-scale hydrogen production will probably be realized in the west or north of the Netherlands. That will certainly be the case in the ADAPT scenario, in which the CO_2 captured during hydrogen production from natural gas must be transported to empty gas fields at the North Sea.

Heat

Due to high costs and energy losses, heat can only be transported over a limited distance (several tens of kilometres). The scenarios assume that heat is produced and consumed within each region (see Figure 4.18). In both scenarios, heat networks are required for transporting heat from industry to the built environment and for horticultural greenhouses. Heat networks are also used when applying geothermal energy or heat from central biomass boilers. Peak demand for heat in the winter months is covered with peak boilers fired with natural gas, hydrogen or biomass or with electric peak boilers. The heat networks will be expanded in both scenarios, as approximately 6 to 7 times more heat is distributed in the built environment in the ADAPT and TRANSFORM scenario in 2050 than in current heat networks. For heating horticulture greenhouses, heat networks will be used on a large scale to transport heat from industry and geothermal wells.

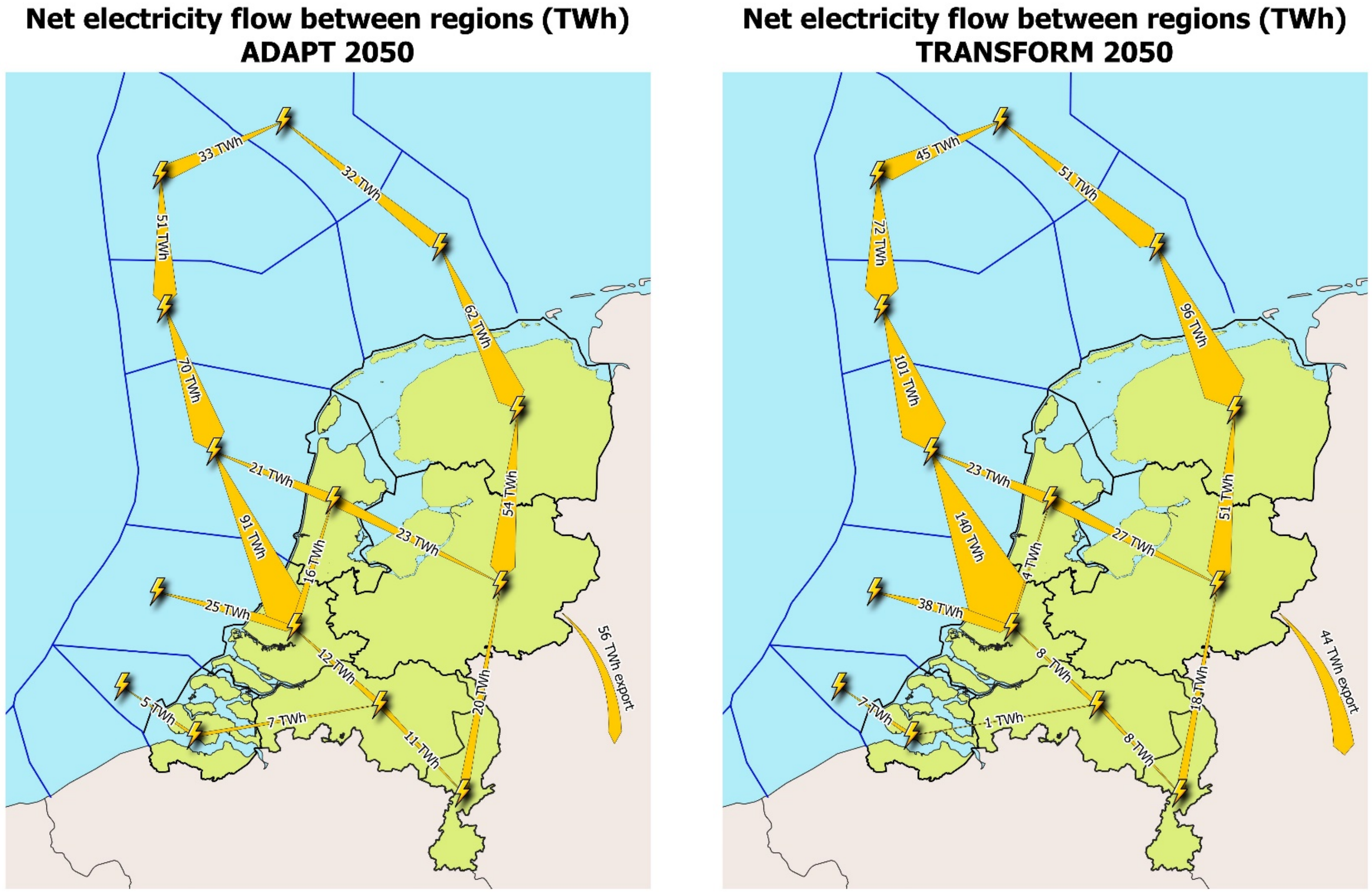
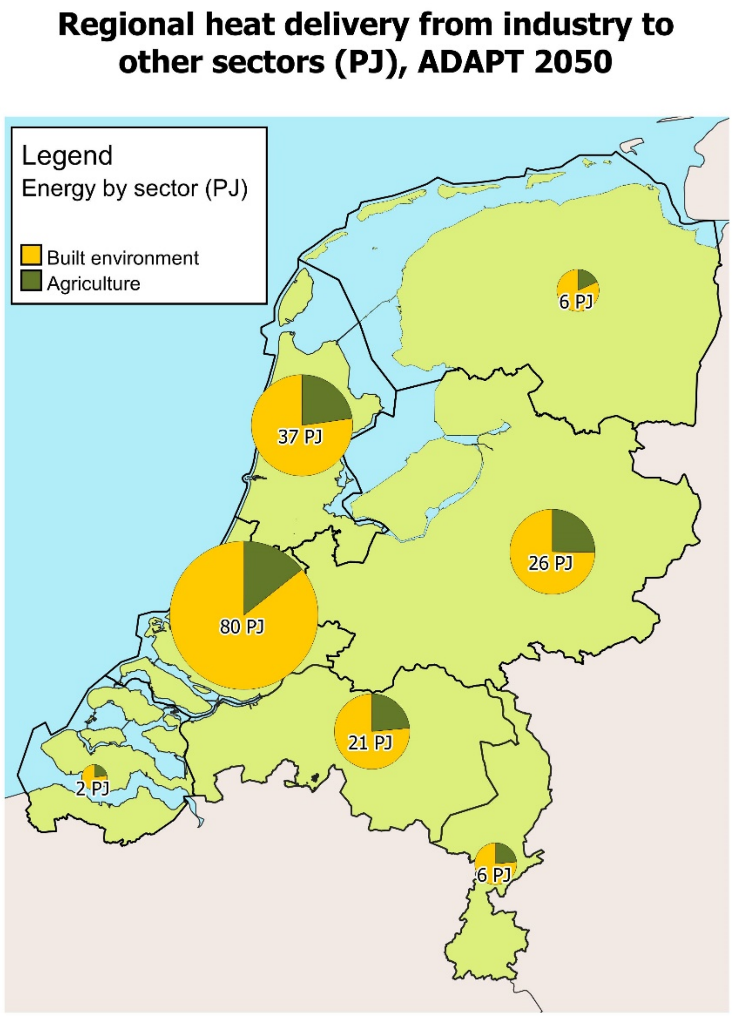


Figure 4.17 Electricity flows between regions



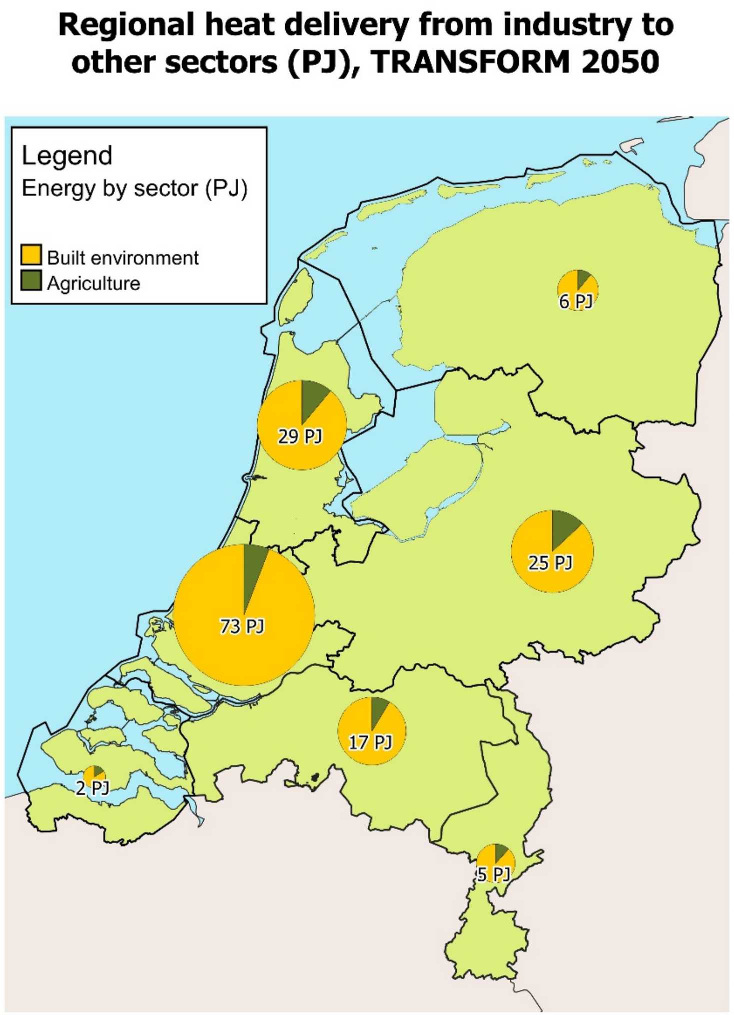


Figure 4.18 Heat supply from industry to the built environment and agriculture sector per region

4.6 Total energy system

The total energy system in 2050 for the ADAPT and the TRANSFORM scenario is shown in Figure 4.19 in a Sankey diagram. A Sankey diagram shows energy flows starting with primary energy (including imports) on the left of the figure, via conversion of energy into energy carriers in the middle, to the end use sectors (including exports and energy losses) on the right. Some energy flows at the right side of the figure are also an input on the left side (e.g. electricity for hydrogen production, or heat from industry to the built environment). Both Sankey diagrams also include non-energy use in industry (feedstock), and fuels for international aviation and shipping.

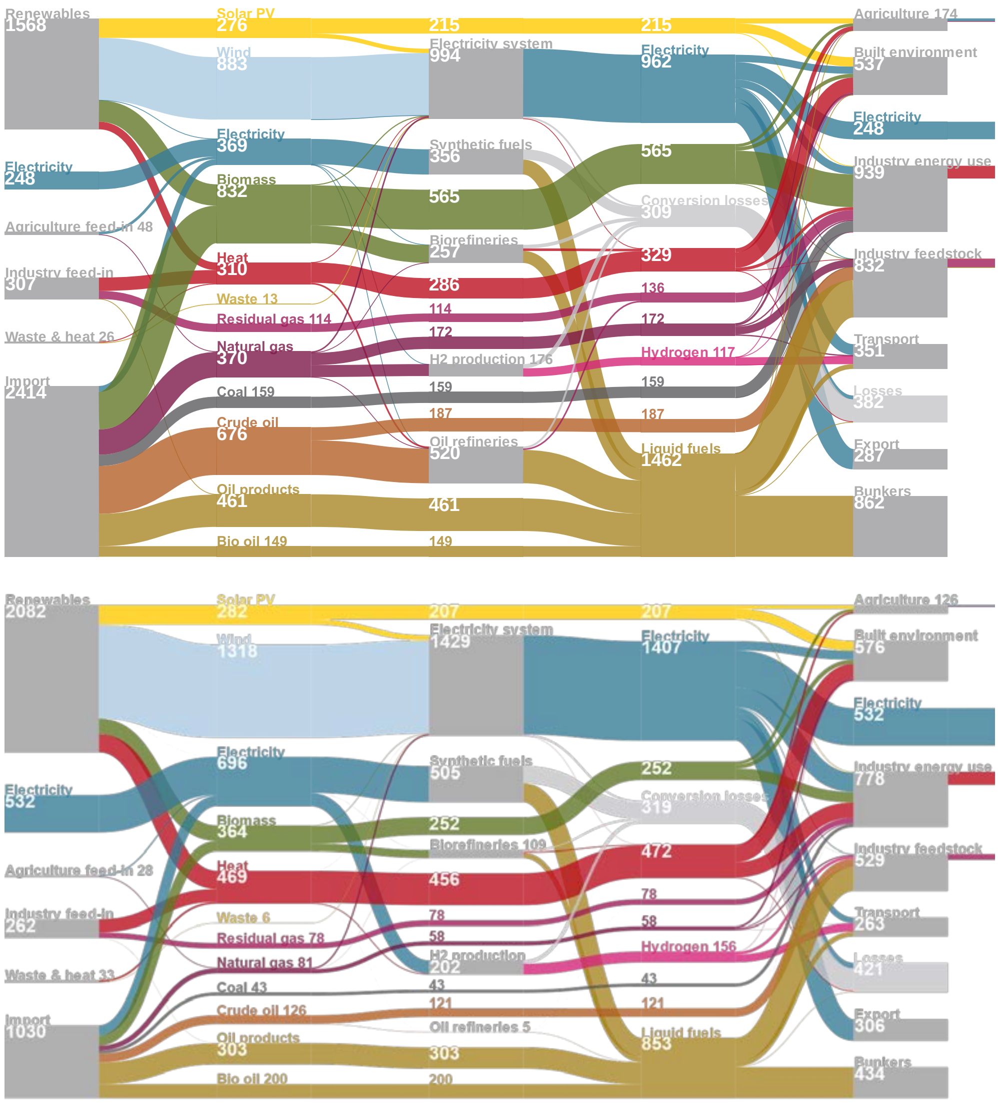


Figure 4.19 Sankey diagrams of the Dutch energy system in 2050 for the ADAPT (top) and TRANSFORM (bottom) scenarios

4.7 Energy system costs

To gain insight in the total system costs for the ADAPT and TRANSFORM scenarios (see Chapter 3 for explanation), a variant of the ADAPT model has been modelled for which no GHG reduction targets apply. In contrast with the ADAPT and TRANSFORM scenarios (which assume constant fossil fuel prices over the years 2030-2050), this no-target scenario variant assumes increasing prices for fossil fuels over this period[11] due to the scarcity of fossil fuels that will eventually arise. Also, coal-fired power stations will remain in use up to 2050. Figure 4.19 shows the total energy supply for the ADAPT, TRANSFORM and ADAPT no-target scenarios. Due to the combination of rising fossil prices, but decreasing costs for sustainable energy technology, in the ADAPT no-target scenario variant a significant part of the energy production will be sustainable in 2050, and GHG emissions will have decreased by 60% (compared to 1990). Coal is dominant in the fossil energy supply because prices for coal rise less rapidly than those for oil and natural gas. Coal is used for electricity production and industry. The transport sector is switching to electricity and biofuels. In contrast with the ADAPT and TRANSFORM scenario, in the ADAPT no-target scenario variant the Netherlands remains highly dependent on imports of fossil fuels.

Figure 4.20 shows that the total system costs for the ADAPT scenario will increase from 2030. Total system costs in the TRANSFORM scenario will be slightly above that for the ADAPT scenario in 2030, but will decrease thereafter. As a result, there will be a substantial difference in costs between the two scenarios in 2050. The change in total system costs is a combination of changing energy demand (growing in the ADAPT scenario and reducing in the TRANSFORM scenario), decreasing technology costs and the application of new, but more expensive technologies (in both scenarios). The total system costs of the ADAPT and TRANSFORM scenarios are lower compared to a scenario where there is no GHG reduction target. In the no-target scenario, investments continue to be made in fossil energy assets. While sustainable technology options become competitive at some point with energy options using fossil fuels, fossil production capacity is only gradually being reduced. As the energy costs for fossil energy rise, system costs increase. The import of fossil fuels in the no-target variant results in extra costs that are more than 10 billion euros per year higher than in the ADAPT scenario.

[11] The fossil fuel price projections from the IEA World Energy Outlook 2019 (scenario Current Policies) were used for ADAPT no-target.

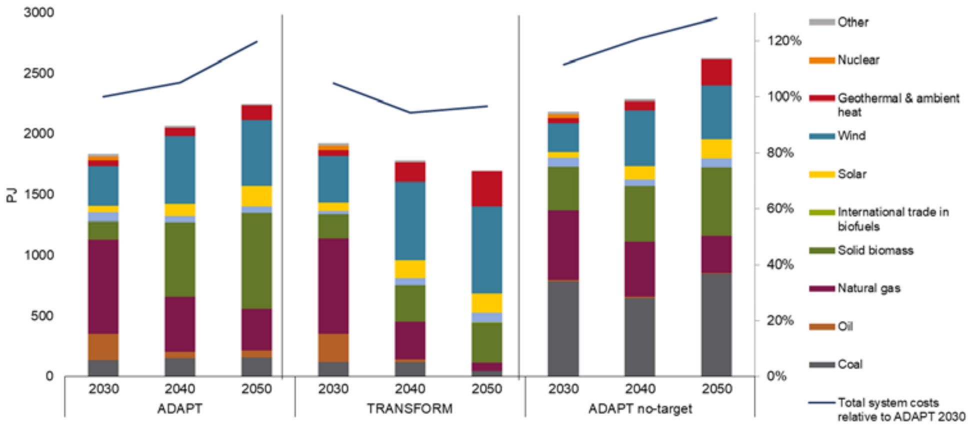


Figure 4.20 Total energy supply (excluding energy for international aviation and shipping and non-energy use in industry) and total system costs (ADAPT 2030=100)

5 Insight analysis

An objective of this study is to gain insight into the underlying factors that can determine the future Dutch sustainable energy system. These insights can be obtained by 'turning the dials of the model', i.e. changing the key assumptions (‘parameters’) of the scenarios. This type of analysis shows the degree of sensitivity of the outcomes to changes in the assumptions and preconditions (and thus the robustness of the insights obtained). The analysis also provides insight into the competition between energy technologies and energy carriers in fulfilling the energy demand which determines the outcomes in a cost-optimized scenario.

It is possible that developments that have been assumed for the ADAPT and TRANSFORM scenarios will take a different course. Changes at the landscape level must be considered (see Section 2.1 for explanation), but can hardly be influenced by governmental policy. This is different for the regime level, where policy interventions can have an effect on the development of the energy system. The insights analysis described in this chapter show to policy makers, technology developers, non-governmental organizations, etc. the potential impact of differences in technological development on the future energy system, and the effects of promoting or limiting certain solutions.

This study investigated two types of changes:
1. A relatively faster decrease in investment costs of a selected number of technologies in comparison with other technologies. Large-scale application of innovative sustainable technologies, such as solar PV, wind turbines and batteries, has shown that substantial and rapid cost reduction is possible and can have an impact on the course of the energy transition. Targeted government policy, both with regard to technology development and to technology deployment, can accelerate technology developments.
2. Limiting or broadening the availability and, therefore, the deployment of various options. The development of certain options may encounter social resistance or, on the contrary, broad social support despite higher costs. Limiting or broadening the deployment of options are often political or policy choices.

The insights are obtained by comparing model results of scenario variants, in which one or more model parameters are changed, with the results of the base scenarios, ADAPT and TRANSFORM. It is important to realize that the scenario variants strive for a least-cost solution that meets the GHG target. Furthermore, it is important to understand that for each energy function in a certain sector, a lowest cost option is explored. Those costs are determined by investment costs and by operating costs, covering the costs of energy supply, including infrastructure costs. In the end-user sectors, there is a direct competition between different options (e.g. heat supplied by heat network vs electric heat pump). In addition, options from different sectors that use the same energy carrier compete with each other. The sum of options with the same energy carrier determines the total demand for this energy carrier (e.g. electricity, hydrogen, biofuel, etc.). If the costs of certain end-user options change, this changes the demand for the energy carrier of this option. If the generation costs of the energy carrier change, this also influences the competitive position of the options in the different end-user sectors.

The insights obtained are analysed by comparing changes in the energy supply and demand and changes in system costs. In this Chapter we discuss 6 different developments of the future energy system:

- The base scenarios show a strong electrification of the future Dutch energy system. What determines the electricity share in the electricity system is analysed and discussed in section 5.1.
- Hydrogen is a new emerging energy carrier for a sustainable energy system. Which factors determine the role of hydrogen in the energy system is further analysed and discussed in section 5.2.
- In section 5.3, we investigate the drivers behind sustainable heat supply.
- In a sustainable energy system biomass is used in various sectors. The prioritisation of biomass use over different sectors and applications is further investigated in section 5.4.
- In Section 5.5, we discuss how the use of the CO_2 storage option determines the choices in energy supply and use.
- Finally, Section 5.6 examines the impact of cost reductions of technology options and limiting the potential availability of technology options on the total system costs.

5.1 Electricity

Electricity will be the most important energy carrier in the future energy system. In 2018, approximately 19% of energy supply was covered by electricity. Electrical energy will have a larger share in the supply mix, because many demand functions for which currently mainly fossil fuels are used will in future be largely supplied by electricity, such as mobility and heating. Furthermore, electricity will be used to produce other energy carriers, such as hydrogen and synthetic fuels. The electricity share is determined by dividing primary energy used for electricity generation by total primary energy[12].

In both scenarios the electricity share increases, see Figure 5.1. The share of electricity in the energy supply doubles in the ADAPT scenario and becomes more than three times as large in the TRANSFORM scenario.

The share of electricity depends on the one hand on the costs of the electrical appliances, and on the other hand on the costs of (renewable) electricity production, the available production potential thereof, and the capacity of the infrastructure to transport the electricity from production locations to the demand regions. The conversion of electricity to heat, hydrogen and synthetic fuels can also be considered as an increase in the degree of electrification, see also Section 5.2.

---

[12] This study shows the share of electricity in relation to total primary energy supply, because it includes also the electricity that will be converted to another energy carrier (e.g. hydrogen, synthetic fuels). The share of electricity in the final energy mix does not show this electricity consumption for producing other energy carriers, and will therefore result in a lower percentage. The electricity share in total primary energy supply (i.e. energy from wind, solar and hydro) ignores, however, the transmission and conversion losses of primary energy sources into secondary energy. It should also be noted that power production with conventional fuels have a low efficiency, and thus their share in primary energy is overrepresented compared to electricity from renewables. Consequently, a shift of power production from conventional to renewable sources results in a lower share of electricity in total primary energy use although actually the amount of final electricity consumed does not change.

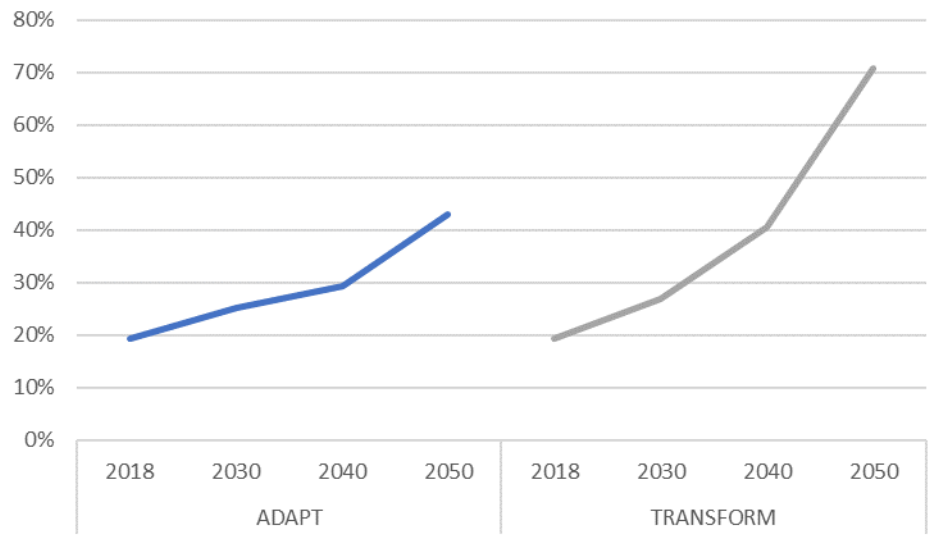


Figure 5.1 Electricity share in total energy supply for the ADAPT and TRANSFORM scenarios

In both the ADAPT and TRANSFORM scenarios, the potential for electricity production (see Table 3.1) from onshore and offshore wind energy is fully exploited in 2050. For solar energy the maximum capacity is not reached. Increasing the production potentials for offshore wind only does not lead to a larger sustainable electricity production. Because the maximum capacity for solar energy has not been utilized, the production potentials does not seem to be a limiting factor. The available capacity for transporting electricity over the high-voltage grid is not fully utilized in the baseline scenarios. This does not seem to limit the production of offshore wind.

There are two other factors that can influence the share of electricity in the energy system. These have been examined:

- Investment costs of electric appliances: The effect of 20% lower investment costs of all electricity-using devices and installations have been investigated for the ADAPT and TRANSFORM scenarios in 2050. This includes electric vehicles, electric heating (electro boilers and heat pumps) and electricity storage technologies, but electrolysers and synthetic fuel production are excluded. The maximum capacity for wind and solar energy production is increased to prevent this from becoming a limiting factor. This change of investment costs leads to an increase in demand for and production of electricity and a higher electrification share of 1.2%-point in the TRANSFORM scenario. The electricity share in the ADAPT scenario hardly changes. The electricity options are less attractive in this scenario, even if the investment costs of electric appliances are lower.
- Investment costs for sustainable electricity generation: The effect of 20% lower investment costs of wind and solar energy generation have been investigated in the ADAPT and TRANSFORM scenarios in 2050. The maximum capacity for production of wind and solar energy is increased. Because of the lower electricity costs, electricity demand increases. In the TRANSFORM scenario, the electrification share increases by 2.2%-point, but also in this variant there is no significant change in the electricity share in the ADAPT scenario.

The effect of lower investment costs for electricity appliances on the utilisation of a selection of technologies is illustrated in Figure 5.2. In both scenarios electricity demand increases in industry and the built environment. For the transport sector an increase in electricity demand is only clearly visible for the TRANSFORM scenario. Figure 5.2 shows the changes in the use of electric vehicles. In the TRANSFORM scenario there is an increase in electric vehicles at the expense of hydrogen fuel cell cars. The cost reductions also lead to an increase in the use of large-scale electricity storage, making this option relatively more important for supplying flexibility to the electricity system. Increased demand for electricity is mainly covered by more offshore wind.

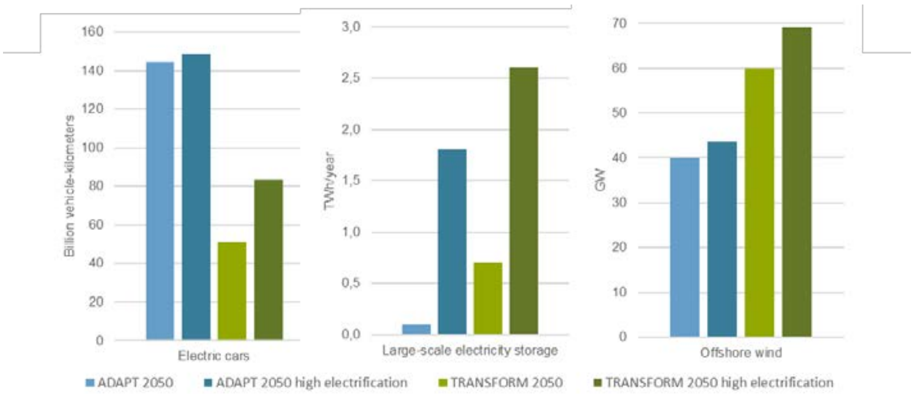


Figure 5.2 Utilisation of some electricity technologies in the ADAPT and TRANSFORM scenarios in 2050 if investments costs for electric appliances are reduced by an extra 20%

5.2 Hydrogen

Hydrogen production and appliance costs
The share of all hydrogen (i.e. hydrogen produced in hydrogen production plants and within industrial processes) in the energy supply is approximately 8% in the ADAPT scenario in 2050, and in the TRANSFORM scenario approximately 10%. The share of hydrogen in the energy system is determined by the investment and operational costs of hydrogen production and appliances, the costs of electricity, and, in the ADAPT scenario, for blue hydrogen production, the costs of natural gas and CCS. The effect of changing the hydrogen production and appliance costs have been investigated.

For both scenarios, the assumption was made that the costs of hydrogen production, and all devices and installations using hydrogen, will be 20% lower in 2050 than the cost reduction already assumed in the base case. Due to the cost reduction, fuel cell passenger cars become more attractive than electric cars, resulting in an increased hydrogen use in the transport sector. In the other sectors, no effect or even a reduction of hydrogen use can be noticed, see Figure 5.3. The latter illustrates that different sectors compete for this energy carrier. Hydrogen production increases in both the ADAPT and TRANSFORM scenarios by approximately 100 and 60 PJ respectively (hydrogen share increases from approx. 8% to 11% in the ADAPT scenario and approx. 10% to 12% in the TRANSFORM scenario). Although green hydrogen production from renewable electricity increases in the ADAPT scenario, the net effect is a lower electricity demand, due to the technology switch in the transport sector. In the ADAPT scenario also more blue hydrogen is produced, which means that a larger share of the available CO_2 storage capacity is needed to store CO_2 from hydrogen production on the expense of other processes that apply CCS. The extra electricity needed in the TRANSFORM scenario for producing green hydrogen is provided by offshore wind and solar energy.

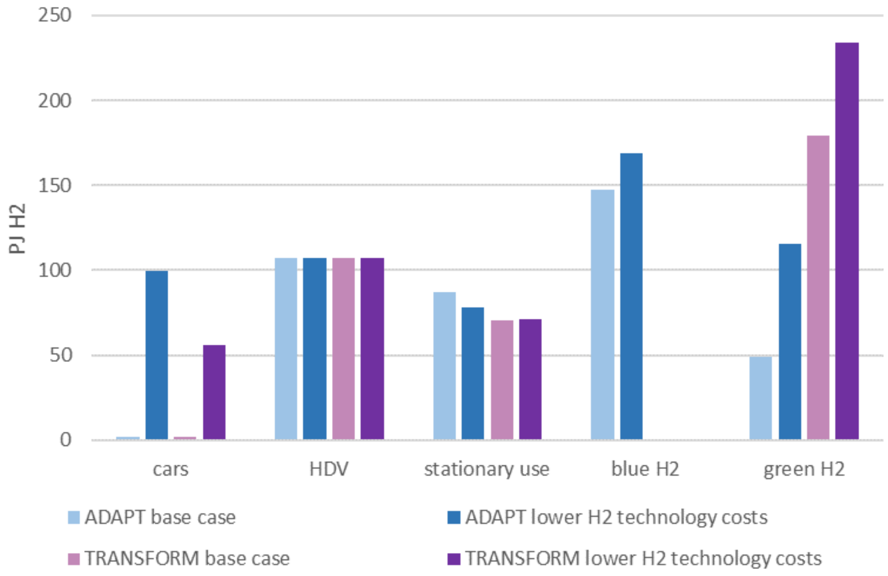


Figure 5.3 Changes in hydrogen consumption and production in 2050 if investments costs are decreased with 20%

Hydrogen import and export
If the costs for hydrogen production abroad and transport of hydrogen to the Netherlands are lower than hydrogen production in the Netherlands, hydrogen will be imported. Hydrogen can also be exported if the hydrogen production costs in the Netherlands are lower than those abroad. Initially we allowed for hydrogen import and export in the base scenarios, but noticed that the border price is a very sensitive parameter. Therefore, we decided to exclude import and export of hydrogen in the base scenarios and to investigate varying border prices for hydrogen separately.

The border price of hydrogen is varied between 1.5 and 3.3 €/kg in steps of 0.3 €/kg (the price for natural gas, relevant in the ADAPT scenario, is kept unchanged at 7.5 €/GJ). Figure 5.4 shows the hydrogen balances for both scenarios in 2050 at different hydrogen import prices: domestic hydrogen consumption by sector and export (positive figures), and domestic production by technology and imports (negative figures). This figure shows that in the ADAPT scenario, at a border price up to 1.5 €/kg 250 PJ of hydrogen is imported. At a border price of 2.1 €/kg domestic hydrogen production takes over the hydrogen supply (in particular blue hydrogen) from imports. At higher prices the Netherlands starts exporting hydrogen. For the TRANSFORM scenario we see a similar pattern, but switching from import to domestic production and export takes place at a price above 2.4 €/kg. This can be explained because only more expensive green hydrogen production is allowed in this scenario. Notice that in both scenarios, even at low border prices there is always some green hydrogen production. This is because there is a surplus of electricity in certain periods, making it attractive to produce hydrogen with electricity. At higher prices, where there is substantial export of hydrogen, a small proportion is still imported. This is because there are periods of scarcity of electricity that makes it worthwhile to import hydrogen.

Figure 5.4 shows that at the lowest import prices the demand for hydrogen is higher (close to 300 PJ in both scenarios) than in the base case for both scenarios. More hydrogen is used in the built environment. With higher import prices, domestic consumption starts to decrease, and if hydrogen is exported at higher price levels, domestic demand decreases further.

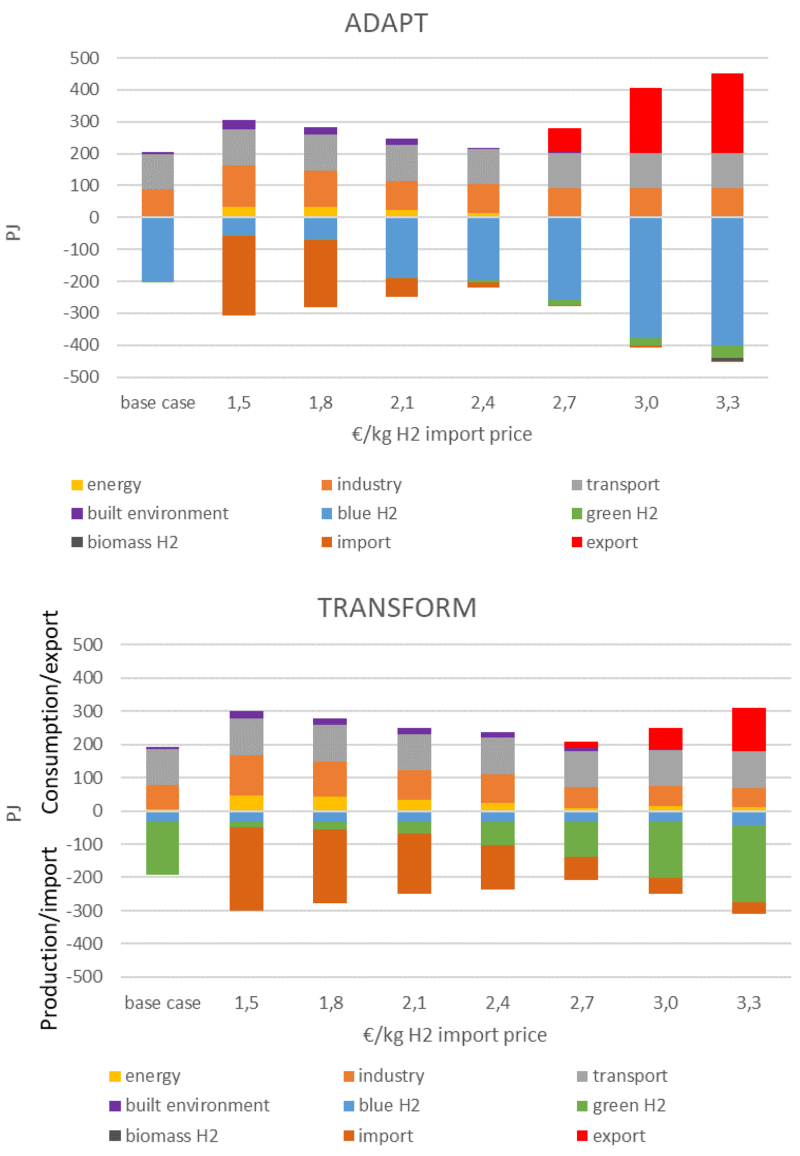


Figure 5.4 Hydrogen balance (demand and supply) for the ADAPT and TRANFORM scenarios in 2050 at different hydrogen border prices

5.3 Heat supply

In the built environment, the agricultural sector (i.e. horticulture greenhouses) and industry, heat demand is met by converting energy carriers (e.g. gas, electricity) into heat or through direct use of sustainable sources (e.g. biomass, geothermal energy). Residual heat from one sector (e.g. industry, electricity production) can also be used in other sectors (e.g. built environment, greenhouse horticulture).

The heat consumption in the three sectors depends on a large number of factors, because different energy sources, energy carriers and technologies for heat generation are involved. We have further investigated two determining factors: the costs of geothermal energy and the heat supply from industry to other sectors. The contribution of biomass to the heat supply is discussed in the next section.

Costs of geothermal energy
In the base case, geothermal energy is used in the industry and horticulture greenhouses, but not in the built environment. An assumed cost reduction of 20% in 2050, in comparison with the base case, doubles geothermal energy use in both scenarios. This extra geothermal heat is mainly used in district heating for the built environment, see Figure 5.5. The share of geothermal energy in the heat supply of the built environment will become approx. 2% in the ADAPT scenario and approx. 9% in the TRANSFORM scenario. This reduces the supply from residual heat from industry to the built environment.

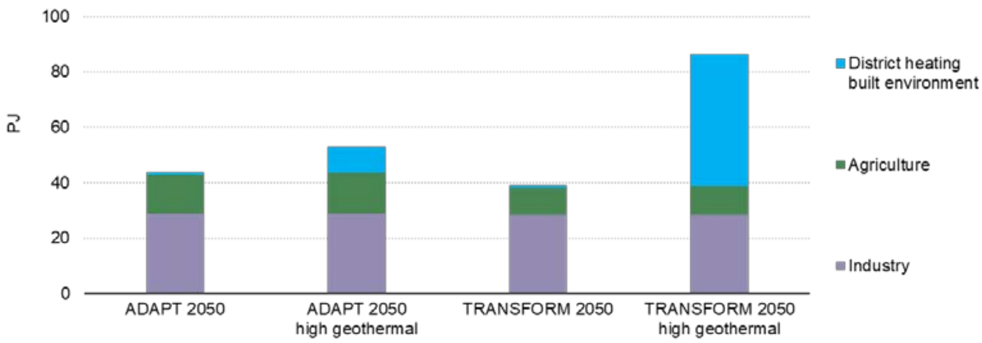
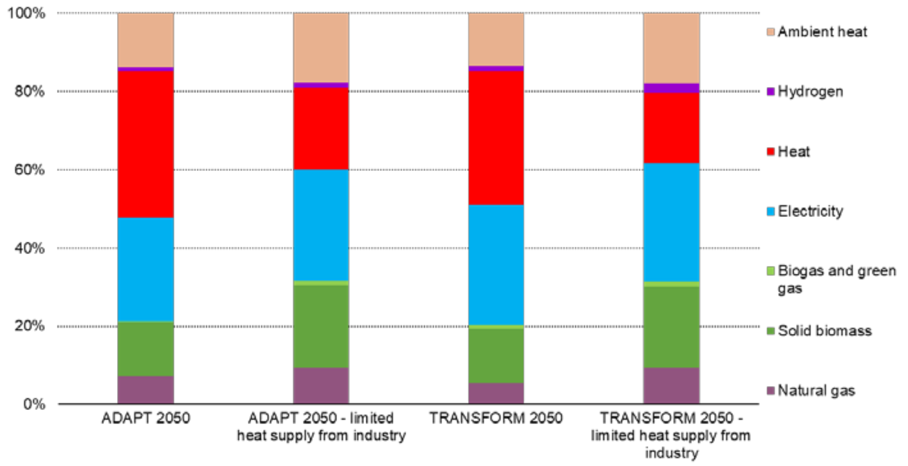


Figure 5.5 Increase in use of geothermal energy if costs of this technology are reduced by an extra 20%

Heat supply from industry
At present, residual heat for district heating currently comes mainly from electricity generation and waste incineration. In the coming decades, industrial residual heat will take over the role of residual heat from thermal power plants when these plants are decommissioned and electricity is almost fully produced with wind and solar energy. The use of industrial residual heat can be further expanded to replace natural gas in both the built environment and the agricultural sector for heating horticultural greenhouses. In the two base scenarios, the use of industrial residual heat is not limited, except that the heat must be used for the built environment and agricultural sector within the same region (see Section 3.1). Replacing and/or expanding the heat supply of existing heat networks, or realizing completely new district heating systems, is a major technical challenge. Complex decision-making in a multi-actor setting and gaining social support are big challenges. It is conceivable that the heat supplied by industry to the built environment and the agricultural

sector, as is calculated in the base scenarios, cannot be fully realized. Therefore, the effect of restricting the heat supply from industry in each region to 50% of the supply in the base case has been investigated.

Limiting of residual heat supply from industry to the built environment and agriculture sector, leads to a shift in the energy demand mix, as shown in Figure 5.6. In both scenarios a smaller heat supply from industry to the built environment is compensated by more electric appliances (heat pumps and electric boilers) and biogas / green gas use. In the agriculture sector the smaller heat supply from industry is also compensated by electric appliances.



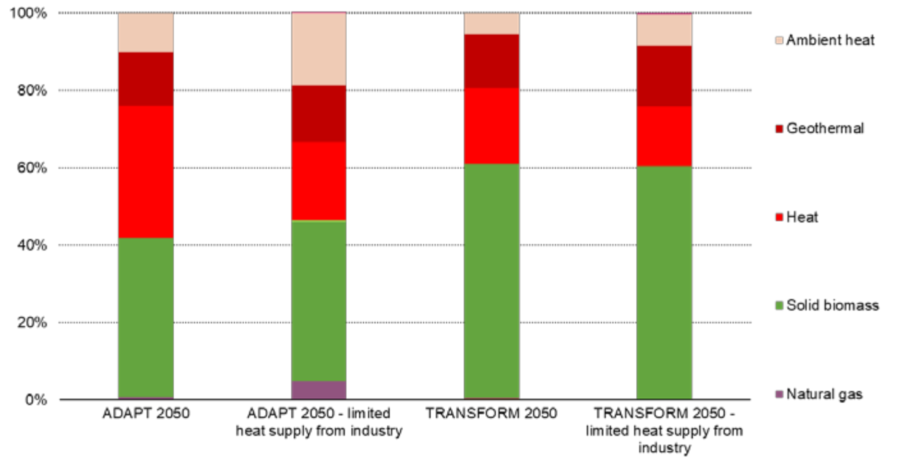


Figure 5.6 Changes in heat supply mix for the built environment (top) and agriculture sector (bottom) if residual heat supply from industry is limited to 50% compared with base scenarios for 2050

5.4 Biomass

Biomass is a sustainable energy source that, in addition to hydrogen, is also a source of sustainable molecules, but unlike hydrogen, does contain carbon. Biomass plays an interesting role in a sustainable energy supply in various respects. Besides the use of sustainable carbon from biomass to replace fossil carbon for making products (i.e. feedstock use), biomass is in particular used for energy applications. As we can see in the base scenarios, biomass is used for heat generation in industry, the built environment and the agriculture sector, and to meet the demand for biofuels, both for domestic transport and international aviation and shipping. In the ADAPT scenario, biomass is used in industry in combination with CSS, which leads to negative emissions (see also Section 5.5).

The use of biomass is not undisputed in society. The storyline of the TRANSFORM scenario takes this into account by limiting the domestic production and import of biomass. In the storyline of the ADAPT scenario it is assumed that this is a lesser problem, the availability of biomass (domestic and import together) is almost 60% higher than in the TRANSFORM scenario. In both scenarios the assumed available biomass imports are fully used in all years and the domestic biomass potential almost fully.

The use of biomass has been investigated in case the import price for biomass is reduced from 8 to 4 €/GJ and biomass imports are increased by 20%. This leads, in the ADAPT scenario in 2050, to an increase of biomass use in industry, where more biomass is used for heat applications, partly in combination with CCS (i.e. BECCS). As a consequence electricity demand in industry decreases. Because CO_2 storage capacity is limited at 50 Mton/year, the increase of BECCS reduces CCS from blue hydrogen production. In this scenario, also more biomass is used for biofuels production in the Dutch industry which reduces biofuel imports. In the TRANSFORM scenario, where the availability of biomass is much lower, the cost decrease of biomass and its increase in availability has a much smaller impact: a relatively small increase in biomass use for heat generation and production of biofuels.

If the investment costs of biomass options (conversion and use) become 20% lower, similar effects can be observed. In that case, the use of green gas in the built environment increases, mainly because of increase biogas production from digesters. A further reduction in investment costs for biomass gasifiers does not lead to an increase in the use of green gas in the built environment, but an increase in the production of biofuels, less biofuel imports, and an increase in biofuels use in domestic transport.

5.5 Carbon storage

There is ongoing debate in society on the use of CO_2 storage. For that reason CO_2 storage is assumed to be not applied in the TRANSFORM scenario. The story line for the ADAPT scenario assumes that carbon capture and storage can be applied. The potential for CCS increases from a maximum CO_2 storage capacity of 7.5 Mton/year in 2030, to 19 Mton/year in 2040 to 50 Mton/year in 2050. The base scenario shows that this maximum capacity is fully utilized in 2040 and 2050. The consequences were investigated when in 2050 only half of the CO_2 storage capacity is available, i.e. a maximum of 25 Mton/year.

Figure 5.7 shows the processes that use CO_2 capture and storage (CCS) in the ADAPT scenario in 2050. Reduction in the use of CCS mainly takes place in the metal industry, the production of blue hydrogen from natural gas, and in the chemical industry. When CO_2 storage capacity is halved, the CO_2 stored from blue hydrogen production and steel production are most affected (steel production shifts partly to electrochemical process). A lower production of blue hydrogen is partly compensated by a higher production of green hydrogen. In industry more electric heat pumps are used to compensate for less heat production by means of biomass with CCS. More electricity as a result of higher green hydrogen production and more industrial heat pumps is supplied by solar PV.

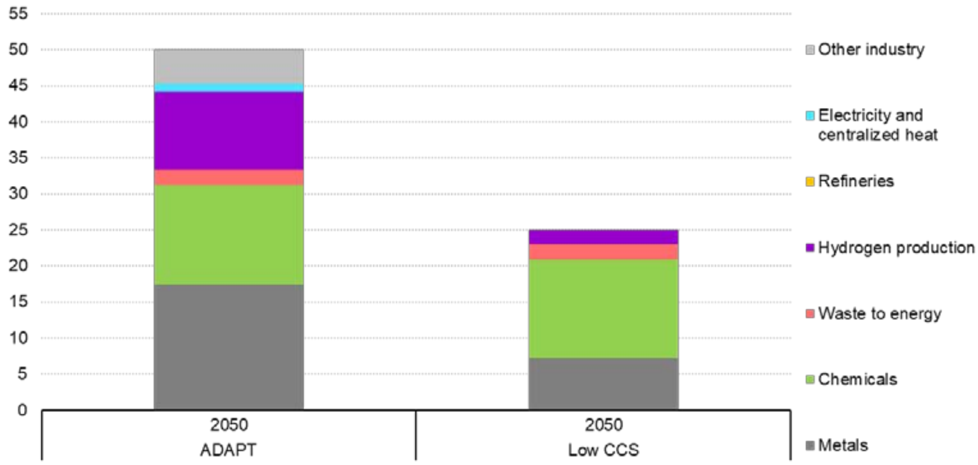


Figure 5.7 Reduction of CO_2 storage capacity in 2050 in the ADAPT scenario by 50%

5.6 Energy system costs

The previous sections showed the influence of the change of parameters on the energy system, and in particular the production and use of different forms of energy. This section discusses the impact on total system costs.

Accelerated cost reduction through innovation
If for certain technologies the cost reductions are stronger than assumed in the base scenarios, the costs of the total energy system will be lower. Lower import prices will have a similar effect. This is shown in Figure 5.8.The larger the role of a technology option in the energy system, the greater the effect on the reduction in total system costs (e.g. electrification options). The effect of reducing costs on the use of a technology option will be less if the option has already reached its maximum potential (e.g. energy-saving options). Cost reduction is partly dependent on innovation efforts, i.e. can be influenced at the regime level. Targeted innovation policy can accelerate the cost reduction of technology options. The effect of cost reductions of multiple options is also shown in Figure 5.8. Since technological options compete with each other, such as electric cars with hydrogen cars, the effect of multiple cost reductions is smaller than the sum of the individual cost reductions.

Limiting sustainable energy options
Some energy options may be less easy to realize because of technical obstacles or that there is insufficient public support. If the use of options is limited, in order to be able to achieve the GHG reduction target, more expensive options will be used resulting in higher energy system costs, see Figure 5.9. Limitation of one option is compensated by greater use of several other options, or by technologies that have not yet been applied. However, if several options are limited at the same time, or even not allowed at all (such as no CO_2 storage, strong limitation of biomass

imports, significant limitation of electricity production from offshore wind), it will no longer be possible to cover energy demand in a sustainable manner.

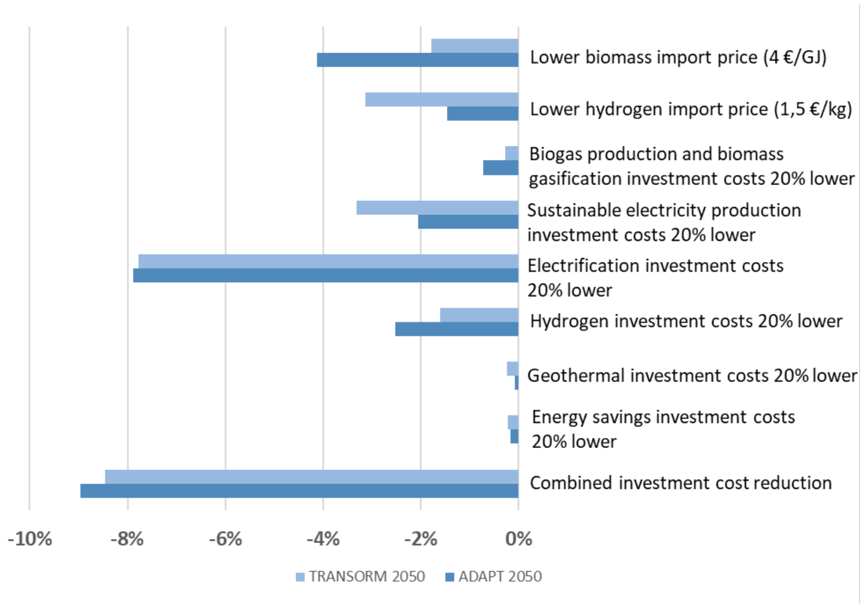


Figure 5.8 Relative decrease of total system costs compared to the ADAPT and TRANSFORM scenarios in 2050 for a variety of separate cases and a mix of the separate investment cost reductions

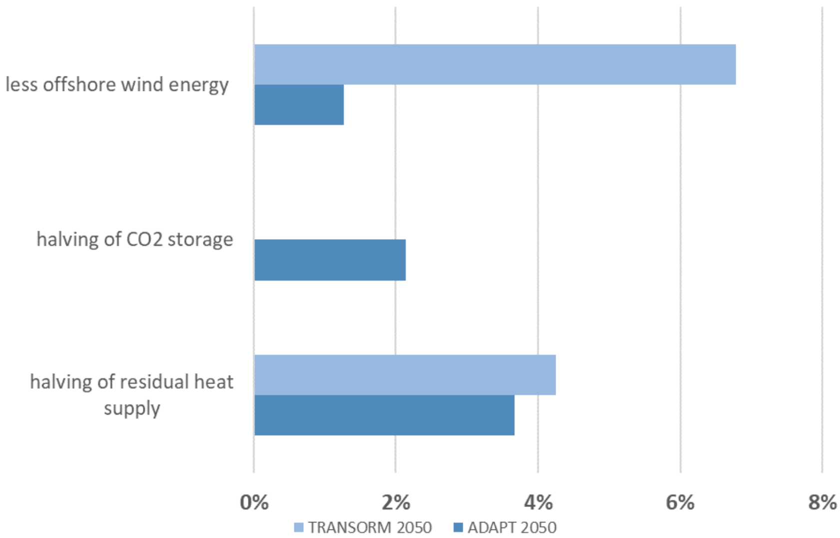


Figure 5.9 Relative increase in total system costs compared with the ADAPT and TRANSFORM scenarios when options are limited: reduction of offshore wind energy (from 40 to 30 GW in the ADAPT scenario and from 60 to 40 GW in the TRANSFORM scenario), halving the CO_2 storage capacity (from 50 to 25 Mton) in 2050 in the ADAPT scenario and reducing the heat supply from industry with 50% to the built environment and greenhouse horticulture in 2050 in each region in both scenarios.

6 Conclusions and recommendations

Analyses with a cost optimisation model show that the GHG reduction targets can be achieved for both energy scenarios, ADAPT and TRANSFORM. The costs of the energy system are lower in both scenarios than for a scenario that does not aim for a climate-neutral energy system, and are lowest for the TRANSFORM scenario.

The two scenarios show a number of comparable results, which seem robust elements of a future Dutch energy system up to 2050. The scope with which energy options are used differs per scenario, but when assumptions are changed, such as technology costs, the changes are limited:

- The share of electricity in the primary energy supply increases from 19% today to 41% by 2050 in the ADAPT scenario and 71% in the TRANSFORM scenario. In 2050, more than 99% of electricity will be generated by wind turbines and solar panels. The increase in electricity use in the Dutch energy system is caused by the electrification of energy functions in all sectors: electric vehicles in the transport sector, electric heat pumps in heat supply for industry, the built environment and the agricultural sector, production of hydrogen with electrolysers and electrification of industrial processes. Only in international aviation and shipping electricity is not directly used, but applied indirectly for the production of synthetic fuels.
- Biomass is mainly used in industry (27% to 48% of the biomass) and for the production of fuels for international aviation and shipping (32% to 48% of the biomass).
- Electrification (approx. 30% of the energy demand) and CO_2-neutral residual heat from industry and waste incineration (approx. 50% of energy demand) play an important role in making the built environment free of natural gas.
- The agricultural sector will become natural gas-free by residual heat from industry (27% to 42% of energy demand), geothermal (17% to 19% of energy demand) and biomass (28% to 44% of energy supply).
- The GHG emission reduction in industry is achieved by using electricity (22% to 55% of energy demand) and biomass (28% to 42% of energy demand).
- Electricity (31% to 44% of energy demand) and hydrogen (32% to 44% of energy demand) are the main energy carriers in the transport sector.

The scenario analyses have also shown that the role of a number of energy options is less straightforward. Their use depends on the scenario or change significantly when the cost or the potential availability of key technology options changes:

- Hydrogen production in the Netherlands will have to compete internationally. If international trade prices are lower than the costs of domestic production, domestic production will be low and hydrogen will be imported. But the reverse also applies: at high international trade prices, the Netherlands will not only produce hydrogen for the domestic market, but also for foreign countries.
- If there is a possibility of CO_2 storage, the production of hydrogen from natural gas with CO_2 capture and storage is the most commonly used technology to produce hydrogen. If CO_2 storage is not possible, hydrogen will be produced with electrolysers.
- CO_2 capture and storage, if allowed, plays an important role in reducing industry emissions, also in combination with the use of biomass resulting in negative emissions.

- The potential for geothermal energy is in 2050 not fully utilized in both scenarios. When investment costs decrease, the use of geothermal energy strongly increases and becomes an important source for heat supply in the built environment.
- In the domestic transport sector, hydrogen, electricity and biofuels are used side by side. In passenger cars electricity competes with hydrogen, and in trucks hydrogen competes with biofuels. What will become the preferred energy carrier is highly dependent on the costs of the fuels and the costs of the propulsion technology of the vehicles.

If certain adjustments to the energy system are more difficult to realize or if certain technology solutions are less socially desirable, the goal of a climate-neutral energy system will remain achievable. However, limiting sustainable energy options does lead to higher system costs. If several options are limited at the same time, or even not allowed at all, it will no longer be possible to cover energy demand in a sustainable manner. Faster technology development through innovation and implementation policies has a positive effect on the accelerated decrease in technology costs, which means that the future costs for the energy system may be significantly lower. Further research and development is of course necessary, not only for technology development, but certainly also to facilitate further implementation. The scenario analyses help to understand how the energy transition can be influenced to make the future Dutch energy system affordable and sustainable.

Recommendations
The scenario analyses provide insights into the underlying mechanisms that determine the development of a sustainable energy system. These insights give policy makers indications about how to influence the energy transition. Furthermore it is important to consider the following points:

- Climate action to achieve the 2030 target should take into account the longer-term development of the energy system (2050). Because major changes must take place in the period 2030-2050, it is important to prevent short-term choices leading to a lock-in, i.e. a solution that seems optimal in the short term, but is more expensive in the longer term.
- The right preconditions must be created for the timely roll-out of a large number of different sustainable energy options and services: good stimulation policy, good participation processes, clear licensing conditions, correct energy infrastructure, etc. Social support is also needed for changing the energy system and the introduction of new sustainable technologies. Implementation difficulties or limitation of options can lead to higher system costs. Thorough knowledge among governments, citizens and businesses about the energy transition and the implications this may have is essential for this, so that new developments can be anticipated properly and flexibly. In addition, citizens and companies, as important actors in the energy transition, will have to be supported in making choices and investment decisions.
- Cost reduction of renewable energy technology is determined by two aspects: the growth of the global use of the technology and technology improvement through innovation. As a small country, the Netherlands has relatively little influence on the increase in the use of energy technology. However, the Netherlands is an important innovation country - the Netherlands is in the top 10 of the most innovative economies - and can contribute to the cost reduction of

energy technology through targeted R&D policy. Targeted R&D policy will ensure that new technology becomes available more quickly, and that already available technology is further improved.

- Thorough knowledge of implementation processes can lead to significant cost savings, not only for the climate-neutral energy system itself, but also for the necessary stimulation and use of financial instruments, such as subsidies, during the transition. A strong commitment to knowledge and innovation can reduce the need for (more) subsidies, making research and development a crucial instrument for a cost-effective energy transition.

Increasing and improving insights requires additional modelling analyses
The model analyses that have been carried out in this study provide many leads for follow-up research. The same macroeconomic development is assumed for the two scenarios. However, the changes in the energy system are so profound that it can also have economic consequences. This raises the questions of what the economic consequences of the two scenarios are, what the mutual interactions between the economic development of the various sectors could be, and what the implications of these macroeconomic and sectoral changes are for the energy system, including energy demand, energy supply and the related GHG emissions? The consequences of the scenarios for spatial planning also deserve further analysis. This also applies to analyses of other environmental effects that occur when renewable energy is used, such as less air pollution and nitrogen emissions, and changes in end use, such as less waste production and more circular use of products and raw materials. The Netherlands is economically strongly linked to other countries and geographically embedded between countries around the North Sea. Developments elsewhere in Europe and the world, and energy and climate policy in neighbouring countries, will have an impact on the energy transition in the Netherlands. Although foreign influences have been included in the assumed decrease in technology costs, and in assumptions about import / export of energy, an integrated analysis of developments in the Netherlands with those in Europe and the world will increase insight into these influences. Macroeconomic effects of the transition, such as growth and shrinking of various sectors, employment and trade balance effects, are also very important in decision making and deserve further analysis. All these questions involve complex interactions in which other model analyses can help to gain an even better insight into the development of the future Dutch energy system and the Dutch economy.

7 References

Den Ouden et al. (2020). *Klimaatneutrale energiescenario's 2050 - Scenariostudie ten behoeve van de integrale infrastructuur verkenning 2030-2050.* Berenschot/Kalavasta.

EBN. (2018). *Masterplan Aardwarmte in Nederland.* Stichting Platform Geothermie.

ECN. (2016). *Nationale energieverkenningen 2016 (NEV 2016).* ECN-O--16-035.

European Commission. (2019). The European Green Deal. *COM(2019) 640 final*.

European Commission. (n.d.). A policy framework for climate and energy in the period from 2020 to 2030.

Geels, F. W. (2011). The multi-level perspective on sustainability transitions: Responses to seven criticisms. *Environmental Innovation and Societal Transitions*.

Hobbs and Rijkers. (2004). Strategic Generation with Conjectured Transmission Price Responses in a Mixed Transmission Systeem I: Formulation. *IEEE Transaction on Power Systems, 19*(2), 707-717.

Klimaatakkoord Industrie. (2019). Klimaatakkoord. Den Haag.

Klimaattafel, I. (2018). Joint Fact Finding CO2-afvang en -opslag.

Lopion P., M. P. (2018). A review of current challenges and trends in energy stystem modelling. *Renewable and Sustainable Energy Reviews, 96*, 156-166.

Matthijsen J., D. E. (2018). *De toekomst van de Noordzee - De Noordzee in 2030 en 2050: een scenario studie.* Den Haag: Planbureau voor de Leefomgeving (PBL).

PBL et al. (2015). *Toekomstverkenning Welvaart en Leefomgeving Nederland in 2030 and 2050.* CPB and PBL.

PBL et al. (2019). *Klimaat- en energieverkenning 2019.* PBL.

Rijksoverheid. (2019). Klimaatwet.

RVO. (sd). Warmteatlas. Opgehaald van https://rvo.b3p.nl/viewer/app/Warmteatlas/v2

Scheepers, M. a. (2003). *A look into the future: Scenarios for distributed generation in Europe.* ECN.

Sijm, J. B. (2020). *Review of energy transition scenario studies of the Netherlands up to 2050.* TNO 2019 P12095.

UNFCCC. (2016). Paris Agreement. United NationsTreaty Collection.

Van Stralen J.N.P., D. L. (2019). OPERA: a new high resolution model for system integration. *Environmental Modelling & Assessment*.

VVD, C. D. (2017). Vertrouwen in de toekomst. *Regeerakkoord 2017-2021*.