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TNO report

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Towards a sustainable energy system for the Netherlands in 2050 – Scenario update and analysis of heat supply and chemical and fuel production from sustainable feedstocks

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Summary

The new Dutch government (Rutte IV) has agreed in its coalition agreement to reduce greenhouse gas emissions in the Netherlands by at least 55% by 2030 (compared to 1990) and to achieve greenhouse gas emissions neutrality by 2050, implementing the new European objectives. The coalition agreement also proposes a climate target for circular economy, which should lead to more use of sustainable feedstocks and materials.

New calculation of ADAPT and TRANSFORM scenarios
Based on the energy scenarios that TNO developed in 2020 (ADAPT and TRANSFORM), this study investigates what the new greenhouse gas reduction targets mean for making the Dutch energy system sustainable in the period 2030-2050. In addition, in this new study, techno-economic parameters and projections for energy demand and industrial production have been updated, model adjustments for industrial processes have been implemented, and an additional target for renewable carbon in the production of chemicals and plastics has been applied. Both scenarios have been quantified using an energy system model that defines an energy system for the Netherlands that can meet the total energy demand and achieve greenhouse gas emission targets at the lowest cost to society.

Due to assumed behavioural changes and further energy saving, the energy demand in the TRANSFORM scenario is lower than in ADAPT. For TRANSFORM it is assumed that international aviation and shipping, whose emissions fall outside the national greenhouse gas reduction target, will take far-reaching reduction measures. Furthermore, a sustainability target applies in this scenario for hydrocarbons used for the production of chemicals and plastics. This raises the bar for the TRANSFORM scenario compared to the 2020 scenario analysis. The ADAPT scenario is less ambitious than TRANSFORM: fossil fuels can still be used as feedstock and emissions from international aviation and shipping are only reduced by 50%. In ADAPT, the Netherlands does meet the European targets, but the contribution to achieving the Paris climate target is more limited than in TRANSFORM.

Focus on sustainable production of chemicals and transport fuels and industrial heat production
Apart from recalculating the two scenarios, this new scenario study focuses on the production of chemicals and transport fuels in Dutch industry. In the petrochemical industry, the production processes for these different products are strongly intertwined. This will remain the case if these processes become more sustainable and use renewable energy and raw materials. For the TRANSFORM scenario, in which society strives for far-reaching sustainability, the new study assumes that by 2050, 90% of the high-value chemicals produced will be made from renewable carbon, i.e. carbon that comes from biomass or CO_2 from the atmosphere. In addition, recycled plastics are used as a circular option. The ADAPT scenario does not include a target for making the carbon in chemicals more sustainable, so that fossil fuels can still be used as feedstock in this scenario. For both scenarios, the new study further assumes that all transport fuels for refuelling in the Netherlands (including fuels for aircraft and seagoing vessels) are produced domestically. The import of fossil fuels and biomass and the exchange of electricity with our

neighbouring countries are taken into account, but no other energy carriers are imported (e.g. hydrogen, biofuels, etc.). These assumptions make it possible to assess the challenges of the energy transition if sustainable energy and green feedstocks from abroad are limited or more expensive compared to production in the Netherlands.

The heat supply for industry at different temperature levels is also further analysed in this study, as well as the heat supply from industry to the built environment and agriculture. In order to do this, heat production in industry has been redefined, taking into account different temperature levels and the distinction between heating via steam and direct heating. By 'turning the dials' of the model, the sensitivity of the results was examined for a number of assumptions, including reducing biomass imports and allowing imports of hydrogen, bio-naphtha and recycled plastics.

TRANSFORM has lower total system costs than ADAPT
The total annual costs of the whole energy system (total system costs) for the ADAPT scenario increase after 2030 due to growing energy demand, but also because more efforts have to be made to reduce greenhouse gases. The total system costs of the TRANSFORM scenario are lower than of ADAPT. This is partly due to the assumption of lower energy demand and lower industrial production compared to ADAPT. As in the ADAPT scenario, the total system costs increase in TRANSFORM, with new, relatively expensive, innovative techniques being used on a larger scale by 2050 to bring the net greenhouse gas emissions to zero. Both scenarios are based on a reduction in the costs of the technology options through innovations and the scale-up (technology learning). As a result, the cost increase is smaller than if this assumption had not been made. More imports of energy carriers (e.g. hydrogen) and feedstocks (e.g. bio-naphtha) can lead to lower system costs, provided the import prices are lower than the cost price in the Netherlands. Limiting or completely excluding options leads to higher system costs.

Demand for electricity increases substantially
In both scenarios, a much larger part of the energy demand is supplied by electricity than is currently the case, such as for industrial processes, transport, and heat supply to buildings. The TRANSFORM scenario explores the limits to which the Dutch energy system can become more sustainable. In this scenario, there is a high demand for hydrogen for the production of chemicals, plastics and synthetic fuels. The TRANSFORM scenario shows that it is possible to produce this hydrogen entirely from electricity generated in the Netherlands, but this will require the maximum available potential for wind and solar in 2050, as well as the use of nuclear energy. In the TRANSFORM scenario, electricity production increases by a factor of 5 to more than 600 TWh in 2050. About 7% of the electricity in the TRANSFORM scenario comes from new nuclear power plants (5 GW). In 2050 electricity production in ADAPT is 2.5 times the current production level (315 TWh) and no new nuclear power plants are built in this scenario. A variant of the TRANSFORM scenario in which no nuclear power plants can be deployed (e.g. costs that are too high or because of society resistance) shows that it is still possible to cover the energy demand and achieve a greenhouse gas neutral energy system without new nuclear power plants. In that case, electricity production decreases and is compensated for by, among other things, reduced electric heat production and additional use of renewable heat sources (geothermal, ambient heat and solar thermal). If in variants of the ADAPT scenario the import of biomass or the

capacity for CO_2 storage is limited, electricity demand increases and new nuclear power plants are also deployed.

CO_2 capture plays an important role in both scenarios
To provide CO_2 for the production of chemicals and synthetic fuels, the maximum available biomass is required, supplemented with CO_2 that is captured from the air. In the ADAPT and TRANSFORM scenarios, approximately the same amount (approximately 50 Mton) of CO_2 is captured in 2050. Where in ADAPT the majority of this CO_2 is of fossil origin and is stored in empty gas fields in the North Sea, most of the CO_2 in TRANSFORM is biogenic and is reused. The scenario analysis also shows that it is necessary in TRANSFORM to store a limited amount of biogenic CO_2 and CO_2 captured from the atmosphere to generate negative emissions to compensate for remaining greenhouse gas emissions for which no or insufficient other reduction options are available.

Bio- and synthetic fuels become important for international transport
For domestic transport, the electrification of passenger cars and delivery vans is deployed earlier in the TRANSFORM scenario than in ADAPT, and in 2050 this fleet consists almost entirely of electric vehicles in both scenarios. Trucks largely continue to use fossil fuels until 2040, after which they switch to fuel cells and hydrogen. The scenario analysis finds that bio-kerosene is the most cost-effective fuel for aviation for both scenarios; synthetic kerosene will play only a minor role. The use of liquefied natural gas (LNG) as a fuel for seagoing vessels leads to a reduction in CO_2 emissions. This LNG can be made more sustainable (bio, synthetic) and, according to the scenario analysis, is a long-term cost-effective fuel for seagoing vessels. But this can lead to emissions of methane – also a greenhouse gas – from marine engines. If these emissions cannot be countered by modifications to the engines, the scenario analysis shows that the transition to LNG will not get off the ground and demand for alternative fuels such as bio- and synthetic methanol will arise. If biomass imports are limited, these biofuels will continue to be used as jet fuel. With lower biomass availability, fewer biofuels are used in domestic transport (instead, more electricity) and the use as marine fuel also shifts to more synthetic fuel use.

High value chemicals produced in TRANSFORM from renewable feedstocks
High-value chemicals (ethylene, propylene, butadiene and benzene) are building blocks for the production of plastics, among other things, and are currently produced in the Netherlands using steam crackers with naphtha, LPG and natural gas condensates as feedstock. This process is responsible for 70% of energy use in the chemical sector excluding fertilizer production. In the TRANSFORM scenario it is assumed that 90% of the carbon content of the HVCs comes from renewable carbon sources. In addition, recycled plastics are used as feedstock for HVC production through chemical recycling (i.e. pyrolysis). Only a limited amount of biomass is used the TRANSFORM scenario for HVC production. Most biomass is used for production of transport fuels, especially for aviation and international shipping, because of a higher conversion efficiency. For HVC production the TRANSFORM scenario shows a substantial shift from conventional steam cracking to HVC production from synthetic methanol (methanol made from hydrogen and CO_2). Biogenic CO_2 is used that is released during the production of biofuels, particularly gasification and Fischer-Tropsch synthesis. In 2050 this is supplemented with CO_2 that is captured from the air (CO_2 direct air capture). For HVC production some bio-naphtha is also used, which is released as a by-product

in biorefineries during the production of biofuels. The ADAPT scenario does not apply a criterion for the renewable carbon content for chemicals. In this scenario, fossil naphtha remains the main feedstock for HVC production in steam crackers. If bio-naphtha and/or recycled plastics are imported, this leads to less methanol use for chemical production, but not to less methanol production. Methanol use shifts towards marine transport fuel.

Availability of industrial residual heat for heat networks is limited
The new scenario results show that for both scenarios the total external heat demand in industry decreases after 2030. As a result of the redefinition of excess heat from industrial processes, application of different temperature levels and reuse of residual heat within industry, the amount of residual heat that industry can supply to the built environment and horticulture greenhouses is limited. Compared to 2019, the scenario analysis show for both scenarios a doubling of heat supply via heat networks in 2030, followed by a slight decrease in 2050. In both scenarios, residual heat from industry is the most important heat source for these heat networks. In 2030, biomass is still used for heat production in both scenarios, but this is replaced by geothermal energy in 2050. In addition to the modest role of heat networks in covering the heat demand in the built environment, the electric heat pump is the most important option for heating homes and buildings. In ADAPT there is also room for a gas network that either distributes a mixture of natural gas and green gas or hydrogen. In the agricultural sector, also geothermal energy is an important source of heat in both scenarios.

Contents

1 Introduction

Model-based energy scenarios are a powerful tool in exploring the future development of the energy system. This is particularly true for an energy system that is in transition. Energy scenarios can help policymakers and other parties involved in the energy transition, such as energy companies, grid operators, technology developers and energy users, gain insight into the development of the energy system and help them make choices and decisions.

1.1 TNO scenarios: ADAPT and TRANSFORM

In 2020, TNO published the results of a scenario study looking toward a sustainable energy system for the Netherlands in 2050 (Scheepers, Faaij, & Van den Brink, White paper, 2020) (Scheepers, et al., 2020). This study described the development of the Dutch energy system using two scenarios: ADAPT and TRANSFORM. In the ADAPT scenario, the Dutch economy builds on existing infrastructure and economic strengths, while preserving the current lifestyle of the Dutch population, but with a significant reduction in CO_2 emissions. In the TRANSFORM scenario, behavioural changes in Dutch society supported a significant shift towards a more sustainable economy, making the Netherlands less energy intensive. Whereas, in the ADAPT scenario carbon capture and storage (CCS) can be applied, this option was excluded from the TRANSFORM scenario due to public objections. Moreover, the TRANSFORM scenario assumed more limited biomass availability compared to the ADAPT scenario.

In the 2020 scenario study, quantitative projections were made for the entire integrated Dutch energy system for both scenarios using the energy system model OPERA. In both scenarios, GHG emissions were reduced by 49% in 2030 compared to emissions in 1990 and by 95% in 2050. The OPERA model calculated an energy system to meet the greenhouse gas (GHG) target with the lowest costs for the energy system from a societal perspective. Model results include the primary energy mix, volumes of secondary energy carriers, final energy mix for each end-use sector and total system costs. By 'turning the dials' of the OPERA model, the influence of differences in technology cost developments were investigated, as well as changes in import prices (hydrogen, biomass) and limitation of the availability of sustainable energy sources (biomass, offshore wind) and CO_2 storage capacity.

1.2 This study: scenario updates and further analysis

In this new study the ADAPT and TRANSFORM scenarios have been updated to reflect new GHG reduction targets. These reduction targets are based on the new European GHG reduction target of 55% for 2030 and GHG neutrality for 2050 (COM/2020/562 final, 2020). These reduction targets have also been adopted in the coalition agreement of the recently formed Dutch government (Rutte IV) (Coalitieakkoord, 2021)[1].

[1] In the Rutte IV coalition agreement, the GHG reduction target for 2030 is at least 55% (with the policy aiming for 60%), 80% for 2040 and GHG neutral by 2050. The scenario study is based on a greenhouse gas reduction target of 55% in 2030, 77.5% in 2040 and GHG neutral in 2050.

Other updates concern projections for energy demand, industrial production and techno-economic parameters. Expectations about future energy demand and industrial production are based on (KEV, 2020)[2]. Techno-economic information on new innovative technologies is constantly changing and the model database has been updated to take into account the latest available data for some of the technologies in this study.

As a result of the previous scenario study, stakeholders have requested analyses of specific aspects of the energy system, such as effects on emissions outside the Dutch energy system (i.e. scope 3 emissions) and heat supply to the built environment and agriculture sectors. This scenario study takes a closer look at the sustainable production of chemicals and transport fuels and at heat production and use in industry, the built environment and the agricultural sector.

In this study, the production of chemicals and transport fuels has been further analysed in a base scenario focusing on production from biomass resources and recycled plastics. For this analysis, the biomass import potential is assumed to be higher than in the previous study and it is assumed that all bunker fuels (for international aviation and shipping) are produced in the Netherlands. This assumption enables a systematic assessment of how limitations in biomass resources and electricity production may influence the Dutch energy system. Furthermore, it allows a comparison with the other sustainable options taking into account their production costs and limitations with regard to supply potentials.

For a more detailed analysis of the heat supply for industry, the built environment and agriculture, this study distinguishes heat at different temperature levels and redefined excess heat in industry.

For the analysis of the sustainable production of chemicals and transport fuels and the heat production, three modifications have been made to the OPERA model:
- Improvement of the representation of industrial production processes for the production of main chemicals and fuels.
- Inclusion of more sustainable chemicals production through the use of alternative feedstocks and recycling.
- Temperature level-specific heat generation and use in industry and residual heat supply to the built environment and the agricultural sector.

These changes mainly concern the industrial sector. However, the industrial sector is connected with other sectors in the energy system: for example, via electricity and hydrogen demand with the energy production sector, via production of transport fuels with the domestic and international transport sector, via residual heat supply with the built environment and the agricultural sector. Therefore, changes in industrial production also lead to changes in energy use in other sectors. Moreover, the Dutch industrial sector is relatively large and changes in industry have a major impact on the total primary energy supply, total energy demand and the way GHG emissions reductions are achieved.

This report presents and discusses results of the calculation of the ADAPT and TRANSFORM scenarios with new GHG reduction targets and other updates. In

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[2] The scenario analyses have been performed before KEV 2021 was published.

addition, analyses of sustainable production of fuels and chemicals and heat supply for industry, built environment and agricultural sector are presented. In these analyses, the influence of changing of a number of key assumptions has been included by means of scenario variants.

1.3 Report structure

The report has the following structure:

- Several modifications were made to the OPERA model for this study. These modifications are explained in Chapter 2.
- The two scenarios used in this study, ADAPT and TRANSFORM, are described in Chapter 3. This chapter also provides an overview of the parameters used for the quantitative analysis of the scenarios. In this new scenario study, several parameters have been adjusted and updated, such as the GHG reduction targets, updates of techno-economic parameters, updates of projections for energy demand and industrial production and an additional target for sustainable carbon in the production of chemicals and plastics. These parameters adjustments and updates are explained in this chapter.
- The results of the calculation of ADAPT and TRANSFORM scenarios with the new GHG reduction targets and other updated and adjusted parameters are presented and discussed in Chapter 4. This concerns results such as primary energy supply and final energy consumption, energy production and consumption in various sectors, GHG emissions and CO_2 in the energy system, and total costs of the energy system. Sankey diagrams of the scenarios are also presented in this chapter.
- Chapter 5 takes a closer look at the transport sector, including both domestic and international transport, and chemicals production, and how their energy use can be made more sustainable. The chapter shows that the production of transport fuels and chemicals use (partly) the same feedstocks and that production processes are interlinked.
- The heat demand and heat production for industry, the built environment and the agricultural sector is analysed in more detail in Chapter 6. The amount of residual heat that industry can supply to the built environment and horticulture greenhouses via heat networks is also examined.
- Finally, Chapter 7 lists the most important new insights that have resulted from this new scenario study. The differences with the results of the previous scenario study are explained and a comparison is made with another scenario study for the Netherlands.

2 The OPERA model and model modifications

This chapter provides in Section 2.1 a brief description of the OPERA model and how it is used in this study. A more detailed description of the model can be found in (Scheepers, et al., 2020) and (van Stralen, 2021). An explanation of the model most recent modifications is given in Section 2.2.

2.1 The OPERA model and its use

OPERA is a technology-rich energy system optimisation model for the Netherlands. Two features that make OPERA especially useful for developing sustainable energy scenarios for the Netherlands are: (1) it covers the complete energy system of the Netherlands and reflects all domestic emissions and types of greenhouse gases; (2) it simulates energy supply and demand, distinguishing different hour series with comparable supply and demand. These features permit the investigation of how to optimally deploy large capacities of intermittent renewable energy, among other things.

OPERA allows its users to examine the implications of technology diffusion, efficiency improvement and policy interventions that reduce emissions of greenhouse gases. For this study, OPERA calculates the configuration of the Dutch energy system and the associated emissions, given specific goals and preconditions, at the lowest system costs for five specific years: 2030, 2035, 2040, 2045 and 2050. Although at present OPERA is not a dynamic model, it does consider existing assets by taking into account investments made in previous years and their technical lifetime[3]. In the year for which the optimization is performed, new investments are added to the existing assets if needed. For energy production and use, the model can choose from more than 600 technology options covering the whole technology chain from production to end-use demand services, including technologies that convert primary into secondary sources. The techno-economic data for these options are retrieved from a database containing current data and projections for parameter values in 2030 and 2050, derived from an extensive literature assessment. This techno-economic data has been reviewed by TNO experts for a large number of technologies and summarized in fact sheets[4]. The fact sheets contain performance and cost parameters for 2030 and 2050 based on learning percentages. For technologies with learning potential for which the learning rate is unknown, an investment cost reduction of 20% is assumed between 2030 and 2050.

The energy system OPERA computes has to meet the annual demand for:
- energy services (heat and electricity) of built environment, industry, service sector and agriculture,
- domestic transport of people and goods,
- fuels for international transport (bunker fuels),
- production of industrial products (including steel, aluminium, ammonia, ethylene, methanol, chlorine, salt, ceramics and glass).

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[3] In the TRANSFORM scenario, existing assets are replaced more quickly by new innovative technologies. For this reason, this scenario assumes a 20% lower effective life for existing assets.

[4] These factsheets can be found on https://energy.nl/

OPERA calculates the primary energy mix and an energy mix for each end-use sector. Fossil primary fuels (oil, coal and natural gas) are assumed to be available at a certain exogenous market price. For domestic renewable energy (solar, onshore and offshore wind, biomass, geothermal energy), a maximum potential applies. In OPERA captured CO_2 can be stored or used in industrial processes. A maximum capacity applies for the storage of CO_2. OPERA can import refined oil products, biomass, biofuels, hydrogen and electricity at a certain price and within assumed supply limits. Electricity trade with neighbouring countries have been determined using the European electricity market model COMPETES (Lise, Sijm, & Hobbs, 2010). To calculate system costs, OPERA uses a national cost-benefit approach with a discount rate of 2.25% (Werkgroep Disconteringsvoet, 2020). Taxes, levies (e.g. CO_2 price) and subsidies are not taken into account. Total system costs are the sum of the annualised investment costs, annual operation and maintenance costs, cost for energy transport and costs for imported energy minus revenues from exported energy. OPERA only takes into account policy preconditions arising from the scenarios, such as closing coal-fired power stations before 2030 or a limited use of CO_2 storage in the TRANSFORM scenario.

2.2 Modifications to the OPERA model

As compared to the version of the OPERA model that was used in (Scheepers, et al., 2020), several structural and data changes to OPERA have been applied.

2.2.1 Structural changes

Built environment
Previously the household sector was modelled as one type of dwelling, with a final heat demand expressed in PJ that needed to be fulfilled. Heat saving levels were determined separately and saving potentials were based on a baseline without savings. The improved model distinguishes different types of dwellings with different heat consumption levels, and the driver is the number of dwellings per type. Each type of dwelling has five possible energy labels. The following type of dwellings are available:
- Apartments
- Terraced houses
- Other dwellings

Similarly, the heat demand of the services sector was expressed as a final heat demand in PJ. The entire services sector was considered as one type of building. For services sector buildings, the driver is Gross Floor Area (GFA) per type of building in the updated model. Similarly to dwellings, there are different possible energy labels. The following building types are available:
- Offices
- Education
- Hospitals
- Industrial halls
- Other services

For both sectors, the following energy labels are available: G-F-E, D-C, B, A and A+. Upgrade from one type of label to another is possible.

Industry
Industry is the sector for which most significant structural changes have been made. An important change is the use of different temperature levels, as compared to the previous version which used only one generic type of heat for the entire energy system. Heat is subdivided in four temperature levels: < 100 ºC, 100-200 ºC, 200-400 ºC and > 400 ºC. The third level, 200-400 ºC, has been split into steam and direct firing. The final heat demand of industrial subsectors is corrected for both intrinsic and extrinsic heat demand of processes that are explicitly modelled in those subsectors.

In addition to the subsectors already identified in the model (steel, fertilisers and high value chemicals production), several additional industrial activities are now explicitly modelled:
- Ceramics production
- Chlorine production
- Glass production
- Methanol production
- Primary aluminium production
- Salt production

Furthermore, non-energy CO_2 emissions from the chemical industry are specified separately from other non-energy CO_2 emissions from the industry.

The division of industry into subsectors has changed. Basic metal has been split into ferrous basic metal (including iron and steel) and non-ferrous basic metal. The food and beverage industry and waste industry[5] are new sectors and the remaining sectors have been merged into a single other industry category, eliminating the distinction between ETS and non-ETS sectors.

For the modelling of feedstocks in the chemical sector, several alternatives to fossil carbon have been added to the model. Furthermore an additional target has been added, which can be used to set a minimum share of renewable carbon in chemicals.

For international shipping, formerly only heavy fuel oil (HFO) / marked gas oil (MGO) and renewable substitutes were available. Liquid natural gas (LNG) and methanol, and their renewable substitutes, have been added to the model.

2.2.2 *Data updates*
The techno-economic data for some technologies has been updated. An overview of the updates can be found in Table 2.1.

[5] The waste industry consists of waste incineration, water treatment, conversion of plastic waste to pyrolysis oil and biogenic fermentation.

Table 2.1 Overview of technology categories for which data updates have been included.

Technology category	Data source
Utilities in industry	(Energinet/Danish Energy Agency, 2020)
Energy label promotion for dwellings	(TNO, 2021)
Heat supply options in dwellings	(TNO, 2021)
Heat supply options in service buildings	(TNO, 2021)
High Value Chemical production	(Uslu, Santos, & Botero, 2020), (Oliveira & Van Dril, 2021)
Biofuel production	(Lensink & Schoots, 2021), (IEA Bioenergy, 2020)
Electricity storage in batteries	(TNO, 2021)
Large scale underground storage	(TNO, 2021)
Wind energy	(TNO, 2021)
Nuclear energy	(Scheepers, De Haas, Roelofs, Jeeninga, & Gerdes, 2021)
Vehicles[6]	(E3-Modelling, 2019)
Electricity infrastructure	(TNO, 2021)
District heating	(Hers, Rooijers, & Meyer, 2018)
Carbon Capture and Storage	(TNO, 2021), (Batool & Wetzels, 2019)
Combined Cycle Gasturbines	(Tsiropoulos, Tarvydas, & Zucker, 2018)
Steel production	(TNO, 2021)
Chorine production	(Scherpbier & Eerens, Decarbonisation Options for the Dutch Chlor-Alkali Industry, 2021a)
Ceramics production	(Besier & Marsidi, 2020)
Glass production	(Papadogeorgos & Schure, 2019)
Primary aluminium production	(Kortes & Van Dril, 2019)
Salt production	(Scherpbier & Eerens, 2021b)
Electrolysis	(TNO, 2021)
SNG production	(Lensink & Schoots, 2021)

[6] This includes an update on costs data and efficiency for passenger cars, trucks and vans. Additionally, more efficient options were added i.e. more efficient diesel trucks, LNG trucks, hydrogen trucks/passenger cars and electric trucks.

3 Input parameters for the scenarios

This chapter describes in Section 3.1 an outlook for the future that provides the basis for each scenario and in Section 3.2 a description is given of the parameterisation for the quantitative analysis with the OPERA model. Section 3.3 provides an overview of the input parameters and discusses which updates have been applied for the new scenario analyses.

3.1 Scenario assumptions

The ADAPT and TRANSFORM scenarios are the result of two different outlooks on the future. The characteristics of these outlooks are summarized in Table 3.1. More details on the outlooks can be found in (Scheepers, et al., 2020).

Table 3.1 Characteristics of the ADAPT and TRANSFORM scenario

ADAPT	TRANSFORM
• Netherlands and EU will meet 2030 and 2050 GHG reduction targets. • Society values the current lifestyle. • EU countries have their own policies in achieving GHG reduction. • Industrial production and economic structure remain basically the same. • National and local government take the lead. • Adapting and optimising the energy system and industrial processes. • Keep options open and structural change post 2050. • Fossil fuels are expected to be utilised in combination with carbon capture and storage (CCS) to abate CO_2 emissions.	• 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 an innovative power house. • Individual and collective action by civilians. • 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 output. • Reduction in other GHG intensive activities (such as animal husbandry and international travel). • A limited use of CO_2 storage and biomass.

3.2 Scenario parameterisation

The demographic development of the Dutch population is the same in both scenarios. In both cases it is also assumed that economic development (measured in GDP) is similar, and recessions are not taken into account within the studied time-frame. Demographic development and economic growth is reflected in the development of energy demand in industry, the built environment and agricultural sector, passenger and freight kilometres for the transport sector, fuel demand for international transport and production volumes in industry. The values for this demand development for the ADAPT scenario are derived from the Klimaat en

Energieverkenning 2020 (KEV, 2020). To reflect the assumed changes in behaviour in the TRANSFORM scenario, a decrease in energy demand for most sectors, a decrease in mobility demand and lower industrial production in most industrial subsectors is assumed as compared to ADAPT.

Technology development and the costs of technology are the same in both scenarios. In line with current Dutch energy policy neither scenarios allows to operate coal-fired power plants in 2030 and beyond and the existing Borssele nuclear power plant is shut down in 2033[7]. However, investments in new nuclear power plants are possible, provided they are competitive within the scenario. In accordance with current policy, CO_2 storage can be used to a limited extent in 2030 in both the ADAPT and the TRANSFORM scenario. An increase in CO_2 storage is possible in the ADAPT scenario, but in the TRANSFORM scenario only to enable negative emissions to compensate for emissions of activities that are difficult to bring to zero (e.g. emissions from non-CO_2 greenhouse gases, non-energy CO_2 emissions and GHG emissions of land use, land use change and forestry (LULUCF)).

Table 3.2 provides an overview of the main and distinctive parameters for the ADAPT and TRANSFORM scenario.

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[7] In the coalition agreement (Coalitieakkoord, 2021), it was agreed to keep the Borssele nuclear power plant in operation after 2033.

Table 3.2 Main and distinctive parameters in the ADAPT and TRANSFORM scenario

	ADAPT	TRANSFORM
National GHG reduction target	2030: 55%[1)] 2050: 100%[2)]	2030: 55%[1)] 2050: 100%[2)]
GHG reduction target international aviation and shipping	2050: 50%[3)]	2050: 95%[3)]
Non-fossil carbon in chemicals	2050: 0%	2050: 90%
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	+++	++
• Imports	+++	++
Use CO_2 storage	+++	+
Use coal-fired power plants	No	No

↑ means growth, ↓ shrinkage and ↑↑ extra growth, +++ means ample, ++ moderate and + limited availability

1) compared to 1990 emissions, excl. LULUCF

2) compared to 1990 emissions, incl. LULUCF

3) compared to 2005/2008 emissions

3.3 Scenario parameters and updates

Following the parameterisation of the scenarios (see previous Section), separate assumptions for ADAPT and TRANSFORM have been entered in OPERA as input data. The tables below summarise the main parameters for each of the scenarios.

Table 3.3 contains the assumptions on the supply side (*updates in italics*):

- For wind and solar electricity production, maximum capacities are used. The maximum production for offshore wind is based on (Matthijsen J., 2018). Based on the storyline for ADAPT, the maximum potential for onshore and offshore wind is smaller than for TRANSFORM, 7.8 and 40 GW respectively. The potential for onshore wind is 12 GW in the TRANSFORM scenario *and for offshore wind the potential has increased to 70 GW in 2050 due to the high demand for electricity.*
- *In 2030, CO_2 storage is allowed in both ADAPT and TRANSFORM.* The maximum capacity is 7.5 Mt (Klimaatakkoord, 2019). In the ADAPT scenario, the storage capacity is increased to a maximum of 50 Mt in 2050 derived from the total available storage capacity of 1,600 to 1,700 Mt in the Dutch part of the North Sea (Klimaattafel, 2018). *In the TRANSFORM scenario, the storage capacity is increased to 15 Mt in 2050 in order to achieve a 100% GHG emission reduction with negative emissions (i.e. compensating for the remaining GHG emissions that are difficult to reduce).*
- 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:

29.7 €/tonne CO_2 for transport and 17.4 €/tonne CO_2 for storage (Lensink & Schoots, 2021).
- Biomass is available from two sources: domestic and foreign resources (i.e. imports). Both potentials are limited. In addition, the border price of biomass also plays a role in affecting the amount of biomass imports. *There is a large uncertainty on defining the biomass import prices as this will depend on many factors. In this study this is simplified as the import potential are presented in two groups: a low price for the first 70% of the import potential and a high price for the remaining 30% (see Table 3.4).* For the ADAPT scenario, it is assumed that the full domestic potential and a decent share[8] of the international potential are available. 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. *Compared to the scenario study from 2020* (Scheepers, et al., 2020)*, the availability of foreign biomass has increased because in this new study all bunker fuels are produced in the Netherlands and in TRANSFORM chemicals are produced from renewable carbon. Different price levels are also used in the new study*. In a scenario variant, the effect of lowering biomass imports is investigated, see Chapter 5.
- The geothermal potential for the ADAPT scenario is taken from the “Masterplan aardwarmte” by Energie Beheer Nederland (EBN) and the geothermal sector (EBN, 2018).
- It is assumed that for the base cases no import or export of hydrogen *and no import of biofuels and synthetic fuels will take place*. This means that in the base scenarios, the total demand for hydrogen, biofuels and synthetic fuels must be covered by domestic production. *To meet the demand for biofuels, the availability of biomass imports has therefore been increased (see above).* To research the sensitivity of the energy system to imports, dedicated scenario variants have been created in which imports of hydrogen and some other commodities has been allowed, see Chapter 5.
- OPERA distinguishes regions in the Netherlands, which are interconnected with a high-voltage grid and gas pipelines for the transport of electricity, natural gas (or green gas) and hydrogen, respectively. The model assumes that electricity transport between regions takes place via the 380 kV high-voltage grid and that its capacity will not be more than 2.5 times the current capacity by 2050. For electricity transport within the region, capacity is assumed to be expanded without restrictions. The pipelines for natural gas are divided into a high, medium and low pressure net. For hydrogen a high pressure backbone gas pipeline is assumed, coupled to medium and low pressure distribution networks. For all energy transport the model calculates the required capacity and the investments involved, including offshore transport of electricity and hydrogen. This implies that no cost-advantage of existing infrastructure is assumed.
- Based on information from the Warmteatlas (RVO) an estimation is made about the maximum potential amount of heat delivery through a (district) heating network for each region, see Table 3.3. Household, service buildings and horticulture greenhouse geographic density on the demand side, and

[8] Biomass import potential is calculated using the Dutch population ratio over the EU population. In the ADAPT scenario the import potential is based on the total maximum EU biomass potential and TRANSFORM on the minimum EU potential presented by (Strengers & Elzenga, 2020).

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 in the model.

The same commodity border prices for primary energy are used for both scenarios. Table 3.4 shows an overview of the commodity prices used.

Table 3.5 contains the overview of the parameters that are driving demand. *The assumptions on the demand side have been updated compared to the scenario results published in 2020. For the ADAPT scenario the demand values are based on* (KEV, 2020) *and extrapolated towards 2050.* The demand values for the TRANSFORM scenario are lower for most sectors, in line with the scenario assumptions.

Table 3.6 shows *the new GHG reduction targets used in the scenarios: for 2030 a 55% GHG emission reduction compared to 1990 levels in line with European ambitions* (COM/2020/562 final, 2020) *and GHG neutrality for 2050.* For the emissions from international aviation and shipping (bunker fuels), not included in the national target, additional assumptions have been made: for the ADAPT scenario a 50% reduction is assumed compared to 2005 levels for aviation and 2008[9] levels for shipping and for the TRANSFORM scenario a 95% reduction for all bunker fuels. These assumptions follow from the storylines in which the ADAPT scenario assumes less effective international cooperation than in TRANSFORM, so that agreements on GHG reductions are less far-reaching.

A sustainable carbon target has been added to implement the assumed shift from fossil to sustainable feedstocks in the TRANSFORM scenario. In the ADAPT scenario, this target does not apply and fossil fuels can continue to be used as feedstock. Besides the GHG targets listed in Table 3.6, additional GHG constraints have been added to the model. For CH_4, N_2O, F-gases and LULUCF (Land Use, Land Use Change and Forestry), the emission levels have been defined per scenario (see Table 3.7), in line with the underlying storylines. 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 applied for LULUCF. *The GHG reduction target for 2030 does not yet cover emissions from LULUCF, but from 2035 onwards, the LULUCF emissions will fall under the reduction target* (COM/202/554 final, 2021).

[9] Different base years were used. This is because while CORSICA refers to 2005 in their ambitions, IMO uses 2008.

Table 3.3: Maximum supply volumes and capacities used in the base scenarios

		ADAPT			TRANSFORM		
	Unit	2030	2040	2050	2030	2040	2050
CO_2 storage potential	Mt/yr	7.5	35	50	7.5	7.5	15
Wind offshore capacity	GW	11.5	36	40	14.5	45	70
Wind onshore capacity	GW	7.8	7.8	7.8	7.8	10	12
PV capacity	GW	29.6	63.2	106.8	40.5	78.2	132.1
Nuclear capacity	GW	0.5	2.5	5.0	0.5	2.5	5.0
Biomass domestic	PJ	160.5	234.7	308.8	146.3	169.5	192.7
Biomass import	PJ	193.7	646.9	1100	155.8	415.4	675
Geothermal potential (> 500 m depth)	PJ	50	125	200	50	125	200
Increase in electricity interconnection capacity between regions compared to current capacity		120%	200%	250%	120%	200%	250%
Maximum share 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%		

Table 3.4: Commodity border prices[10]

		ADAPT and TRANSFORM		
	Unit	2030	2040	2050
Natural gas	€2015/GJ	6.9	6.9	6.9
Oil	€2015/GJ	12.8	12.8	12.8
Coal	€2015/GJ	2.5	2.5	2.5
Biomass, used cooking oil (UCO)	€2015/GJ	16.2	16.2	16.2
Biomass, woody, domestic	€2015/GJ	5.9	5.9	5.9
Biomass, woody, import, cheap	€2015/GJ	8.0	8.0	8.0
Biomass, woody, import, expensive[11]	€2015/GJ	11.0	11.0	11.0

[10] Fossil energy prices and biomass border prices are taken from Climate and Energy Outlook (KEV) 2020

[11] This applies for the last 30% of the import potential. The prices are 3 €/GJ higher than the cheap price level and fall in the range of 8-12 €/GJ reported by IIASA wood pellet & wood chip import price indication for 2020.

Table 3.5: Demand values used in the base scenarios[12]

	Unit	ADAPT			TRANSFORM		
		2030	2040	2050	2030	2040	2050
Steel production	Mt	7.50	7.50	7.50	6.75	6.19	5.63
Primary aluminium production	Mt	0.06	0.06	0.06	0.06	0.05	0.05
Ammonia production	Mt	2.83	3.01	3.20	2.38	1.90	1.34
Ethylene production	Mt	4.45	4.64	4.83	3.90	3.92	3.94
Methanol production	Mt	0.48	0.49	0.51	0.48	0.49	0.51
Chlorine production	Mt	1.06	1.10	1.14	0.87	0.80	0.73
Salt production	Mt	7.62	7.90	8.19	6.25	5.77	5.24
Glass production	Mt	0.97	1.02	1.07	0.87	0.84	0.85
Ceramics production	Mt	3.04	3.05	3.06	2.73	2.51	2.41
Waste incinerated	PJ	64.5	64.5	64.5	64.5	48.4	32.3
Passenger road traffic	Billion vehicle kilometre	127.0	138.1	149.2	103.0	95.0	84.3
Light freight road traffic	Billion vehicle kilometre	21.2	22.4	23.6	21.2	22.4	23.6
Heavy freight road traffic	Billion vehicle kilometre	8.1	8.5	8.8	8.1	8.5	8.8
Energy demand mobile machinery							
Agriculture	PJ	14.6	14.6	14.3	14.6	14.6	14.3
Industry	PJ	26.0	26.3	28.1	18.6	16.5	14.4
Service sector	PJ	6.8	6.8	6.8	6.9	7.6	9.3
International aviation	PJ	204	209	213	204	176	148
International navigation	PJ	472	511	551	472	434	396
Heating household sector							
Number of apartments	Million	2.91	2.96	2.96	2.91	2.96	2.96
Number of terraced dwellings	Million	3.34	3.40	3.40	3.34	3.40	3.40
Number of other dwellings	Million	1.68	1.71	1.71	1.68	1.71	1.71

[12] ADAPT 2030 values are based on KEV 2020, values for 2040 and 2050 and extrapolated. Some values for TRANSFORM are adjusted in line with the scenario assumptions.

	Unit	ADAPT			TRANSFORM		
		2030	2040	2050	2030	2040	2050
Services sector							
Gross floor area – education	Million m^2	37.2	38.5	39.9	37.2	38.5	39.9
Gross floor area – hospitals	Million m^2	22.3	23.1	23.9	22.3	23.1	23.9
Gross floor area – commercial buildings	Million m^2	153.9	159.5	165.1	153.9	159.5	165.1
Gross floor area – offices	Million m^2	67.2	69.6	72.1	70.5	76.6	82.9
Gross floor area – rest services sector	Million m^2	185.5	192.3	199.1	194.8	211.5	228.9
Remaining heat demand							
Agriculture	PJ	92.7	84.8	88.3	74.2	59.3	53.0
Basic metal – ferrous	PJ	14.0	14.1	14.4	12.6	11.6	10.8
Basic metal – non-ferrous	PJ	2.8	2.7	2.7	2.5	2.3	2.1
Fertiliser industry	PJ	10.7	10.8	11.5	9.0	6.8	4.8
Chemical industry	PJ	60.1	52.4	47.5	40.4	39.3	38.8
Food and beverage industry	PJ	53.9	54.3	58.1	53.9	54.3	58.1
Other industries	PJ	54.6	48.4	49.3	58.5	52.6	53.9
Waste industry	PJ	6.8	9.3	10.0	8.6	5.5	3.9
Remaining fuel demand Transport	PJ	35.1	34.9	34.9	35.6	35.8	36.2
Remaining electricity demand							
Households	TWh	20.8	21.9	22.8	20.8	21.9	22.8
Services sector[13]	TWh	34.9	37.0	36.9	38.4	42.9	44.3
Agriculture	TWh	11.2	11.3	11.8	14.5	15.9	17.7
Basic metal – ferrous	TWh	2.7	2.8	2.8	2.5	2.3	2.1
Basic metal – non-ferrous	TWh	2.1	2.1	2.1	1.9	1.7	1.6
Fertiliser industry	TWh	0.0	0.0	0.0	0.0	0.0	0.0
Chemical industry	TWh	0.0	0.0	0.0	0.0	0.0	0.0
Food and beverage industry	TWh	7.3	7.9	8.5	7.3	7.9	8.5
Other industries	TWh	10.7	10.1	10.3	11.3	10.7	10.9
Waste industry	TWh	2.4	2.0	2.2	1.9	1.9	1.4
Transport	TWh	2.4	2.4	2.4	2.4	2.5	2.6

[13] Including data centers

Table 3.6 GHG targets and non-fossil carbon in feedstocks used in the base scenarios

		Reduction wrt	Emissions base year [Mt CO_2 eq.]	ADAPT 2030	ADAPT 2040	ADAPT 2050	TRANSFORM 2030	TRANSFORM 2040	TRANSFORM 2050
Total Dutch energy system	%	1990	221.2	-55%[1)]	-77%	-100%	-55%[1)]	-77%	-100%
	Mt			103.1	51.5	0.0	103.1	51.5	0.0
International aviation	%	2005	11.0	[2)]	30%	50%	[2)]	53%	95%
	Mt			12.7	8.3	5.5	12.7	5.8	0.6
International shipping	%	2008	53.3		45%	50%		70%	95%
	Mt			53.3	29.3	26.7	53.3	16.0	2.7
Non-fossil carbon in chemicals[3)]	%			0%	0%	0%	5%	35%	90%

1) Excluding LULUCF emissions. The LULUCF emissions in 2030 are 3.5 Mt CO_2.eq

2) GHG emissions are reduced compared to demand growth, but higher than in 2005

3) Carbon from biomass and carbon from the air. Carbon in recycled plastics is also regarded as non-fossil, although initially this carbon will still be of fossil origin.

Table 3.7 Additional GHG constraints used in the base scenarios

	Unit	ADAPT 2030	ADAPT 2040	ADAPT 2050	TRANSFORM 2030	TRANSFORM 2040	TRANSFORM 2050
CH_4 from agriculture	Mt CO_2-eq	15.2	14.6	13.9	12.9	11.4	9.9
N_2O from agriculture	Mt CO_2-eq	7.5	7.5	7.5	6.1	5.5	4.8
F-gases	Mt CO_2-eq	1.5	1.4	1.4	1.5	1.4	1.4
Indirect CO_2 emissions	Mt CO_2-eq	2.6	2.6	2.6	2.4	2.4	2.3
LULUCF	Mt CO_2-eq	3.5	3.5	3.5	3.5	3.5	3.5

4 The ADAPT and TRANSFORM base scenarios

This chapter presents the results of the quantitative modelling for the updated ADAPT and TRANSFORM scenarios with the modified OPERA model. The OPERA model calculates an energy system for 5 milestone years (2030, 2035, 2040, 2045 and 2050)[14] which meets total energy demand, transport demand and industrial production volumes, without exceeding maximum GHG emission targets, while minimising social costs. Considering all end-use sectors and all types of demand (e.g. electricity, heat, vehicle kilometres, industrial production, etc.), the model selects the set of technologies, including energy supply and conversion technologies. The model takes into account fluctuating supply, available energy production options and capacities of energy transport networks. The ADAPT and TRANSFORM scenarios form the basis for further analyses into the factors that determine the technology choices and design of the energy system. Results of these analyses are presented in Chapter 5 and Chapter 6.

The quantitative values determined by the OPERA model are shown for both scenarios for 2030, 2040 and 2050. For comparison, the same values, derived from statistical data, are shown for 2019 (CBS, 2021). This quantitative presentation of the scenarios is divided into 6 sections: total primary energy supply (Section 4.1), final energy demand (Section 4.2), energy production and consumption (Section 4.3), GHG emissions (Section 4.4), energy infrastructure (Section 4.5), total energy system (Section 4.7) and energy system costs (Section 4.6).

4.1 Total primary energy supply

Figure 4.1 shows the primary energy supply of the Dutch energy system in the coming decades according to the ADAPT and TRANSFORM scenarios. The primary energy supply mix shown relates to the consumption of different sectors (industry, built environment, agriculture and domestic transport), energy for international aviation and shipping (bunker fuels) and non-energy use (raw materials for industrial production), plus the conversion and transport losses.

In 2030, the primary energy supply is lower than in 2019. There are two reasons for this:

- The primary energy supply for 2030 is the result of a cost optimisation, while the energy system is in reality not cost optimal, resulting in a higher value for primary energy supply for 2019.
- Energy savings and reduced conversion losses in, among others, electricity production (i.e. wind and solar replace less efficient thermal power plants) and the transport sector (i.e. electric vehicles replace vehicles with less efficient combustion engines) reduce primary energy needs in 2030.

After 2030, the primary energy supply in ADAPT increases again. The strong growth in 2040 is mainly due to growth in demand for bunker fuels and higher conversion losses in sustainable fuels production compared to oil-based transport fuels. Figure 4.2 shows the primary energy supply for both scenarios for only

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[14] The results of 2035 and 2045 are not shown in this report. These extra years allow the investments of the transition pathway to be determined more accurately.

industry, built environment, agriculture and domestic transport, excluding energy use in international aviation and shipping and feedstock use. After the increase in 2040, the primary energy supply in ADAPT falls again in 2050. This increase and decrease in primary energy supply is the overall result of energy demand growth, energy savings (lower energy demand due to, for example, insulation measures), extra energy consumption (e.g. energy for CCS) and higher energy conversion losses from new processes (e.g. hydrogen production). These effects also occur in the TRANSFORM scenario, but a lower final energy demand compared to ADAPT, mainly due to the behavioural changes assumed for the TRANSFORM scenario, results in lower primary energy supply.

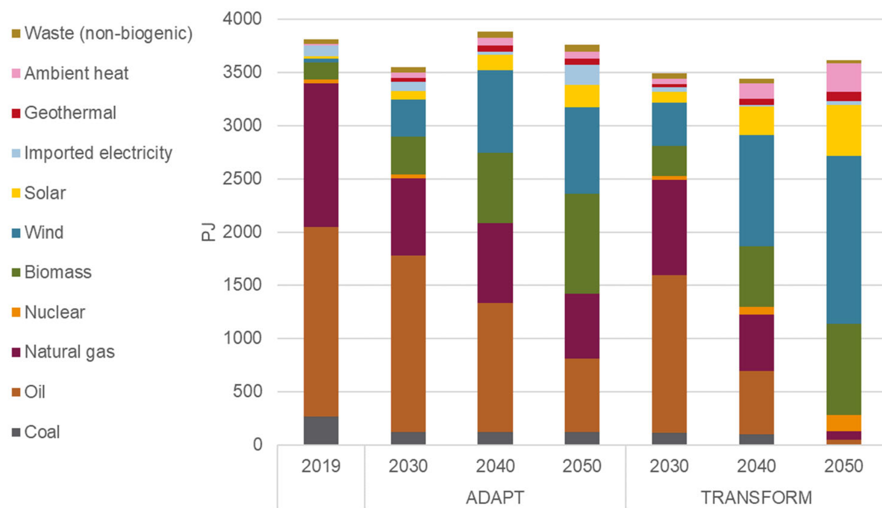

Figure 4.1 Total primary energy supply in 2019 (CBS, 2021) and 2030-2050 for ADAPT and TRANSFORM, including energy for international aviation and shipping and feedstock use

The supply mix in both graphs shows the shift from fossil primary energy to renewable energy. In 2050, fossil fuels still have a role in ADAPT because the associated GHG emissions are captured and stored, international aviation and shipping still party use fossil fuels and fossil hydrocarbons are used as feedstock. In TRANSFORM, a smaller amount of oil and natural gas remains, of which 85% relates to feedstock use. Solar and wind energy become dominant energy sources in both scenarios. In the TRANSFORM scenario (but not in ADAPT) electricity is also supplied by new nuclear power plants that occur in 2040, after closure of the Borssele plant in 2033 (see Section 4.3 for further explanation). In both scenarios a large part of the biomass is used for the production of fuels for inland shipping & non-road machinery and international aviation and shipping. In addition, a small amount of biomass (as solid fuel or as biogas) is used for heat supply in the built environment and agriculture sector and in industry. Ambient heat (i.e. heat from soil, water and air used by heat pumps) is an important primary heat source in the TRANSFORM scenario. Ambient heat is also used in ADAPT, but to a lesser extent. Geothermal energy is used as a primary source of heat in both scenarios. Finally, the primary energy supply mix includes also some imported electricity (see Section 4.3 for more details).

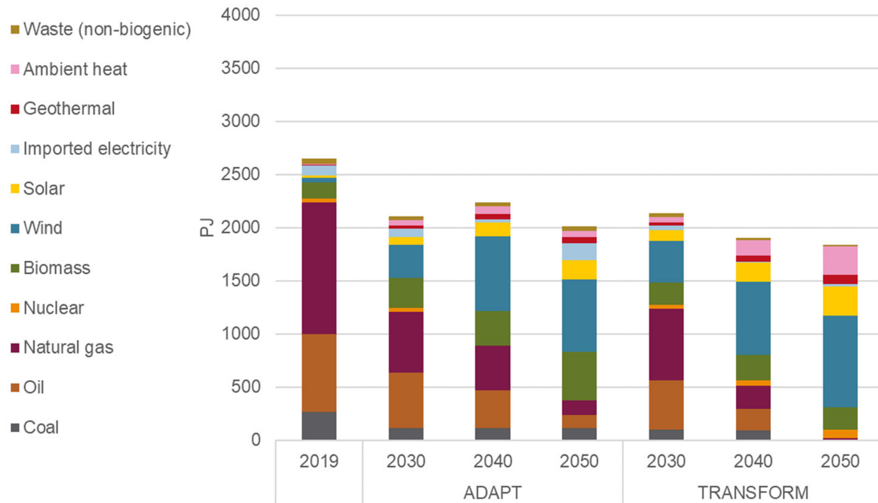

Figure 4.2 Total primary energy supply in 2019 (CBS, 2021) and 2030-2050 for ADAPT and TRANSFORM, excluding energy for international aviation and shipping and feedstock use

4.2 Final energy consumption

In the energy system, primary energy sources are converted into final energy (electricity, heat, transport fuels, etc.) and chemicals. Energy losses occur during energy conversions and during transport and distribution of energy. Total primary energy minus conversion and losses results in total final energy consumption. Figure 4.3 shows the total final energy consumption for industry, built environment, agriculture, domestic transport and bunker fuels as well as the use of feedstock for the production of chemicals. The figure shows that in the ADAPT scenario the total final energy consumption in 2050 is approximately equal to that of 2030. This is the balance of the energy demand growth, energy saving improvements and changes in energy conversion efficiency. The final energy consumption for the TRANSFORM scenario is lower in 2050 than in 2030. Apart from improved energy savings and changes in conversion efficiency, this is mainly due to the assumption of lower final energy demand because of behavioural changes.

In the final energy mix, the fossil share in both scenarios decreases substantially after 2030, similar to the primary energy supply. In TRANSFORM, part of the feedstock use in 2050 will come from non-fossil carbon sources, such as biomass, synthetic methanol, and recycled plastics[15]. A small part (34 PJ, less than 4% of the annual feedstock) still comes from fossil oil. The scenario assumption is that 90% of the carbon in the feedstocks for high value chemicals must be of non-fossil origin. For the ADAPT scenario there is no such target. As a result, feedstocks continue to be derived from fossil sources. In ADAPT, bunker fuels are also partly of fossil origin.The use of electricity increases in both scenarios. Electricity is also generated by end users themselves with solar panels; this increases significantly in the TRANSFORM scenario (see for more details Section 6.2 and 6.3). From 2040 onwards, end users use hydrogen as an energy source in both scenarios, more in TRANSFORM than in ADAPT. The use of synthetic fuels mainly takes place in

[15] Since plastics are produced from non-fossil carbon in TRANSFORM, it is assumed that carbon from plastic recycling is also of non-fossil origin. Initially, however, this will not be the case.

TRANSFORM in 2050. In addition to heating based on electricity and fuels (natural gas, hydrogen, biomass, biogas), solar heat, geothermal heat, ambient heat (with heat pumps) and heat from heat networks (built environment and agricultural sector) are also used (shown as heat in Figure 4.3). Compared to 2019, these forms of heat use increases by a factor of four in the ADAPT scenario and by a factor of ten in TRANSFORM. A more detailed analysis is given in Chapter 6.

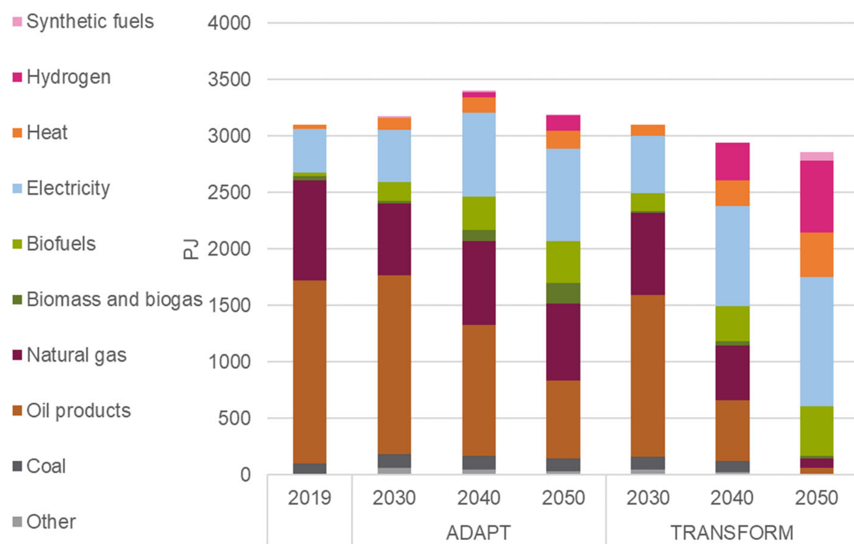

Figure 4.3 Final energy consumption in 2019 (CBS, 2021) and 2030-2050 for ADAPT and TRANSFORM, including non-energy use and energy for international aviation and shipping

4.3 Energy production and consumption

4.3.1 Electricity

In both scenarios electricity demand increases significantly (see Figure 4.4). This is due to a strong electrification of energy functions in the end-use sectors, such as the application of electric boilers and heat pumps, the use of electric vehicles, electrified production processes, and because of the production of hydrogen from electricity. The growth in electricity demand in the transport sector in TRANSFORM is smaller than in ADAPT, due to lower transport demand (see Section 5.1). In the TRANSFORM scenario, the electricity demand in industry is higher than in ADAPT due to the use of new, partly electrified processes. Most hydrogen is produced by electrolysers (see Section 4.3.2) and demand for hydrogen comes largely from the transport sector and industry (see Chapter 5).

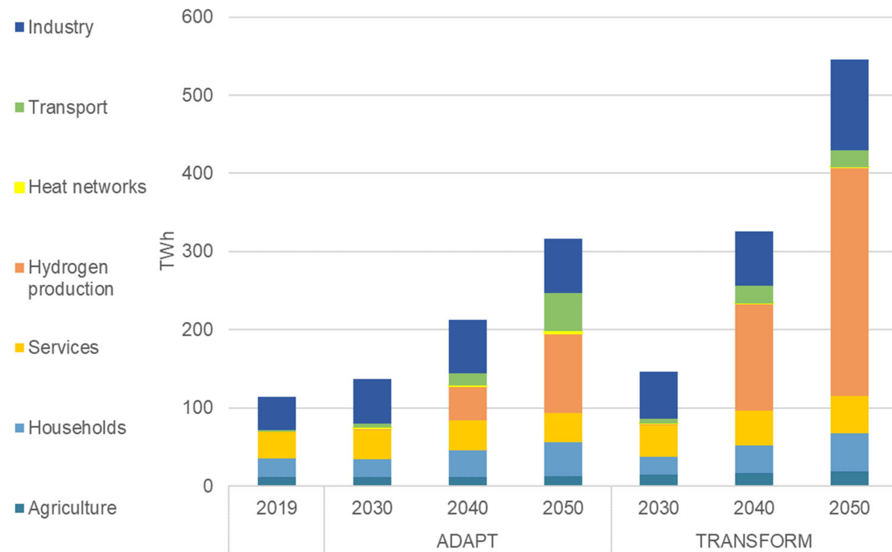

Figure 4.4 Electricity demand in 2019 (CBS, 2021) and in the ADAPT and TRANSFORM scenarios.

The electricity supply is shown in Figure 4.5. Electricity production in the ADAPT scenario increases in 2050 to a level almost three times as high as in 2019. In TRANSFORM 2050, strong increases in offshore wind and solar PV energy lead to electricity production levels almost five times as high as in 2019. Figure 4.5 also shows electricity production as share of total primary energy supply[16]. The share of electricity in the energy supply more than doubles in the ADAPT scenario, while in the TRANSFORM scenario, the share is more than four times higher than in 2019.

[16] This share is calculated as total electricity production divided by total primary energy, including non-energy use and bunker fuels. The share also includes the electricity that will be converted to the final energy, such as hydrogen, synthetic fuels and heat. An electricity share relative to final energy does not show electricity consumption for producing these final energy carriers, and will therefore result in a lower percentage. An electricity share relative to total primary energy supply ignores, however, the transmission and conversion losses of primary energy sources into final energy carriers. 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.

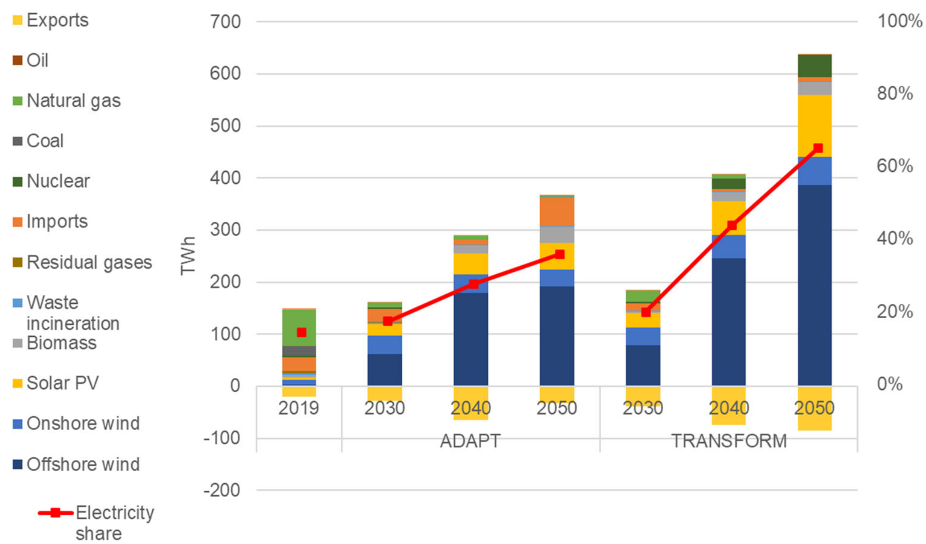

Figure 4.5 Electricity supply in (CBS, 2021) and in the ADAPT and TRANSFORM scenarios. Electricity relative to the total energy supply is shown (right axis) as well as the electricity export (negative figures).

Power exchange with neighbouring countries
The Dutch electricity system is part of the European electricity network and exchanges electricity with neighbouring countries (Germany, Belgium, Norway, United Kingdom and Denmark)[17]. Electricity exchange with foreign countries contributes to balancing electricity supply and demand, including the variable supply of renewable electricity (VRE) from wind and solar energy. A close look to Figure 4.5 shows that over a whole year there are annual net exports in almost all years. In the ADAPT scenario, net exports rise to 20% of total electricity production (57 TWh) in 2040, but turn around in 2050 to net imports of 7% (21 TWh). In TRANSFORM, electricity exports take place in all years, but decrease in relative terms from 15% (26 TWh) in 2030 to 12% of total electricity production (77 TWh) in 2050[18]. In ADAPT in 2050, the marginal electricity price abroad is lower on average than in the Netherlands. In the TRANSFORM scenario, the demand for electricity in both the Netherlands and neighbouring countries is much higher. The Netherlands is able to increase electricity production relatively more than the neighbouring countries, resulting in a net export of electricity.

Electricity generation and flexibility
In both scenarios in 2030, more than 80% of the electricity is generated from wind and solar energy. In the ADAPT scenario, by 2050 wind and solar capacity expands and provides 96% of the generated electricity; in TRANSFORM they account for 91% in 2050. In addition to centralised electricity generation, electricity production also takes place in the end-use sectors: in industry electricity is produced from residual gases from biomass processes and in the built environment and agriculture

[17] The total interconnection capacity is 15.2 GW for both scenario's and all years, and includes an assumed investment in new capacity of 3.5 GW.
[18] These exchanges have been calculated with the European electricity market model COMPETES. Based on similar assumptions regarding electricity demand and renewable power plant capacity for the Netherlands and the other EU countries, COMPETES (Lise, Sijm, & Hobbs, 2010) calculates the hourly volumes and prices for import and export of electricity to and from the Netherlands..

sector with solar panels. In TRANSFORM in 2050, solar electricity generation in the agriculture sector exceeds its own consumption by 15 TWh. In the TRANSFORM scenario (but not in ADAPT), new nuclear power stations are used for electricity production accounting for 5% of total electricity production in 2040 and 7% in 2050. See the text box A for further explanation.

Growing shares of electricity supply from wind and solar PV increase the need for flexibility and other balancing strategies in order to keep electricity supply and demand in balance. As previously mentioned, this balancing requirement is partially met with trade with neighbouring countries, but also with flexible power generation (with natural gas and biomass in both scenarios, and in ADAPT also with hydrogen), demand response (e.g. EV's, electric boilers, electric heat pumps, electrolysers for hydrogen production), curtailment of wind and solar energy, and energy storage (batteries and hydrogen storage in salt caverns). In the OPERA model, the balancing and flexibility options are determined by optimising the system using hourly supply and demand profiles. As the share of solar and wind in electricity production increases, the use of these options grows. Curtailment contributes with 0.6 TWh in the ADAPT scenario in 2030 and 5.1 TWh in 2050. In TRANSFORM, these figures are lower, resp. 1.0 and 3.1 TWh, because electricity demand in this scenario is high, electricity production from solar and wind cannot be increased further (the maximum potential has been reached) and curtailment would lower the electricity production. For energy storage options, electricity is stored in the event of surpluses and supplied to the system in the event of shortages. In 2030, electricity storage supplies 1 TWh to the electricity system in the ADAPT scenario and 12.3 TWh in 2050. For the TRANSFORM scenario, these figures are 1.6 and 6.9 TWh respectively. The largest contribution to flexibility, however, comes from flexibly operated electrolysers that produce hydrogen (using hydrogen storage as a buffer to balance hydrogen supply and demand). In 2050, in the TRANSFORM scenario, the electrolyser capacity in 2050 is 67 GW, much larger than the 20 GW capacity in ADAPT. For that reason, the flexibility contributions in 2050 in TRANSFORM from curtailment and energy storage are smaller than in ADAPT.

Installed capacities

Figure 4.6 shows the installed capacity for the different types of electricity production. The maximum available potentials for wind, solar PV and nuclear are also shown in this figure (and in Table 3.3). In the TRANSFORM scenario, the assumed potentials for wind and solar energy are larger than in ADAPT[19]. In both the ADAPT and TRANSFORM scenarios, the maximum potential for onshore wind is almost fully used in all three milestone years. This is also the case for offshore wind in TRANSFORM in all three years, but not for ADAPT. For solar PV, the available potential is fully exploited in TRANSFORM in 2050. Taking into account the realisation period for new nuclear power stations, it is assumed in both scenarios that 2.5 GW of new nuclear production capacity can be realised in 2040 and 5 GW in 2050. This only happens in the TRANSFORM scenario.

Peak power plants are fuelled with natural gas and hydrogen. In 2050, there are still natural gas power plants in operation in both scenarios (in ADAPT 8.5 GW, 3.6 TWh resulting in 1.2 Mt CO_2-eq; in TRANSFORM 4.2 GW, 0.3 TWh resulting in 0.1 Mt CO_2-eq) because CO_2-emissions can be offset by negative emissions (e.g.

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[19] For wind and solar energy the following full load hours have been used: Onshore wind 4468 hours, offshore wind 5365 hours, solar PV roof top 890 hours and solar PV park 969 hours.

BECCS, see Section 4.4). In 2050, peak power is also generated with hydrogen (5.1 GW, 1.3 TWh) in the ADAPT scenario, but not in TRANSFORM because hydrogen is entirely used for synthetic chemical and fuel production (see Section 4.3.2).

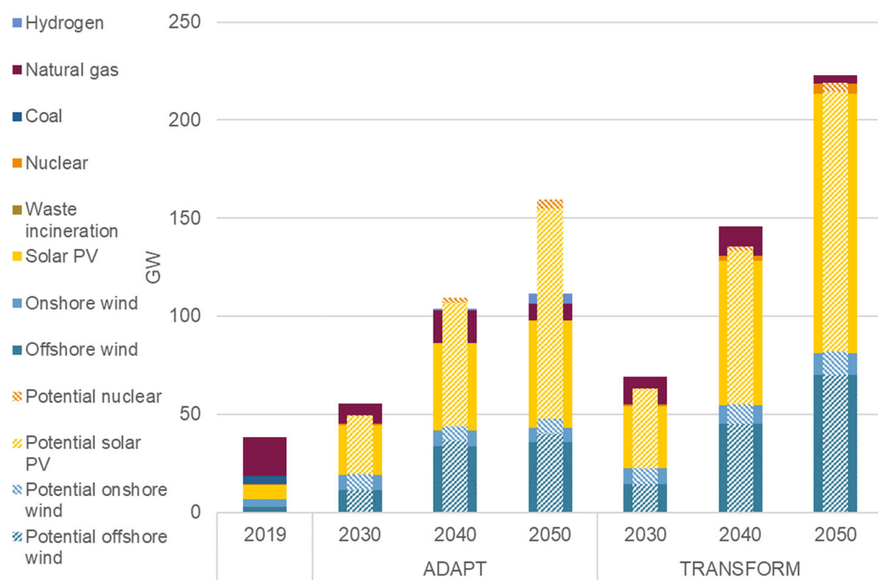

Figure 4.6 Electricity generation capacity in 2019 (CBS, 2021) and in the ADAPT and TRANSFORM scenarios. Also the assumed potential capacities are shown.

Text Box A

Scenarios with and without nuclear power

New nuclear power plants are deployed in the TRANSFORM scenario in 2040 and 2050, but not in the ADAPT scenario. The main reason for deploying nuclear power plants in TRANSFORM is that the electricity production capacities for wind and solar PV reach their maximum limits, while electricity demand is not entirely covered. In the ADAPT scenario, the constraint on wind and solar capacity is not binding.

TRANSFORM scenario without nuclear energy

This raises the question of what would happen if nuclear energy is much more expensive than assumed in this scenario analysis or is socially not accepted. This has been investigated in a no-nuclear variant of the TRANSFORM scenario. This scenario variant shows that without nuclear energy, it is still possible to cover the total energy demand and to achieve the objective of a GHG neutral energy system. In 2040, the total electricity production in the no-nuclear variant decreases. The reduction in electricity production from nuclear energy of 20.9 TWh is only partly compensated for by 4 TWh extra electricity from solar PV. In 2050, solar PV or wind energy cannot compensate for the nuclear energy production because these options have already reached their maximum potential.

In TRANSFORM 2050, renewable heat sources, i.e. geothermal energy (+49 PJ), ambient heat (+42 PJ) and solar thermal heat (+55 PJ), almost completely compensate for the absence of 153 PJ (42.5 TWh) of nuclear energy. The deployment of heat pumps instead of electric boilers for heating leads to a more efficient use of electricity. An important contribution is from the direct air capture process, which in the optimisation switches from a process requiring electricity to a process requiring low temperature heat which is provided by geothermal and solar heat. Hydrogen production and consumption is slightly reduced (-25 PJ) with minor effects on production of chemicals and synthetic LNG.

In the base scenario, nuclear energy is used to supply base load electricity. In the no-nuclear variant this base load production is absent and the demand for balancing and flexibility increases. Extra flexibility is provided by additional electricity and hydrogen storage; the storage capacity increases by 2.4 TWh and 21.1 TWh, respectively.

As may be expected, the total system costs are higher (+8% in 2050) in the scenario variant without nuclear. This is the result of more deployment of heat pumps in industry and built environment, more investments in upgrading energy labels in the built environment, more expensive direct air capture technologies and more investments in energy storage.

Text Box A (continued)

TRANSFORM scenario with more nuclear power generation
The pace at which new nuclear power plants can be built has practical limits (such as lead times for permits and construction, availability of sufficient specialised personnel, etc.). In the base scenarios, therefore, it is assumed that no more than 2.5 GW of new nuclear capacity can be realized by 2040 and no more than 5 GW by 2050. In a scenario variant in which the potential for nuclear energy is increased to 12 GW in 2050, additional nuclear power is deployed in TRANSFORM up to this new limit. But that is not at the expense of electricity production from wind and solar. In the cost-optimised energy system, the extra electricity production covers growth in electricity demand for the heat supply of the built environment and agricultural sector and the production of hydrogen. Electricity demand in the chemical industry also increases. These shifts lead to lower total system costs (-5% compared with the base scenario). The amount of electricity available has a major impact on electricity consumption in the end-use sectors. This is also visible if electricity exports in the TRANSFORM scenario are limited to half the levels of the base scenario. This has hardly any effect on total electricity production or the use of nuclear energy. The electricity that is not exported is used in industry, for hydrogen production and for heat supply to the built environment.

ADAPT scenario with nuclear energy
If biomass imports are reduced by 40% in the ADAPT scenario, the electricity demand increases by 4% in 2040 and 2050 compared to the base scenario. In particular, more electricity is used in the industrial sector and for the production of green hydrogen. In 2040, the extra electricity comes almost entirely from offshore wind and in 2050, offshore wind accounts for 75% of additional electricity generation. In 2050, a new nuclear power plant is deployed (0.5 GW) that covers 25% of the electricity demand growth.

Another constraint for the ADAPT scenario has the same effect: if CO_2 storage capacity is limited to 35 Mt from 2040 onwards, new nuclear power plants (3.3 GW) are also deployed in ADAPT and. electricity production is 25% higher than in the base case. In addition to electricity from nuclear energy, electricity production from solar and wind is also higher (12% higher than in the base scenario).The total system costs increase by 8%.

No nuclear power in the previous scenario study
In the previous scenario study (Scheepers, et al., 2020), no new nuclear power plants were deployed by the OPERA model. This was because it had a less strict GHG reduction target in 2050 (95% GHG reduction) and lower electricity demand. In comparison: the new TRANSFORM scenario shows a 15% higher electricity demand in 2050, especially because much more hydrogen is produced for the production of chemicals and synthetic fuels.

4.3.2 *Hydrogen*

In the Netherlands, almost all hydrogen is currently produced from fossil fuels and as by-product in electrolytic chlorine production (estimated at 180 PJ, see (Weeda & Segers, 2020)). In the ADAPT and TRANSFORM scenarios, industrial hydrogen demand for production of chemicals and synthetic fuels increases to 195 and 728 PJ, respectively. A distinction should be made between hydrogen produced and used within chemical processes (for example in fertiliser production and refinery processes) and hydrogen that can be supplied externally from dedicated hydrogen plants (tradable or merchant hydrogen). Figure 4.7 shows the hydrogen demand that can be supplied by these dedicated hydrogen plants. Note that in addition to hydrogen production within chemical processes, chemical processes can also use hydrogen obtained from external sources. In 2030, the demand for merchant hydrogen is still limited to approximately 20 PJ in both scenarios. However, after 2030, this demand increases strongly, more in the TRANSFORM scenario than in ADAPT. In the ADAPT scenario, the demand for merchant hydrogen initially grows in the built environment and industry (e.g. as feedstock for methanol and fertiliser production) and later also in the transport sector to a total of 259 PJ in 2050. In the TRANSFORM scenario, demand growth is driven by the chemical industry and transport sector. Hydrogen consumption in the built environment is small in TRANSFORM (only 5 PJ in 2050). Hydrogen is not used for steel production in either scenario. In the ADAPT scenario, steel is produced via a coal-based process (from 2040 on in combination with CCS)[20] and in the TRANSFORM scenario in 2050, electricity is used in for steel making via an iron ore electrolytic process.

Some hydrogen is stored in salt caverns and in tanks in the distribution network and at H_2 filling stations. Storage volumes increases to 112 PJ in 2050 for the ADAPT scenario (of which 81 PJ in salt caverns) and 190 PJ in 2050 for TRANSFORM (of which 164 PJ in salt caverns). Part of the hydrogen production takes place offshore (on platforms near offshore wind farms). Due to fluctuating wind energy production, hydrogen production on the offshore platforms also fluctuates. These fluctuations are absorbed by the hydrogen storage in salt caverns. In addition, hydrogen storage also helps to respond to fluctuations in hydrogen demand for electricity production and heat supply in the built environment (particularly in the ADAPT scenario).

[20] In 2030 blast furnace-basic oxygen furnace (BF-BOF) without CCS. From 2040 on top gas recycling blast furnace (TGR-BF) with CCS.

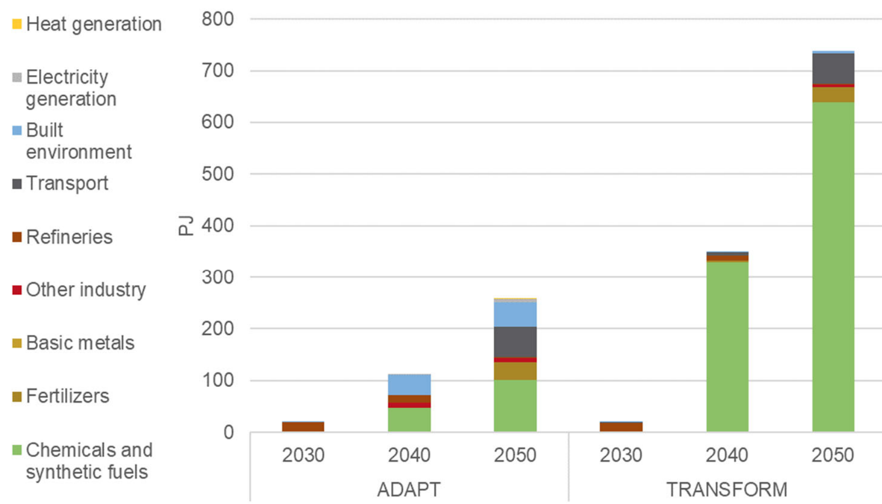

Figure 4.7 Hydrogen consumption (for fuels and as feedstock) in the ADAPT and TRANSFORM scenarios (hydrogen produced and used within chemical processes are not shown).

In both scenarios, most hydrogen is produced with electrolysers, i.e. from renewable electricity (green hydrogen). In both scenarios, some hydrogen (less than 10 PJ) is produced with steam methane reforming (SMR) with carbon capture. From the use of electrolysers in the ADAPT scenario, it can be concluded that after 2030 hydrogen from electricity (i.e. green hydrogen) is more cost-effective than production from natural gas with CO_2 storage (i.e. blue hydrogen). In the TRANSFORM scenario in 2050, photocatalysis is also applied for hydrogen production, but the production level is very small, less than 1 PJ.

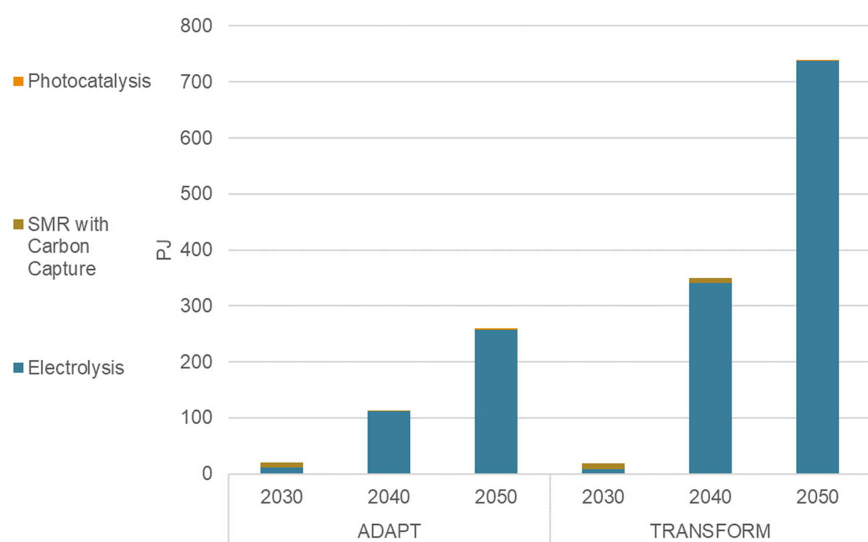

Figure 4.8 Hydrogen production in the ADAPT and TRANSFORM scenarios

4.3.3 *Biomass*

In both scenarios, imported biomass is used in addition to domestic biomass. Although the potential for both domestic biomass and imported biomass is considerably larger in the ADAPT scenario than in TRANSFORM (see Table 3.3), the large potential in ADAPT is exploited for only 67%, whereas 98% in TRANSFORM. As a result, the difference in biomass use between the two scenarios is much smaller than the difference in potential, as Figure 4.9 shows. In both scenarios, a significant part of the biomass is used for the production of fuels for aircraft, inland marine transport, international shipping and off-road machinery. The industrial sector also uses biomass, both for energy applications and for the production of chemicals (feedstock use). The share of energy applications in industry is considerably smaller in the TRANSFORM scenario than in ADAPT. The use of biomass for transport fuels in TRANSFORM is almost 20% higher than in ADAPT by 2050. This is due to a more ambitious GHG reduction target for international aviation and shipping in the TRANSFORM scenario, despite the lower total transport demand. The production of transport fuels is preferred over its use in energy and feedstock applications in industry.

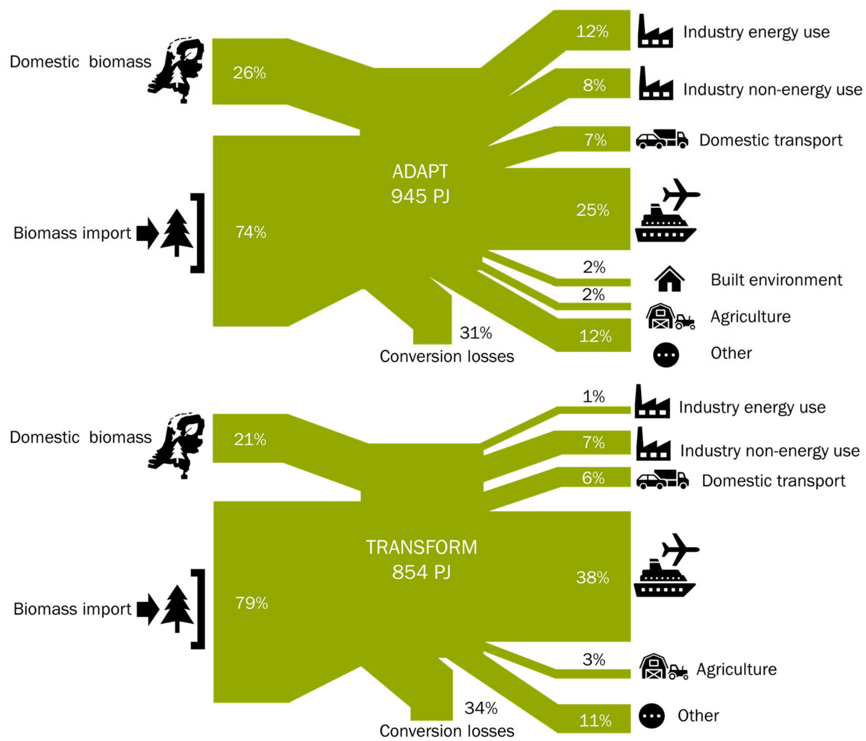

Figure 4.9 Biomass origin and destination in the ADAPT and TRANSFORM scenarios in 2050

4.4 GHG emissions and CO_2 in the energy system

4.4.1 Remaining CO_2, non-CO_2 and LULUCF emissions

In each of the modelled years there are remaining GHG emissions, see Figure 4.10. Besides CO_2, there are also remaining emissions of non-CO_2 greenhouse gases, such as nitrous oxide (N_2O), methane (CH_4) and hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6), the latter three summarized as F-gases. Land use, land use change and forestry (LULUCF) also cause GHG emissions, mainly CO_2, but also CH_4 and N_2O; these are aggregated[21]. Options to reduce non-CO_2 and LULUCF emissions (e.g. reforestation) are used to a limited extent in the ADAPT scenario: non-CO_2 emissions fall by 11% in 2050 compared to 2030 and LULUCF by 46%. The remaining emissions are compensated with net negative emissions (19 Mt), i.e. CO_2 capture and storage from biomass processes (BECCS). In the TRANSFORM scenario, the options to reduce non-CO_2 and LULUCF emissions are used more widely, especially in the reduction of CH_4. The reductions in 2050 compared to 2030 are 55% for both categories. In the TRANSFORM scenario as well, the remaining GHG emissions are offset by net negative emissions from the storage of CO_2 from biomass processes (BECCS) and direct air capture (9 Mt).

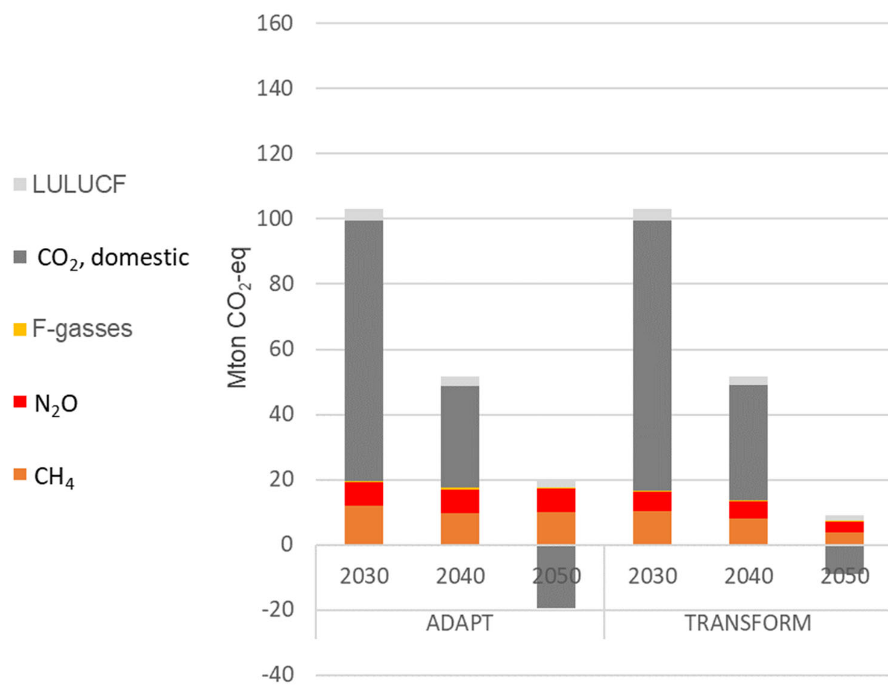

Figure 4.10 Remaining CO_2, non-CO_2 and LULUCF GHG emissions and negative CO_2-emissions in the ADAPT and TRANSFORM scenarios, excluding international aviation and shipping

4.4.2 Carbon dioxide

Carbon dioxide is the main greenhouse gas emitted by the energy system. Climate policy is aimed at achieving a transition to a sustainable energy system without

[21] Although the LULUCF sector is not part of the energy system, it is included in the model because of its contribution to greenhouse gas emissions.

emissions of carbon dioxide of fossil origin. At the same time, carbon is an important building block for molecules. These molecules are made to be used energetically, such as in fuels, or as material building blocks in chemical products. Therefore, a sustainable energy system will still contain carbon. Figure 4.11 shows carbon balances for the energy systems of the ADAPT and TRANSFORM scenarios for 2030 and 2050.

The total amount of carbon is larger in the ADAPT scenario than in TRANSFORM. This is due to the scenario assumption of higher energy demand and production volumes in industry than in TRANSFORM. In the ADAPT scenario, the amount of carbon is 6% smaller in 2050 than in 2030. This relatively small carbon reduction is the result of the continuation of fossil fuel use in combination with an increase in the use of biomass as a sustainable carbon source. In the TRANSFORM scenario, the amount of carbon decreases sharply (40% lower in 2050 than in 2030) because hardly any fossil fuels are used in 2050 and a smaller amount of biomass is used than in ADAPT.

The positive numbers in Figure 4.11 (right side) indicate the origin of the carbon while the negative numbers (left side) show the destination of the carbon. Origin and destination based of the carbon can be read from Figure 4.12. Figure 4.11 shows that in both scenarios and both years CO_2 is emitted into the atmosphere. Figure 4.12 indicates that the fossil carbon decreases sharply in 2050, but is not yet nil: the remaining fossil carbon dioxide emitted to atmosphere in ADAPT is 31 Mt and 3 Mt in TRANSFORM. This is because of the assumption that international aviation and shipping (bunker fuels) still allow some CO_2 emissions (50% in ADAPT and 5% in TRANSFORM). In both scenario fossil carbon can also still be emitted domestically because negative emissions, e.g. BECCS, can compensate these emissions.

In both scenarios, some of the CO_2 is captured. In the ADAPT scenario, 98% of this is stored in empty gas fields in the North Sea in 2050, of which 76% comes from biomass and thus leads to negative emissions (see Figure 4.12). In the TRANSFORM scenario in 2050, 56% of the total captured CO_2 is re-used, which is why CCU appears on both the left and the right side in Figure 4.11. This scenario allows a limited use of CCS, which is necessary for negative emissions that must compensate for the remaining GHG emissions (see Section 4.4.1). The CO_2 is stored in empty gas fields in the North Sea. Without carbon capture and storage options, it is not possible to achieve a 100% GHG emission reduction in the TRANSFORM scenario.

A small part of the carbon comes from waste and is partly reused (as pyrolysis oil from plastic waste) in chemicals. In order to meet the demand for carbon for chemicals and fuels production, carbon is also captured from the atmosphere in 2050 in the TRANSFORM scenario (Direct Air Capture). Scarcity of carbon within the energy and industry system makes it necessary to use this relatively expensive technique in this scenario.

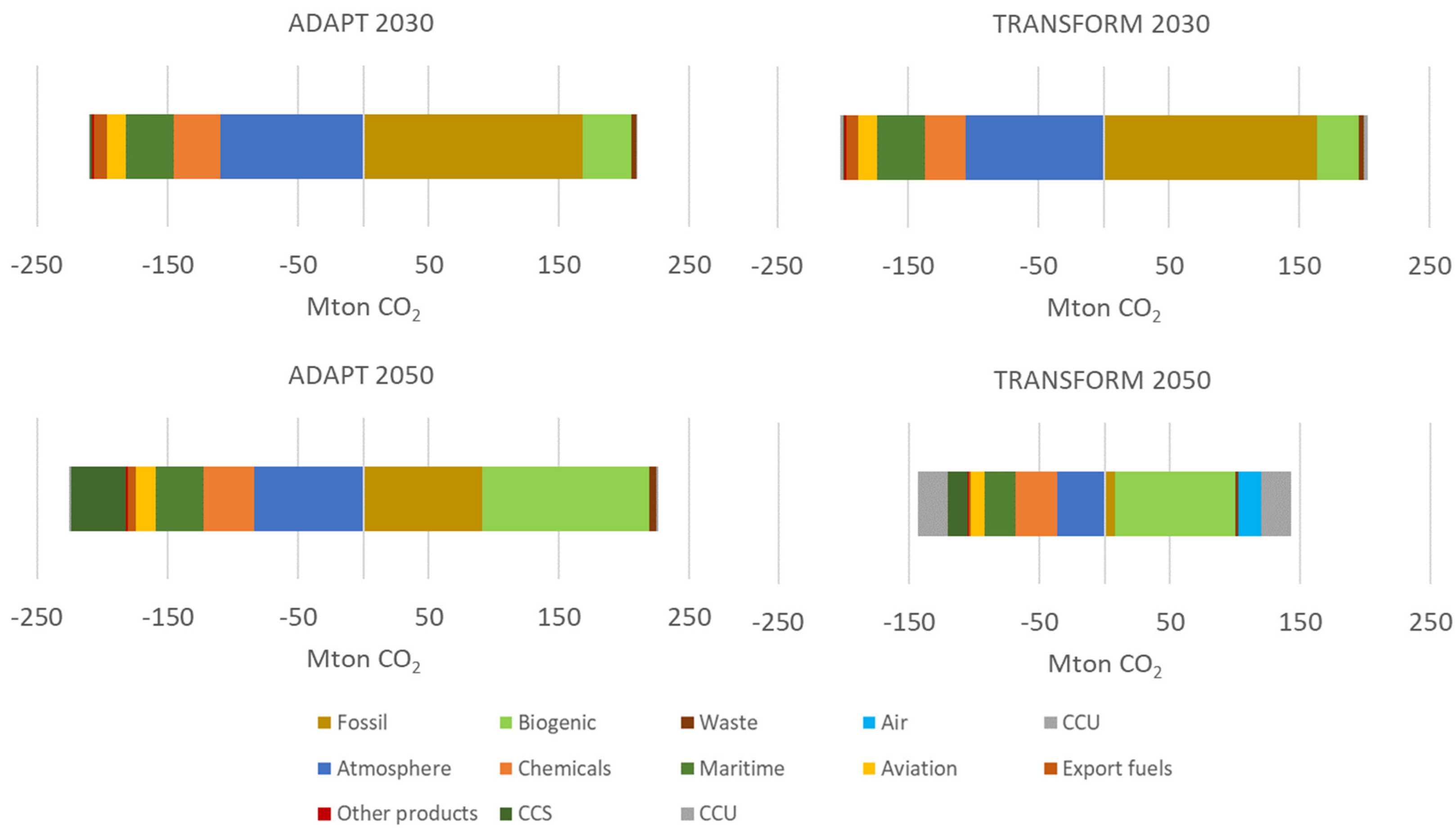

Figure 4.11 Carbon balance (in CO_2 terms) for the ADAPT and TRANSFORM scenarios in 2030 and 2050, including international aviation and shipping. 'Other products' refers to carbon that is used as a feedstock in industrial products outside the chemical sector, e.g. carbon in steel, etc.

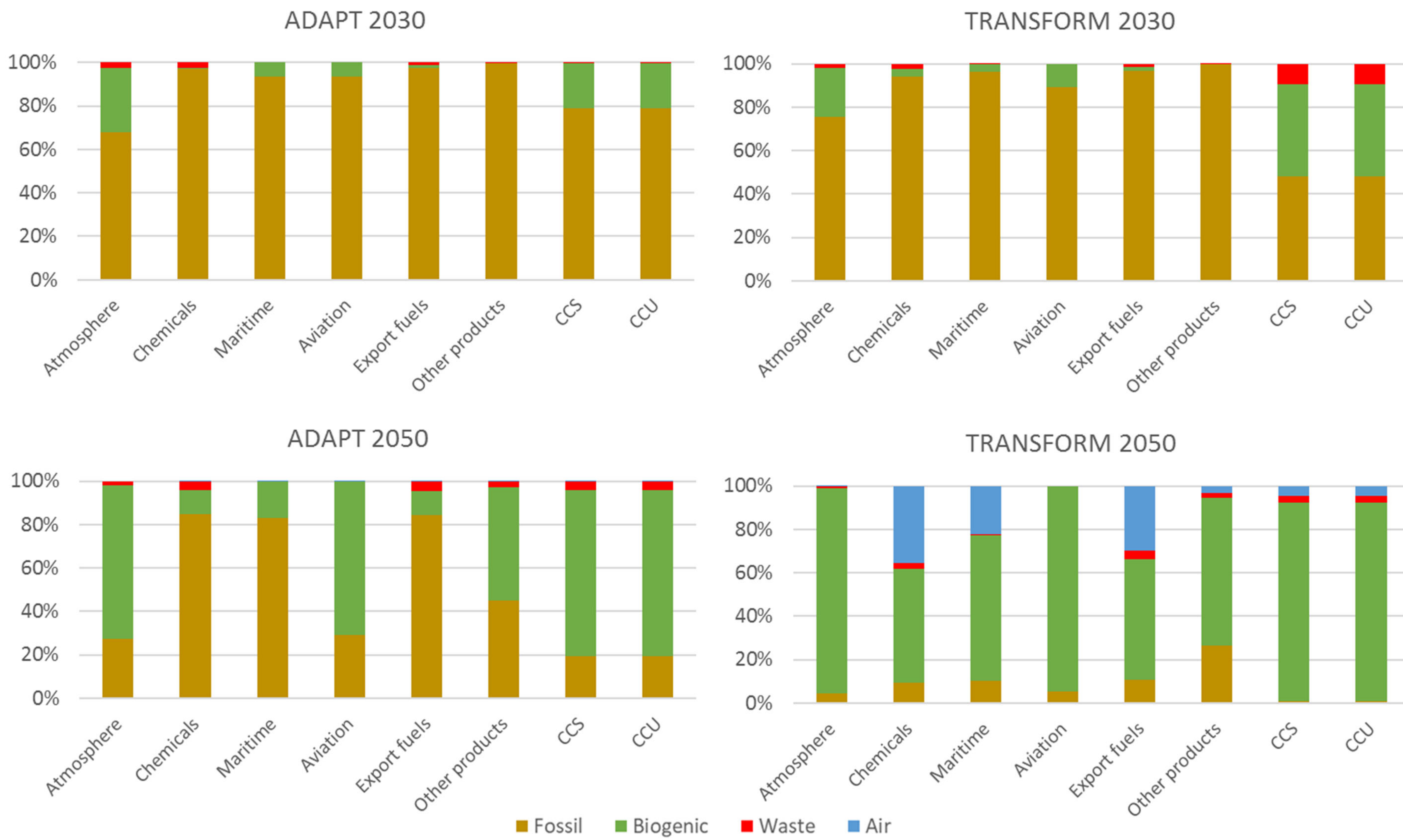

Figure 4.12 Carbon origin (colours) and destination (columns) in the ADAPT and TRANSFORM scenarios in 2030 and 2050, including international aviation and shipping. 'Other products' refers to carbon that is used as a feedstock in industrial products outside the chemical sector, e.g. carbon in steel, etc.

4.4.3 *CO_2 Capture, Storage & Use*

In both scenarios, CO_2 capture increases significantly and the annual maximum allowed storage volumes are fully used. Figure 4.13 shows the different processes in which the CO_2 is captured. The quantities of CO_2 captured are initially slightly larger from the ADAPT scenario than in TRANSFORM. In 2050, more CO_2 is captured in the TRANSFORM scenario, which is the result of the deployment of direct air capture. In both scenarios and in all years a substantial amount of CO_2 is captured at refineries (including bio-refineries). In the TRANSFORM scenario, for steel production in 2050 a transition is made from steel production using coal towards electrochemical steel making without CO_2 emissions. The steel production in the ADAPT scenario continues to use coal, but is equipped with CO_2 capture. In the ADAPT scenario, existing plants for production of chemicals and fertilisers are equipped with CO_2 capture technology, whereas in the TRANSFORM scenario new processes (e.g. electrified process and processes using biomass and recycled plastics) are introduced that do not emit fossil CO_2. In TRANSFORM 2050, CO_2 is also captured from biogas and synthetic gas production (SNG). In both scenarios CO_2 capture is also applied at waste incineration plants and small amounts of CO_2 are captured from hydrogen production with steam methane reforming and electricity production with natural gas.

Figure 4.14 shows the destination of the captured CO_2. In both scenarios, CO_2 is stored in empty gas fields in the North Sea. In 2030, the quantities are the same for both scenarios (7.5 Mt). Thereafter, the stored quantities in the ADAPT scenario increases sharply to 50 Mt in 2050, while in TRANSFORM this growth is limited to 15 Mt. In 2030, a small amount of the captured CO_2 is used for power to liquid (P2L) processes in refineries in both scenarios. In ADAPT, this use in P2L continues in 2040 but in the TRANSFORM scenario, 72% of the captured CO_2 is used for production of chemicals. In 2050, more than 30 Mt captured CO_2 is used for chemicals, i.e. stored in chemical products and not released into the atmosphere. In both scenarios some captured CO_2 is used also used in the fertilizer production (urea).

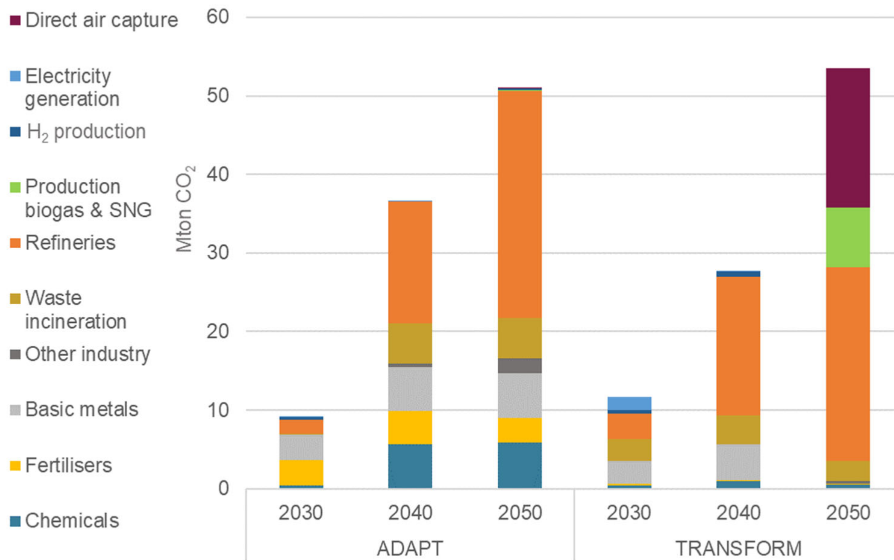

Figure 4.13 CO_2 capture by process in the ADAPT and TRANSFORM scenario

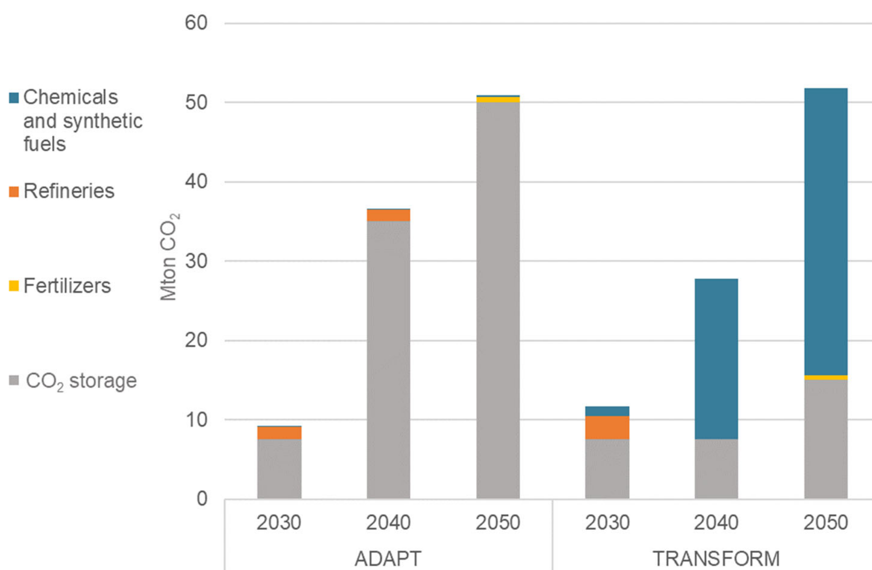

Figure 4.14 CO_2 storage and use in the ADAPT and TRANSFORM scenario

4.5 Energy infrastructure (inter regional energy transport)

4.5.1 Electricity transport

The OPERA model distinguishes 14 different regions: 7 land regions and 7 sea regions. The transport between these regions is modelled at the level of the transmission grid (for more details, see (Scheepers, et al., 2020)). Figure 4.15 shows the total net annual electricity flows between the regions in 2050 for both scenarios. The model calculates the flows for peak periods with high demand and high supply. The transport flow is never larger than 2.5 times the current transport capacity on land, a precondition that has been given to the model. The figures show the electricity flows from offshore wind to the coastal regions. In 2050, the production of offshore wind in TRANSFORM will be higher than in ADAPT. This extra production comes from wind farms further out in the North Sea and leads to larger transport volumes to the northern region. Subsequently, part of the electricity is transported inland from the coastal regions. It is assumed that new nuclear power stations will be built in South Holland (Maasvlakte) and Zeeland (Borssele). The figure also shows the net import or export flows to neighbouring countries (flows to Norway, Denmark and North-Germany are merged).

4.5.2 Hydrogen transport

Because transporting hydrogen via pipelines at a greater distance from the coast is more cost-effective than transporting electricity via cables, the OPERA model assumes that part of the hydrogen on platforms in the North Sea is produced with wind energy. Figure 4.16 shows the hydrogen transport between the 7 sea regions and 7 land regions in 2050 for both scenarios. No hydrogen is produced offshore along the coast of Zeeland, as the cables required to connect to offshore wind in Zeeland have already been built. A share of the hydrogen is produced in the land regions, e.g. at industrial plants and at hydrogen filling stations. A significant share of the hydrogen flows through hydrogen storage in salt caverns in the northern region. In ADAPT in 2050, 81 PJ hydrogen is stored in salt caverns and in TRANSFORM this is 164 PJ[22]. Because the figures show only net flows, hydrogen transport to and from the hydrogen storage in the northern region is not fully shown.

[22] The model assumes storage in salt caverns, but these volumes are likely to exceed the maximum potential. Hydrogen storage in depleted gas fields is an alternative.

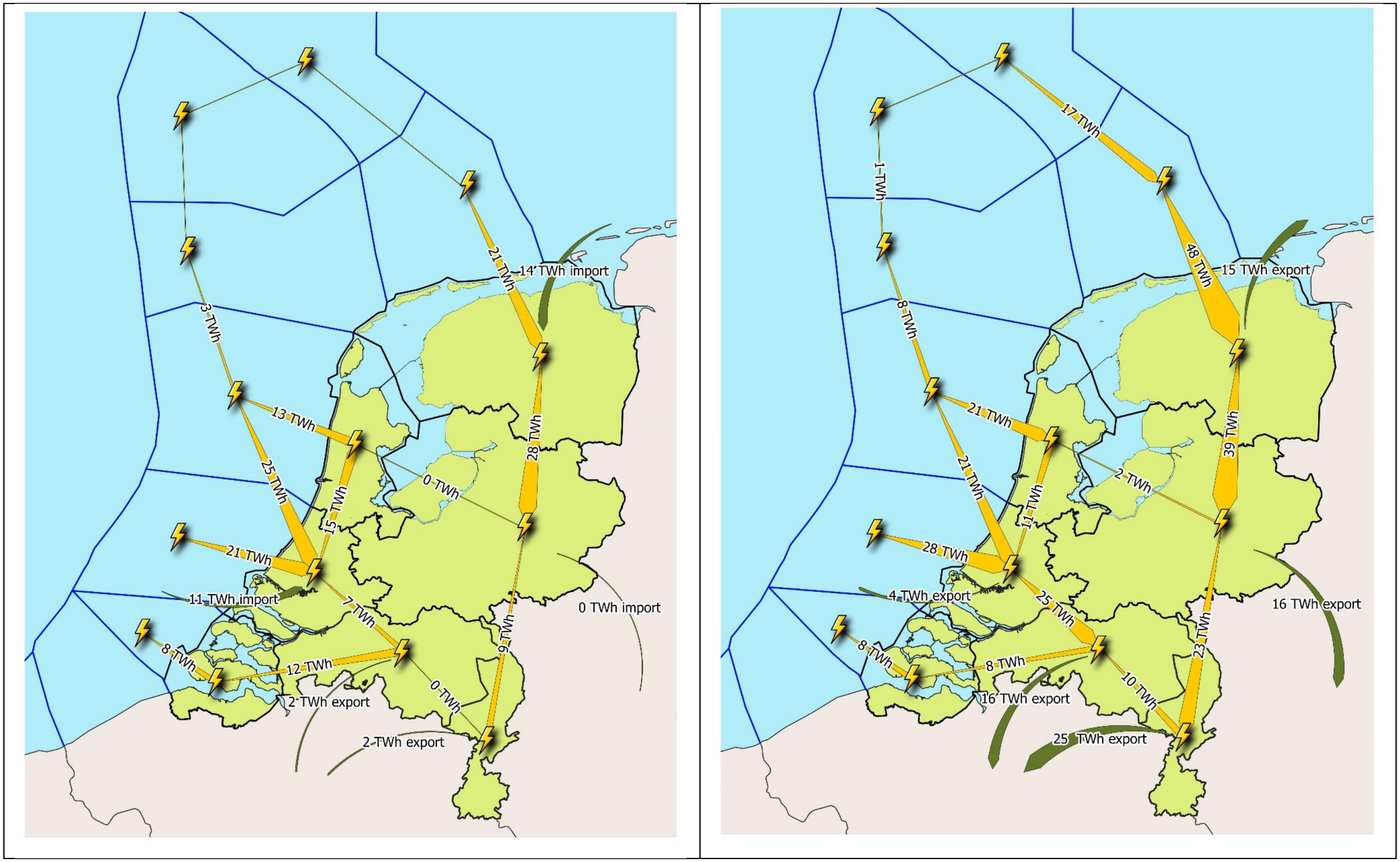

Figure 4.15 Net total annual electricity flows in TWh between regions in 2050 for the ADAPT (left) and TRANSFORM (right) scenarios

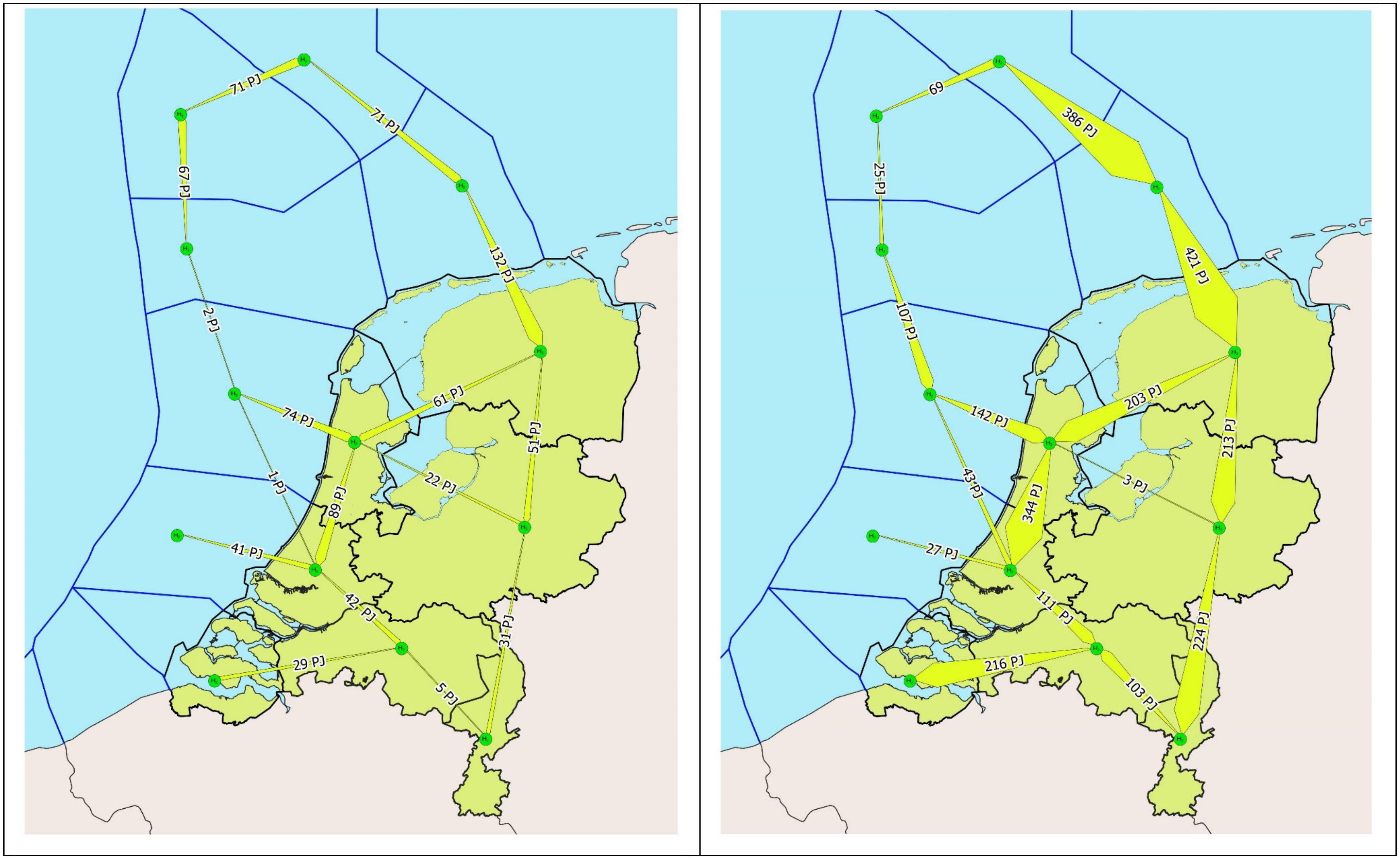

Figure 4.16 Net total annual hydrogen flows in PJ between regions in 2050 for the ADAPT (left) and TRANSFORM (right) scenarios

4.6 Energy system costs

The Dutch energy system has been optimised for the lowest system costs for both scenarios. Figure 4.17 shows the change in costs for each scenario compared to ADAPT 2030. The system costs for the ADAPT scenario increase after 2030 due to an increase in energy demand, but also because more efforts have to be made to reduce greenhouse gases. The total system costs in the TRANSFORM scenario are lower than in ADAPT due to lower energy demand and lower industrial production. Higher sustainability targets in TRANSFORM (more ambitious GHG reduction targets for international aviation and shipping and use of renewable carbon in chemical production) increase the total system costs after 2030. Despite the deployment of new innovative techniques on a larger scale, the total system costs for TRANSFORM are in 2050 lower than in ADAPT. Both scenarios assume a reduction in costs for the innovative technologies to be deployed (technology learning). As a result, the cost increase is smaller than if this assumption was not made.

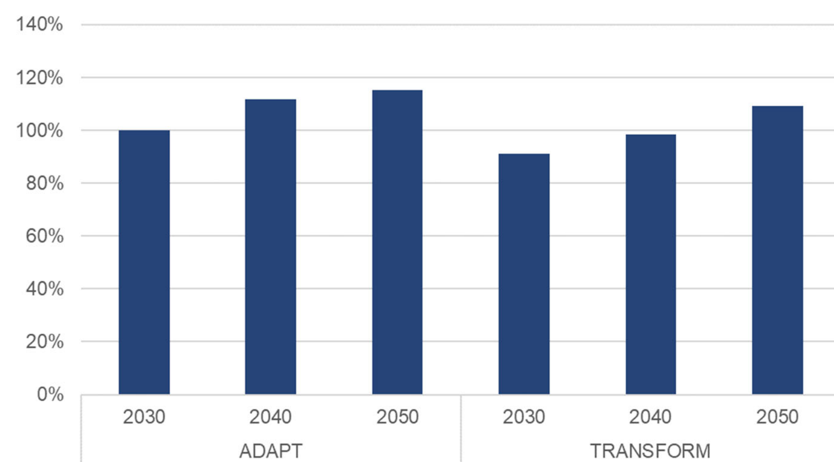

Figure 4.17 Relative change of total system costs for the ADAPT and TRANSFORM scenarios. Costs for ADAPT 2030 are 100%.

4.7 Total energy system (Sankey diagrams)

Sankey diagrams of the energy flows for the ADAPT and the TRANSFORM scenarios in 2030, 2040 and 2050 are shown in Figure 4.18 and respectively. On the left side of the Sankey diagram are the primary energy sources and the energy imports. The primary energy flows are converted into other energy carriers (centre in the diagram), such as electricity and hydrogen, and provide the end-use sectors with energy on the right side of diagram. Exports and energy losses arising from energy conversion are also shown on the right side. Energy and non-energy conversions can also take place in the end-user sectors. For example, the production of methanol takes place in industry, but this conversion is placed in the middle of the figure. The industrial sector supplies residual heat to the built environment and synthetic fuels to aviation and shipping. The Sankey diagrams also include non-energy use in industry (feedstock).

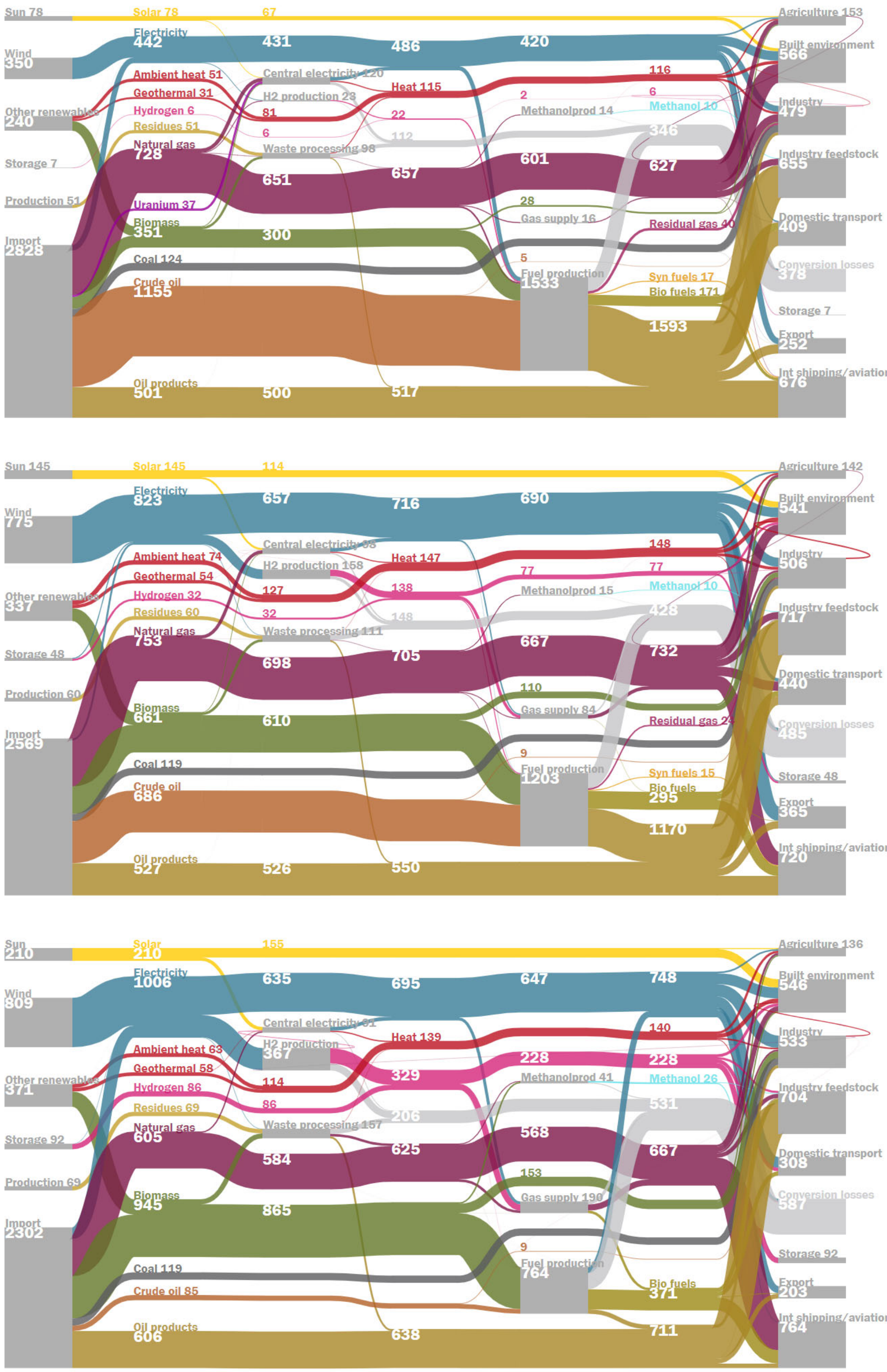

Figure 4.18 Sankey diagrams of the ADAPT scenario for 2030 (top), 2040 (middle) and 2050 (bottom)

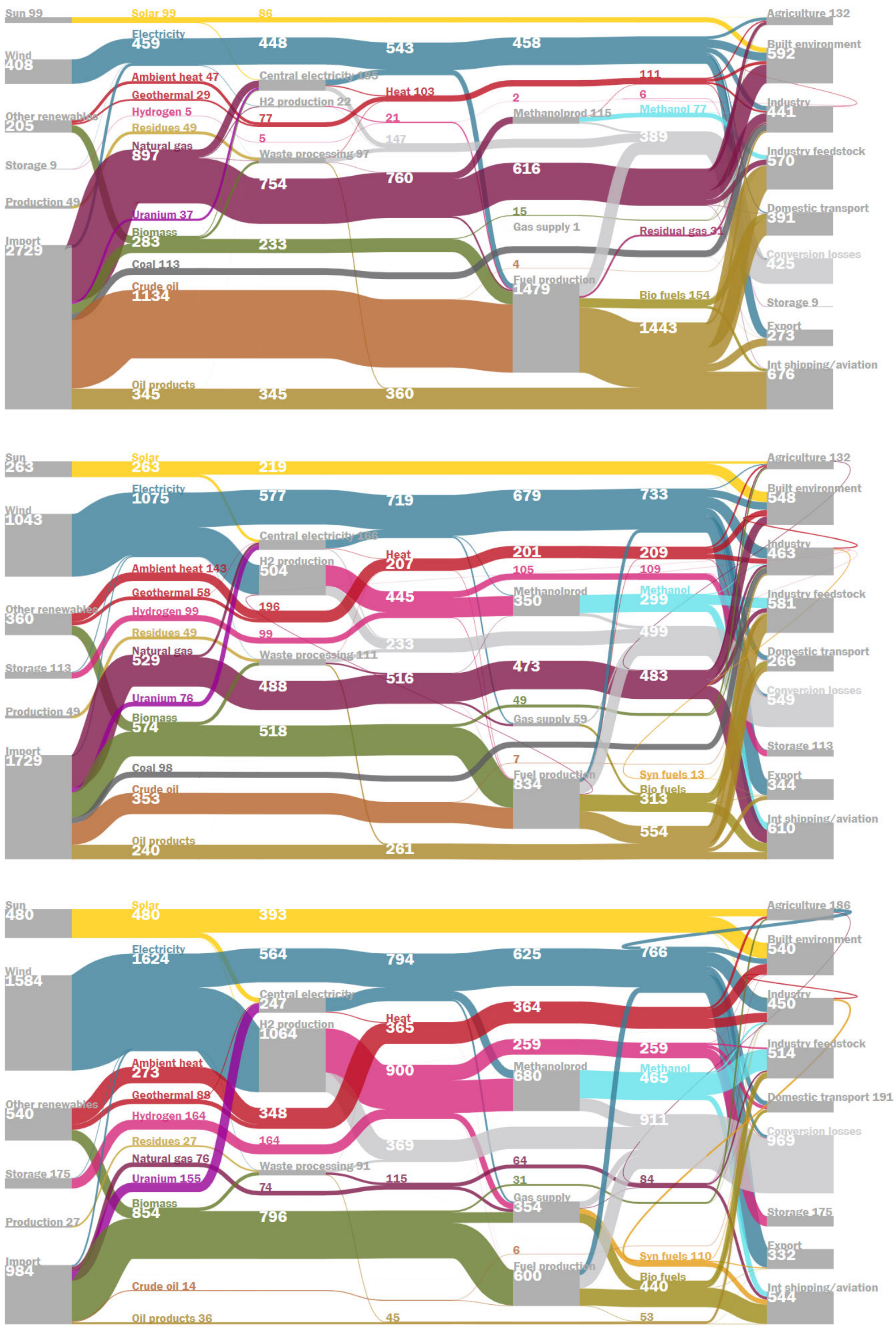

Figure 4.19 Sankey diagrams of the TRANSFORM scenario for 2030 (top), 2040 (middle) and 2050 (bottom)

5 Transport fuels and high value chemicals

This chapter focuses on emissions reduction and renewable feedstock use for transport and high value chemicals. The transport sector's dependence on fossil fuels makes it challenging to reduce GHG emissions. The chemical industry uses significant amounts of energy to run its processes, but also requires carbon feedstocks to manufacture a broad range of carbon-based products. To mitigate climate change and reach the overall goal of net-zero emissions in the Netherlands, both the transport sector and the chemical industry will need to move away from fossil hydrocarbons and replace these as much as possible with renewable options. The production of transport fuels and chemicals is interrelated. This applies to the current oil refineries and petrochemical industry, but, as will become apparent in this chapter, also apply to sustainable fuel production and production of chemical from sustainable feedstocks.

Domestic transport consists of road transport and other transport modes. Road transport includes passenger cars, light duty vehicles (LDV), and heavy duty vehicles (HDV). Other transport modes included are rail transport, inland shipping, and non-road machinery. While the OPERA model optimizes over the full value chain for road transport, including fuel supply to vehicle fleet, for other transport modes (e.g. trains, ships, and also aviation sector) only fuel supply is included in the optimisation for these transport modes. The fleet-related costs are not included.

High value chemicals (HVCs) refer to olefins (e.g. ethylene, propylene and butadiene) and aromatics (e.g. benzene) currently produced via steam cracking in the Dutch chemical industry. Steam cracking of naphtha is the main route to producing HVCs today, and these conventional steam crackers are included as the reference route in the OPERA model. These crackers can be fed with fossil naphtha or bio-naphtha. Plastic pyrolysis oil, following a hydrotreatment, can also be co-fed to the stream crackers. Alternative production options for HVCs, namely production of HVCs via methanol to olefins (fossil, biobased or synthetic methanol), and bio-based ethanol to ethylene are also included in the OPERA model.

This chapter consists of the following sections:
- Section 5.1 includes transport sector-related demand projections. These are one of the main input parameters.
- Section 5.2 presents the OPERA modelling results related to renewable fuel supply.
- Section 5.3 presents the impacts of the limited availability of biomass on transport sector decarbonisation. In addition, the issue of methane leakage in ships and its consequences are analysed in this section.
- Section 5.4 introduces the HVC-related demand projections and also how recycling has been included in this modelling activity.
- In Section 5.5 the OPERA modelling results on HVCs production are presented.
- Section 5.6 details the impacts of limited biomass availability versus greater biomass imports on the production of HVCs. This section also looks into greater availability of pyrolysis oil from plastics.

5.1 Demand projections for transport sector and related emissions

Domestic transport activities and final energy demand for aviation and international shipping are estimated up to 2050, according to the ADAPT and TRANSFORM storylines. These estimates translate into different final energy demands and inherently result in a change in GHG emissions, which can be attributed to lifestyle changes and consumer choices. The TRANSFORM scenario assumes a more climate-conscious society in the future. This can be interpreted as less use of long-distance transport and less consumption of overseas goods, which result in lower aviation and shipping activities. This section introduces such demand side management-related emission reductions to better analyse the modelling results regarding the renewable fuel supply options and their contributions to climate change mitigation.

5.1.1 Domestic transport

In the ADAPT scenario, projections of the domestic transport activity from the Klimaat en Energieverkenning 2020 (KEV, 2020) are used up to 2030 and after that, the same growth rates are used as in (Scheepers, et al., 2020). In TRANSFORM, however, passenger transport activity is assumed to be reduced by 10% in 2030 and 25% in 2050, compared to 2020. This reduction is, to some degree, compensated for by increased activity in other modes of domestic transport, specifically public transport. Thus, public transport final energy use is increased by 3% in 2030 and 8% in 2050, compared to 2020. The activity changes related to domestic transport can be found in table 3.5. While the structural changes in the TRANSFORM scenario certainly influence the GHG emissions, the final outcome will depend on many factors, including the diffusion of zero emission vehicles (ZEVs). The total emission reductions for each scenario are presented in section 5.2.

5.1.2 Bunker fuels (aviation and international navigation)

Figure 5.1 introduces the aviation sector final energy demand projections for the two scenarios, which are built upon projections from KEV 2020. In accordance with the scenario storyline, final energy demand in ADAPT continues to grow. In TRANSFORM, there is a significant reduction in final energy demand. This figure also illustrates the reference GHG emissions of the two scenarios when no emission reduction targets are introduced. If no climate change mitigation interventions are introduced, in ADAPT, aviation sector emissions continue to grow and reach approximately 43% higher than the emissions in 2005. The TRANSFORM scenario sketches a different future. Due to societal changes, final energy demand decreases continually through 2050, leading to emissions reductions even without mitigation interventions. Emissions levels are almost equal to 2005 levels in 2050. As shown in Table 3.6, within ADAPT and TRANSFORM, further emission reduction targets are introduced. In 2030, total emissions in aviation must not exceed 12.4 Mt CO_2-eq. Further reductions are required in 2050: maximum emissions are set at 8.3 Mt for ADAPT and 0.6 Mt for TRANSFORM. These relate to the emission reduction targets introduced for bunker fuels for 2050: 50% emission reduction in ADAPT and 95% emission reduction in TRANSFORM compared to emission levels in 2005.

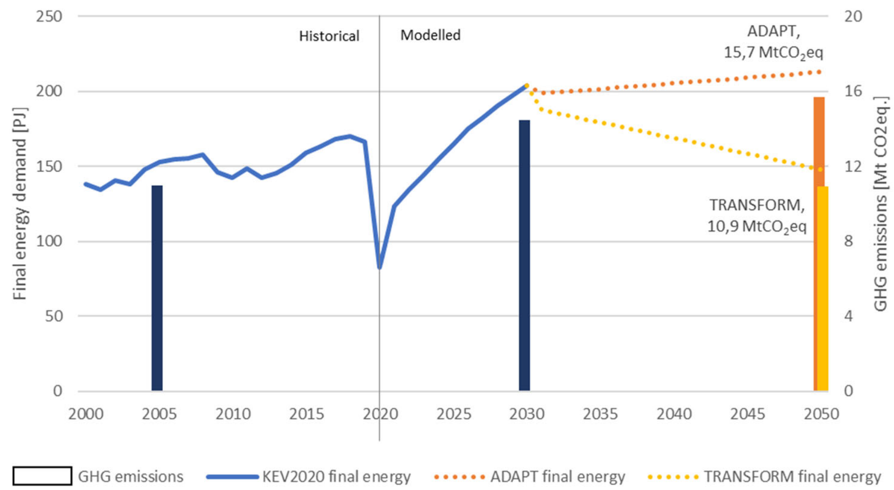

Figure 5.1 Aviation sector final energy demand projections and the reference GHG emissions when no emission reduction targets applies and fossil kerosene remain the main fuel supply option.

Final energy demand has been reduced significantly since 2008 in international navigation (see Figure 5.2). KEV 2020 projections indicate that the final energy demand will increase slightly between 2020 and 2030. The ADAPT scenario assumes this gradual increase continues until 2050. Naturally, related GHG emissions also continue to increase since fossil fuels are assumed to remain the most significant energy source. Nevertheless, there is a 25% GHG emission reduction in 2050 compared to 2008, due to energy efficiency increase. This reduction is almost doubled in the TRANSFORM scenario as the reduction in final energy demand is much higher. This means that the 50% emission reduction target introduced by the International Maritime Organisation (IMO) can be almost completely achieved by demand reduction due to behavioural changes in the TRANSFORM scenario (this is a scenario assumption, see Section 3.1). However, additional options are required to achieve the assumed 95% reduction target for the TRANSFORM scenario.

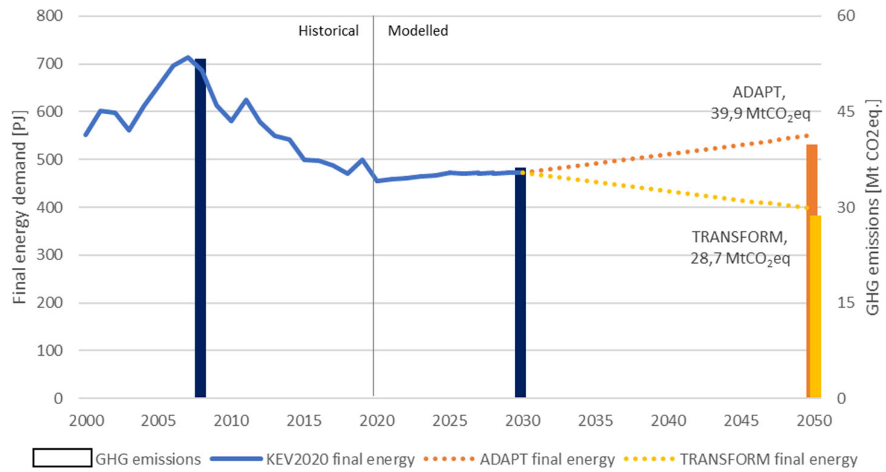

Figure 5.2 International navigation sector final energy demand and the reference GHG emissions when no emission reduction targets applies and fossil fuels remain be the main fuel supply option.

5.2 Transport sector decarbonisation and renewable fuel supply

5.2.1 Domestic transport

In this study, no specific GHG emission reduction target is introduced for the domestic transport sector. Instead, emissions are reduced as part of the overall emission reduction target set for the total domestic energy system. This is particularly relevant for 2030. Supply of renewable fuels is considered on the basis of cost competitiveness among the many different emission reduction options in the total energy system. There is, however, one exception. Renewable energy targets that are set in the Dutch ordinance[23] for 2030 are introduced as the minimum renewable fuel supply thresholds. More specifically, biofuels from food and feed crops are capped at no more than 1.2% of the final energy demand. A cap on biofuels produced from used cooking oils and animal fats is also introduced. Those biofuels must not be more than 4.2% of the final energy demand for domestic transport. Furthermore, a minimum of 3.5% advanced biofuels in domestic transport fuel demand is introduced in 2030.

Figure 5.3 illustrates the model results regarding GHG emission reductions in domestic transport. As mentioned previously, emission reductions in this sector relate to cost-optimal renewable and low-carbon energy supply options across the whole energy system in the Netherlands to meet the 55% emission reduction in 2030 and achieve a net GHG-free energy system in 2050. In this context, model results suggest a 32% emission reduction for domestic transport in the ADAPT scenario and 29% emission reduction in the TRANSFORM scenario, in 2030. To achieve a net GHG-neutral energy system in 2050, emissions in the domestic transport sector are reduced by 99% in 2050. Negative emissions in industry compensate for the remaining emissions, resulting in net-zero emissions in the domestic energy system.

[23] See: https://www.rijksoverheid.nl/onderwerpen/duurzame-energie/meer-duurzame-energie-in-de-toekomst

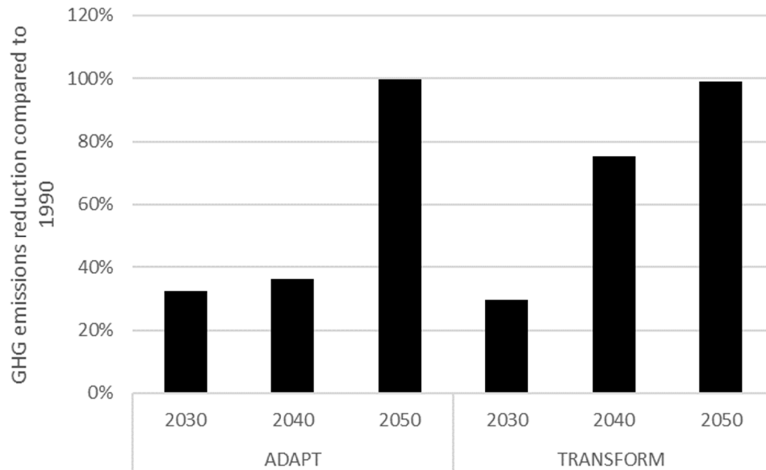

Figure 5.3 Domestic transport GHG emission reductions compared to 1990 levels.

Road vehicle drivetrain technologies
Figure 5.4 shows the passenger activities, further broken down to the type of vehicle. Note that based on scenario assumptions, the volume of the passenger activities is lower in the TRANSFORM scenario than in ADAPT (see Table 3.5). The model results for the ADAPT and TRANSFORM scenarios show that conventional drivetrains (internal combustion engines (ICE) using diesel or gasoline) continue to make up most of the passenger vehicle fleet in 2030. In 2040, the car fleet shifts to vehicles with internal combustion engines using gaseous fuels, such as compressed natural gas (CNG) vehicles, and electric vehicles (EVs) in the ADAPT scenario. In TRANSFORM, almost the entire passenger car fleet consists of EVs in 2040 and this is also the case in 2050 for both ADAPT and TRANSFORM. The amount of fuel cell electric vehicles (FCEV) that use hydrogen is negligible. The shift to CNG vehicles in ADAPT in 2040 is remarkable. This model result is highly sensitive to natural gas prices, which are lower than the costs of alternative renewable fuel options, specifically biofuels made from woody biomass. Moreover, the modelling does not include natural gas fuelling stations, which may affect the cost competitiveness of this fuel. Nevertheless, CNG appears to be the low-cost option in ADAPT in 2040 to reduce GHG emissions thanks to lower CO_2 exhaust emissions compared to gasoline.

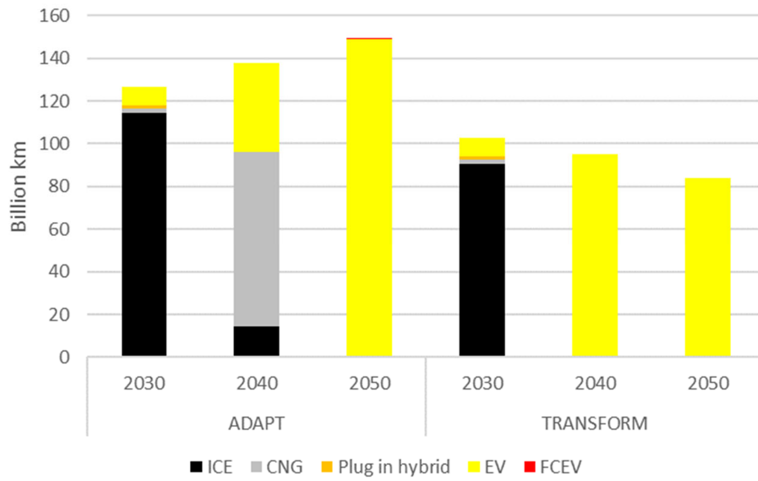

Figure 5.4 Deployment of car fleet in the ADAPT and TRANSFORM scenarios.

Light duty vehicle (LDV) activity is assumed to be the same in ADAPT and TRANSFORM, increasing by 11% between 2030 and 2050. Conventional ICEs continue to dominate the vehicle fleet up to 2040 in the ADAPT scenario. In TRANSFORM in 2040, plug-in hybrid vehicles and EVs contribute more than half of the fleet activity. In 2050, the fleet is almost fully replaced by EVs, in both scenarios, indicating that the direct CO_2 emissions from LDVs reaches zero. Figure 5.5 illustrates the LDV activity in the two scenarios.

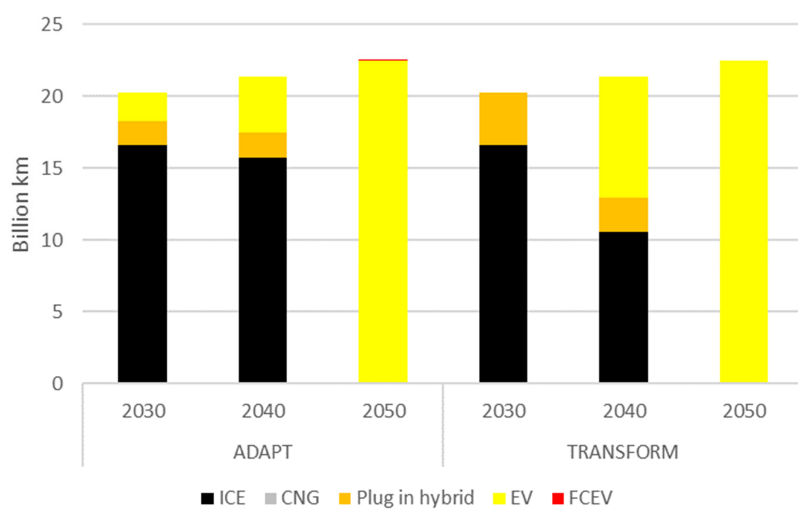

Figure 5.5 Light duty vehicle (LDV) fleet according to the ADAPT and TRANSFORM scenarios.

Transport activity of heavy duty vehicles (HDV) is also kept the same in both scenarios. Activity increases by 9% between 2030 and 2050. Figure 5.6 shows the HDV activity, broken down into vehicle types. In the ADAPT scenario, the fleet is entirely dominated by conventional ICEs in 2030 and 2040. In TRANSFORM, there is a shift to FCEVs beginning in 2040. In 2050, the fleet is fully replaced by FCEVs using hydrogen in both scenarios. It is important to note that in OPERA modelling no differentiation is made between long distance and short distance trucks;an average of 50,000 km per year was implemented for HDVs. However, if the representation is further detailed based on the truck capacity and range of trip, the result may favour a different distribution than only hydrogen-based trucks. In fact, the uptake of hydrogen trucks is mainly expected for trucks with the long distance trips for which electric trucks may become less favourable due to the necessary large batteries and long charging time. Electric trucks could become cost-competitive for short distance trips and the 2050 fleet distribution could change accordingly.

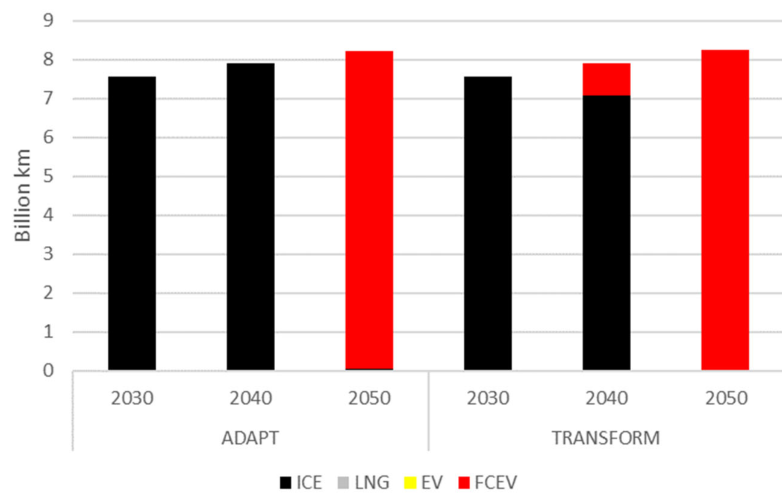

Figure 5.6 Heavy duty vehicle (HDV) fleet activity according to the ADAPT and TRANSFORM scenarios.

Domestic transport fuel mix
Figure 5.7 shows the total fuel mix in domestic transport in 2030, 2040 and 2050 in the two scenarios. In 2030, biofuels continue to play a key role in the total fuel mix in domestic transport, partly due to the implemented targets and caps for such biofuels. In 2020, the total amount of biofuel consumed in the Netherlands was approximately 26 PJ (NEa, 2020), excluding biofuels used in the shipping sector. Biofuel use in ADAPT in 2030 is almost 3.5 times the biofuel use in 2020 and twice the 2020 level in TRANSFORM in 2030. In 2050, biofuel use in domestic transport decreases slightly (in absolute terms) as direct electrification increases in both scenarios. In relative terms, biofuels continue to play an important role, contributing 24% of the total fuel demand in ADAPT and 58% of the fuel mix in TRANSFORM, in 2050. Biofuels are then mainly used in inland shipping and non-road machinery.

Direct electrification increases significantly beyond 2030. As presented in the previous sections on vehicle fleet, the entire passenger car and LDV fleets consists of EVs in both scenarios by 2050. This corresponds to 57% and 93% of the total final energy supply to domestic transport according to the ADAPT and TRANSFORM scenario results. Hydrogen covers almost the entire fuel demand in HDVs in 2050, in both scenarios. Hydrogen consumption corresponds to 19% and 30% of the total energy demand of the domestic transport sector in 2050 in ADAPT and TRANSFORM, respectively. Total consumption of hydrogen in domestic transport is almost the same in absolute terms in the two scenarios.

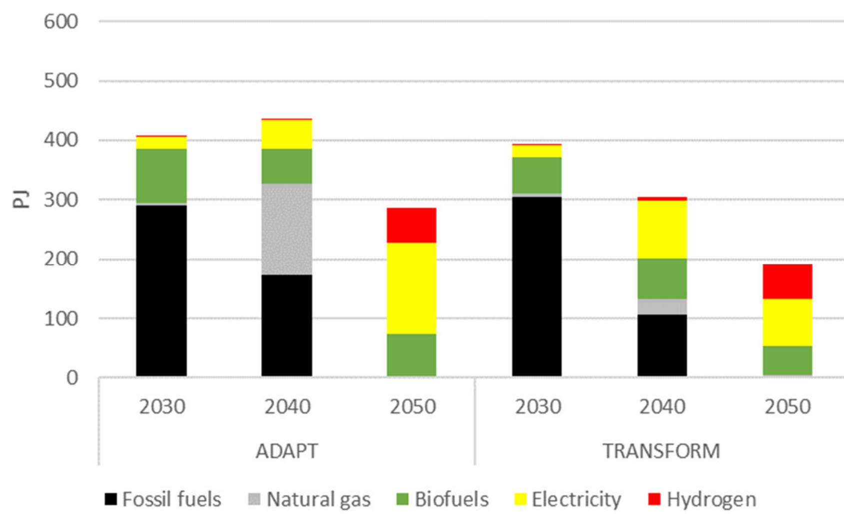

Figure 5.7 Fuel mix in domestic transport in the ADAPT and TRANSFORM scenarios.

5.2.2 *Fuel mix for international aviation and shipping (bunker fuels)*

International aviation

Figure 5.8 illustrates the resulting fuel mixes that meet the GHG emission reduction targets for the aviation sector. Achieving a 10% emission reduction in 2030 results in the use of biokerosene and synthetic kerosene for aviation (together 10% of the total aviation fuel demand in ADAPT in 2030). In this scenario, biokerosene demand continues to increase and supplies almost 71% of the total aviation fuel demand in 2050, about 151 PJ. This high demand for renewable aviation fuel relates to the continuous increase in aviation activity. While the model results include some synthetic kerosene deployment in 2030, this almost disappears in 2040 and 2050, illustrating the importance of biomass availability. Biomass supply potential, particularly the imports, are kept low in 2030 and the total biomass potential is fully utilised in 2030. In the absence of biomass, synthetic kerosene appears as the next possible renewable supply option. Beyond 2030, the biomass supply potential increases significantly. In addition, biomass use shifts more to aviation and shipping sectors due to significant electrification in road transport.

In the TRANSFORM scenario, the ambitious GHG emission reduction target introduced for 2050 (95%) results in 95% biokerosene use. Results from both scenarios show a limited role for synthetic kerosene. There are a number of reasons behind this. First, biokerosene production is less costly than synthetic kerosene production. Second, the biogenic CO_2 captured during the gasification and gas cleaning stage of biokerosene production is either stored in the ADAPT scenario and provides negative emissions for the domestic energy system, or valued as carbon and used in the petrochemical industry to produce high value chemicals in the TRANSFORM scenario. As such, the model favours the multifunctionality of the biorefineries.

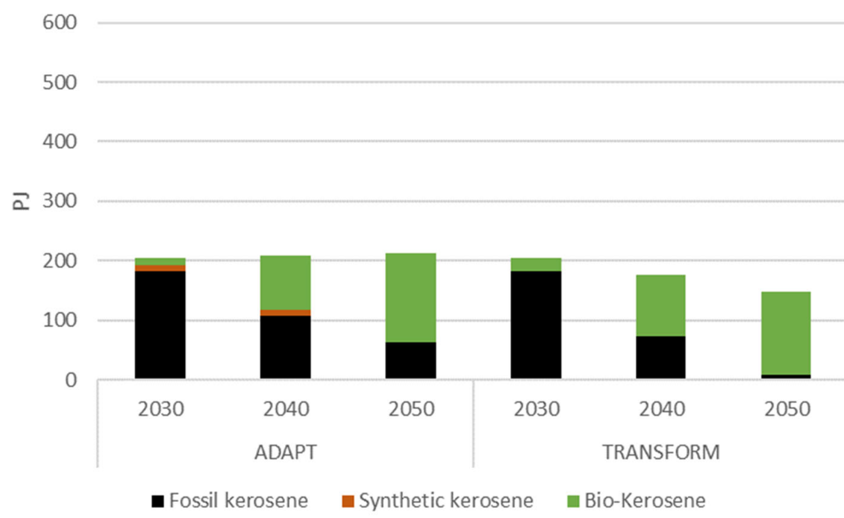

Figure 5.8 Fuel mix in aviation sector according to the ADAPT and TRANSFORM scenarios.

International shipping
Figure 5.9 shows the scenario model results for the international shipping sector. Heavy fuel oil remains the dominant fuel source in 2030, supplying more than 90% of the shipping fuel. In the ADAPT scenario, in which 50% GHG emission reduction requirement is introduced, fossil LNG appears as the dominant low-emission fuel both in 2040 and 2050. As highlighted at the beginning of this chapter, reduced demand in the shipping sector already contributes half of the emission reductions necessary to meet the target. The other half is met with the use of fossil LNG, a fossil energy source with lower carbon emissions compared to heavy fuel oil. Biofuels, including bio-LNG, play a smaller role in meeting the GHG emission reduction target. Fossil LNG appears more cost-competitive compared to renewable fuel supply options, including biofuels, considering the relatively unambitious emission reduction target.

In the TRANSFORM scenario, fossil LNG and synthetic methanol produced from green hydrogen appear as the two main supply options for 2040. Initially, biofuels play a limited role, because of the limited availability of biomass resources and their significant deployment in the aviation sector. Achieving an emission reduction of 95% in 2050, however, results in a significant shift from fossil LNG to bio-LNG. In 2050, more biomass is available through imports and biomass shifts from industrial use to more use in the shipping sector.

The scenarios indicate the supply of alternative fuels as cost-optimal solutions, which require major changes to the existing seagoing vessels. In this scenario modelling, the demand is met by the cost-optimal mix of renewable and low-carbon fuel supply options. The costs of the ships themselves are not included. Any additional costs needed for the fleet changes or adaptations are not taken into consideration. Whether such additional costs may could lead to a different cost-optimal mix has not been studied in this analysis.

As the ship fleet specifications are not included in the modelling, an important issue related to LNG use, possible methane (CH_4) leakage, is ignored. Climate implications of LNG use in shipping have been discussed widely. According to an ICCT (ICCT, 2020) publication, for instance, the maximum life-cycle GHG benefit of LNG is a 15% reduction compared with marine gasoil (MGO), and only if ships use a high-pressure injection dual fuel engine and upstream methane emissions are well controlled. While this analysis is not based on life-cycle emissions, the downstream methane slip from LNG needs to be considered. This was further explored using a scenario variant, discussed in the next section.

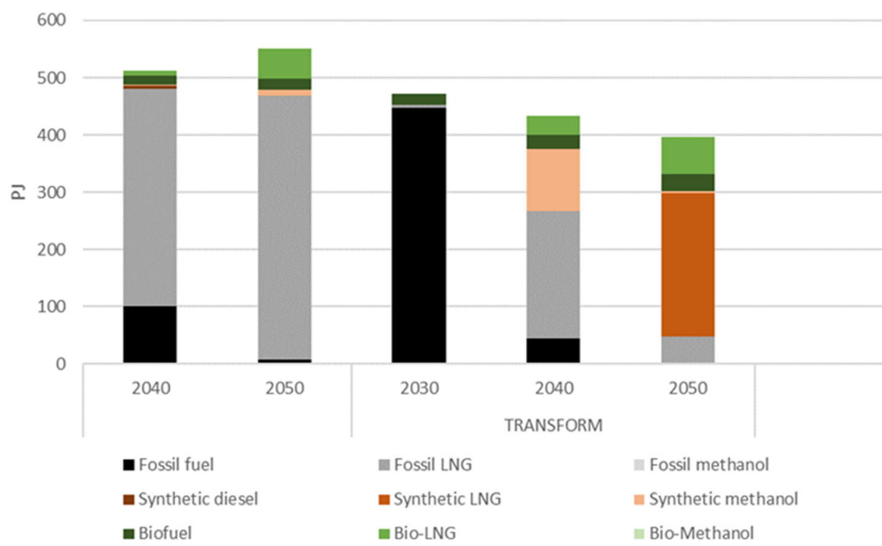

Figure 5.9 Fuel mix in international shipping according to the ADAPT and TRANSFORM scenarios

5.3 Impact of parameter changes on transport fuel mix

5.3.1 Low biomass availability

The potential and the sufficient availability of sustainable biomass resources have been widely discussed. In this study, domestic biomass potentials are based on (Strengers & Elzenga, 2020). Biomass import potential is also built upon the EU biomass potential range in this study. The biomass import potential to the Netherlands is calculated based on the population ratio of the Netherlands to the EU. Since there are many uncertainties about the available import potential for the Netherlands, the effect on the energy system of a more limited import potential in 2050 was investigated in a scenario variant: 50% less solid biomass import in ADAPT and 25% in TRANSFORM.

Figure 5.10 presents the domestic transport fuel mix comparison of this scenario variant (bio low) with the base runs for the two scenarios as described in section 5.2. There is slightly less deployment of biofuels, compared with the baseline in 2050 in ADAPT scenario. This is because around 60% the biomass import potential was utilised in the baseline run. Thus, a 50% reduction of import potential does not cause any major change in the ADAPT scenario.

Biomass restrictions introduced in the TRANSFORM scenario are lower in relative terms, however, the supply potential in the base case was already low and almost fully utilised. A 25% reduction of import potential lowers the biofuel use in domestic transport by around 20%. This is compensated for by increased direct electrification.

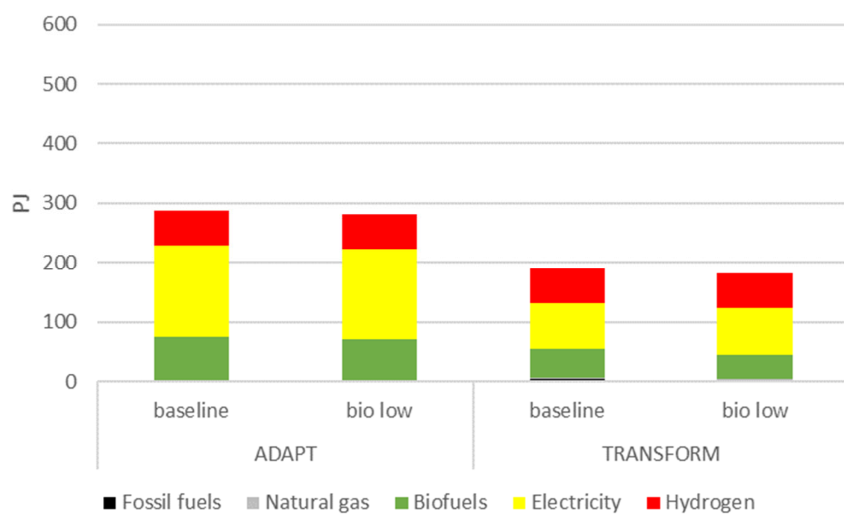

Figure 5.10 Comparison of baseline results on the domestic transport energy use with the low biomass scenario results.

For aviation bunker fuels, the 50% lower solid biomass import potential has a limited effect on biokerosene use in 2050, in the ADAPT scenario. Biokerosene supply is reduced by 10% (15 PJ), but this is not compensated for by an alternative renewable fuel, such as synthetic kerosene. This is because in the base case more GHG emission reductions are achieved than the set 50% emission reduction target. This relates to the multi-product value chain: biomass Fischer Tropsch (FT) synthesis-based kerosene production, where the biogenic CO_2 is captured and the other by-products are used in different sectors. Biomass restrictions in TRANSFORM do not affect the aviation fuel mix in 2050, however there is a direct effect in the bunker fuels for the shipping sector (see Figure 5.12). The fuel mix in shipping does appear to be sensitive to the assumptions around biomass potential, particularly when the emission reduction target is very ambitious and the supply potential is quite limited, as is the case in the TRANSFORM scenario. In 2050, the total biofuels supply to bunker fuels (including bio-LNG, biomethanol and other forms of biofuel) are reduced by almost 50% in the scenario variant with low biomass import potential. In absolute terms, approximately 90 PJ less biofuel appears in the low biomass scenario, compared to the base case in 2050 for TRANSFORM. To compensate for this, synthetic fuels, mainly in the form of LNG, become the most dominant fuel type.

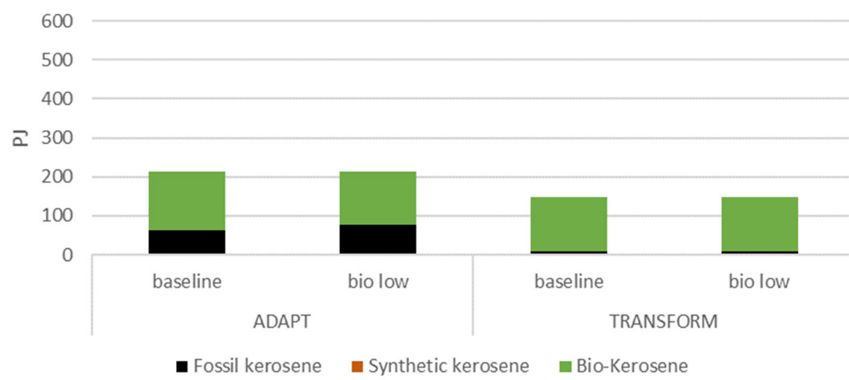

Figure 5.11 Comparison of the aviation sector baseline results with the low biomass case in 2050.

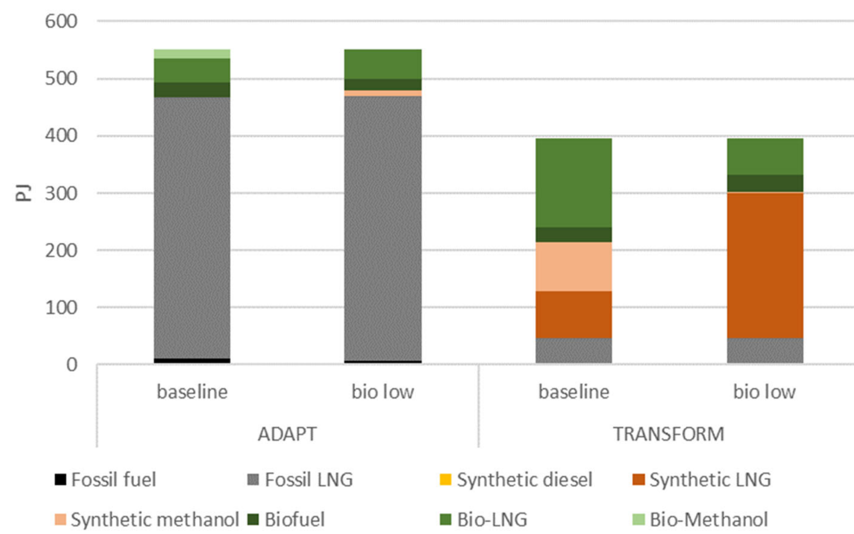

Figure 5.12 Comparison of the shipping bunker fuel mix in the baseline with the low biomass case in 2050.

5.3.2 *Methane slip*

According to the model results, fossil LNG becomes an important transition fuel for the shipping sector. When less stringent GHG emission reduction targets are used in the model, for instance a 50% reduction in emissions (ADAPT scenario), the model favours this low-cost option. As stated in Section 5.2.2, possible methane slip from LNG use can result in unburned methane emissions. This unburned methane arises primarily from incomplete combustion. According to the literature (ICCT, 2020; MARIN, 2021), the methane slip can range between 0.04 and 7 gCH_4/kWh, depending on ship and engine type. The low value relates to a steam turbine, which has limited future in international shipping applications (ICCT, 2020). The high value relates to medium speed, four-stroke low-pressure dual-fuel engines. According to a recent study “Sea shipping emissions 2019: Netherlands Continental Shelf” (MARIN, 2021), the methane slip emission factor is calculated as 6.9 g CH_4/kWh for the medium speed dual-fuel engines and this number is implemented in this scenario variant as additional emission to LNG[24].

Figure 5.13 presents the model results for 2040 and 2050 if methane emissions from ships are considered (CH4Slip), compared to the base case scenario results. LNG use disappears completely from the fuel mix in 2040 and 2050 in both scenarios. This value chain is no longer a viable decarbonisation option for the shipping sector in the long run. This indicates the importance of reducing such slip. Synthetic methanol and biofuels appear as the two renewable fuel supply options in 2040 in both scenarios. In 2050, bio-methanol is also projected to help reduce GHG emissions in the ADAPT scenario. In TRANSFORM, synthetic methanol becomes the largest fuel supply option for the shipping sector in 2050.

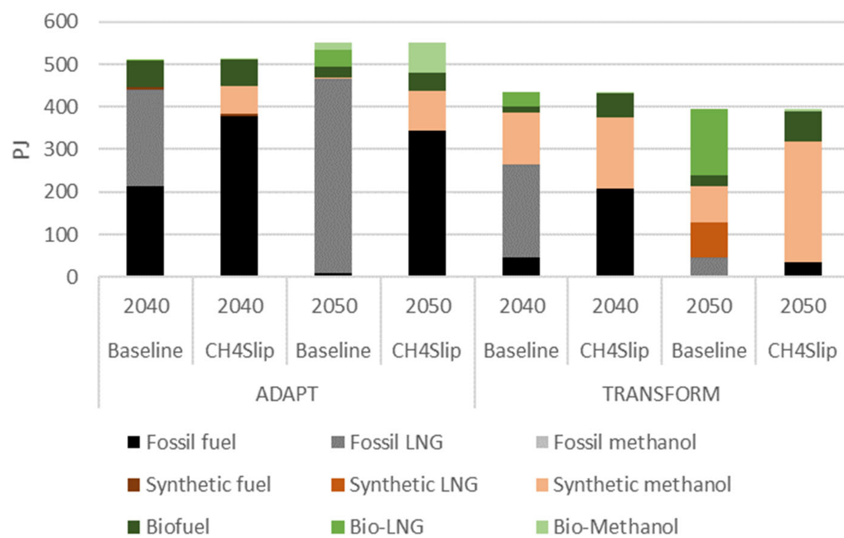

Figure 5.13 Comparison of the base run results with the what if related to methane slip in ships

5.3.3 *Impacts on the total energy system*

In addition to impacting the transport sector, lowering the biomass import potential also affects the entire energy system. In 2050, due to electrification and an increase in synthetic fuel production, hydrogen production in ADAPT is 8% higher compared to the base case and in TRANSFORM the increase is 14%. Electricity production will increase by 4% in 2050 in the ADAPT scenario (mainly from offshore wind), but in the TRANSFORM scenario, electricity production cannot increase further, because the maximum potential for wind, solar and nuclear energy in the base case has already been reached. Additional electricity demand for the production of synthetic fuels leads to a shift in the use of electricity, such as a more efficient use

[24] Another recent study conducted by Spera for the SEA-LNG limited and SGMF, indicates the methane slip is lower; 2-3.98 g/kWh for 4-stroke medium speed engines based on the IMO E2/E3 cycle, and for 2-stroke slow speed engines 0.23-2.14 g/kWh. This study concludes that the tank-to wheel GHG emission reduction for LNG fuels engines is 20% to 30% for 2-stroke slow speed engines and between 11% and 21% for 4-stroke medium speed engines, when compared with CLSFO fuelled engines. See [Study reveals LNG reduces shipping GHG emissions by up to 21% | Port of Rotterdam]

of electricity through the use of heat pumps (using more ambient heat) at the expense of cheaper, direct electric heating.

5.4 Petrochemical industry feedstock use to produce high value chemicals (HVCs)

For the modelling in this study, the HVC production projections of the Dutch petrochemical industry are built upon the KEV 2020 projections[25] up to 2030. For the ADAPT scenario, the growth rates are held constant until 2050. For the TRANSFORM scenario, physical production is kept constant after 2030.

Mechanical and chemical recycling are partially included in this study. A certain share of plastics is assumed to be mechanically recycled and the corresponding amount is subtracted from the total demand of HVCs in this scenario analysis. Chemical recycling via pyrolysis of plastic waste is included explicitly in the modelling. Pyrolysis technology converts waste into pyrolysis oil, which can be upgraded and co-fed with fossil naphtha in steam crackers. It is assumed that the recycled pyrolysis oil can be co-fed to the existing crackers up to 5% of total inputs in 2030, increasing to 10% in 2050 in the ADAPT scenario. In TRANSFORM, this is 15% in 2030, increasing to 30% in 2050.

In the Netherlands, around 33% of all post-consumer plastic waste was recycled in 2019 (PlasticsEurope, 2020) and this waste was treated only via mechanical recycling. Based on this information, it is assumed that the total recycling rate (mechanical and chemical recycling) of plastics increases to 35% by weight in 2030 and 50% in 2050 in the ADAPT scenario. In TRANSFORM, the total recycling rate is assumed to increase to 70% in 2030 and 100% in 2050. While the pyrolysis technology is present in both the ADAPT and TRANSFORM scenarios in 2030, it becomes more relevant in 2050. Therefore, the scenario-specific production volumes are differentiated according to the expected plastic recycling rates for 2030 and 2050.

The pyrolysis process emits direct CO_2 emissions due to the heat demand from the reactor. These emissions are considered fossil-based in the model. However, the use of plastic pyrolysis is promoted via carbon credit, meaning that the model reduces the CO_2 emissions from the steam crackers in the same proportion as the share of naphtha replaced by pyrolysis oil. For instance, if 5% of naphtha is substituted by pyrolysis oil from plastics, the total CO_2 emissions from the HVCs production are considered to be reduced by 5%.

Furthermore, a renewable carbon target is introduced for the TRANSFORM scenario: in 2050, 90% of the carbon content of the HVCs will need to be derived from renewable carbon sources. This can be from biomass or captured CO_2. Table 5.1 introduces the main scenario assumptions and Table 5.2 provides the main input data used in the model.

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[25] Based on the index from KEV and the production volumes for the high value chemicals in the Netherlands in 2017 (Oliveira & Van Dril, 2021), the future production volumes are estimated for 2030 and 2050.

Table 5.1 Main assumptions regarding the recycling rates (as share of total plastics in the Netherlands) and the renewable carbon targets used for the scenario modelling.

ADAPT			
Year	Mechanical recycling	Chemical recycling	Renewable carbon content of HVCs
2030	17%	18%	0%
2050	10%	40%	0%
TRANSFORM			
Year	Mechanical recycling	Chemical recycling	Renewable carbon content of HVCs
2030	34%	36%	5%
2050	20%	80%	90%

Table 5.2 Total HVC production volumes including recycling replacement in the ADAPT and TRANSFORM scenarios.

ADAPT					
Year	Origin of raw material	Ethylene (kt/yr)	Propylene (kt/yr)	Butadienes (kt/yr)	Benzene* (kt/yr)
2030	Virgin raw materials	4387	2623	446	1783
	Mechanical recycling	70	51	0	0
	Chemical recycling	60	36	6	24
2050	Virgin raw materials	4657	2787	471	1884
	Mechanical recycling	53	38	0	0
	Chemical recycling	169	101	17	68
TRANSFORM					
Year	Origin of raw material	Ethylene (kt/yr)	Propylene (kt/yr)	Butadienes (kt/yr)	Benzene* (kt/yr)
2030	Virgin raw materials	3785	2253	393	1570
	Mechanical recycling	141	102	0	0
	Chemical recycling	119	72	12	48
2050	Virgin raw materials	3602	2148	371	1483
	Mechanical recycling	105	77	0	0
	Chemical recycling	338	202.6	33.8	135.1

*from steam crackers

5.4.1 *Renewable feedstock supply to produce HVCs*

Figure 5.14 presents the ethylene production according to the different scenarios. This figure also illustrates the resource origin of ethylene production. The ethylene production volume is presented as a proxy that represents HVCs. Therefore, 1 tonne of ethylene production represents also 0.6 tonne of propylene, 0.1 tonne of butadiene and 0.4 tonne of aromatics. Figure 5.15 shows the total energy and feedstock used to produce HVCs, including energy use in the HVC production process.

Fossil naphtha remains the main feedstock in steam crackers in the ADAPT scenario. Bio-naphtha has a limited role because in the base scenario only domestically produced bio-naphtha can be used. Since bio-naphtha is the by-product of the biorefineries producing biofuels for transport, namely biofuel production via FT synthesis and the HVO[26] production process, its availability is limited by the amount of such biofuels.

The TRANSFORM scenario shows a substantial process shift from conventional steam cracking to the methanol-to-olefins (MTO) process using synthetic methanol. This choice results from a number of factors. First, biomass resources, both domestic and imported, are limited in this scenario and they are almost fully utilised in other sectors. According to the model results, they are used to meet the GHG emission reduction targets in transport, particularly in the aviation and international shipping sectors. The by-product bio-naphtha is the only bio-based fuel used as feedstock in the chemical industry. This is due to higher efficiency in biofuel production, when compared with the production of light olefins. In addition, no credits are given to the embodied biogenic carbon in the products. There is an ongoing discussion on the accounting of biogenic carbon in products in GHG accounting methods. The climate change mitigation potential of such products depends heavily on the lifespan of the product and what happens at the end-of-life. The results of this study may appear to conflict with the cascading use of biomass resources, where biomass combustion is seen as one of the last options to consider. Note that in the modelling a large share of the CO_2 used to produce synthetic methanol is from biogenic sources. Similar to bio-naphtha, biogenic CO_2 captured from the biofuel production processes, particularly gasification and FT synthesis, is used to produce synthetic methanol. As such, some part of the biogenic CO_2 is circulated in this system. A second reason for the shift to methanol-based olefins is the limited CCS potential in TRANSFORM scenario. Due to the limited availability of biomass and CCS, synthetic methanol with CO_2 direct air capture (DAC) and biogenic CO_2 remain the only viable options to achieve zero-emissions in the chemical industry.

Plastic recycling contributes around 2-4% of the total ethylene production in the two scenarios. Final use of pyrolysis oil appears to be small in both scenarios, nevertheless, they require large amounts of waste plastics. The plastic waste supply in the model is determined based on future projections that indicate plastic waste volumes reaching approximately 1.6 Mt in 2050 in the Netherlands (Wijngaard, et al., 2020). In 2017, this value was around 0.9 Mt. The plastic waste availability in 2030 is assumed to be around 1.3 Mt, which is based on interpolation between 2017 and 2050.

[26] Hydrotreated Vegetable Oils

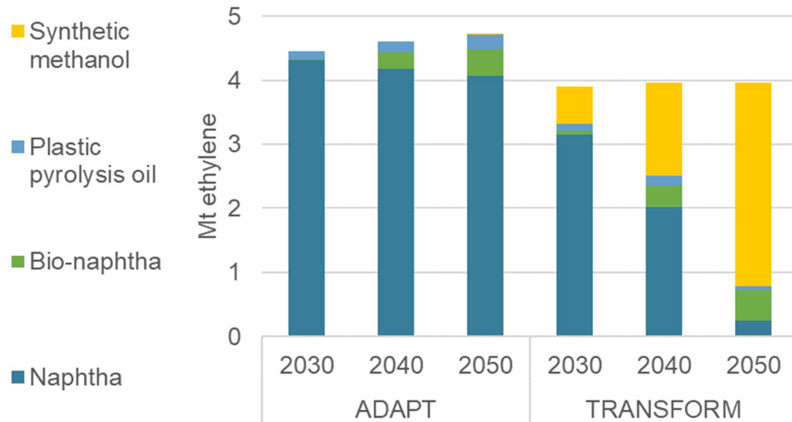

Figure 5.14 Ethylene production according to the two scenarios.

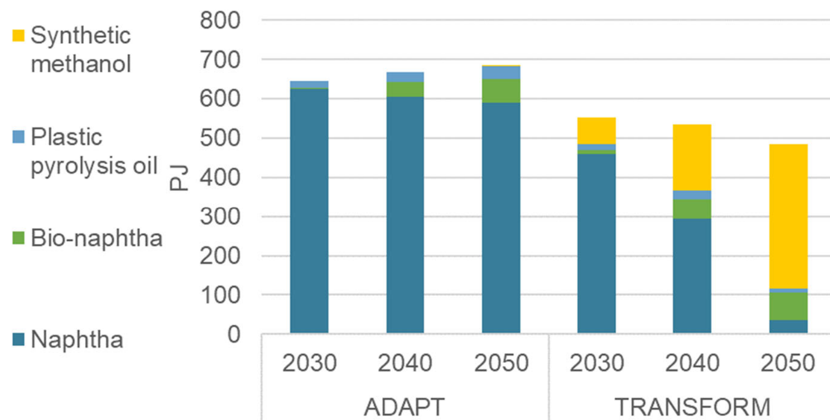

Figure 5.15 Total energy and feedstock use to produce HVCs.

5.5 Impact of parameter changes on HVC production

5.5.1 Biomass availability and bio-naphtha import

Model results indicate a limited role for direct use of biomass as feedstock. Fossil feedstocks continue to be used in the ADAPT scenario because there is no target for renewable feedstocks. In the TRANSFORM scenario, where such a target does apply, this relates, among other factors, to the limited availability of biomass resources, large demand from other sectors, particularly aviation and shipping, and the lower conversion efficiencies when compared with energy applications. Two scenario variants are implemented to analyse the effects of biomass availability on the feedstock demand. One of them looks at a case where biomass supply is even more limited than in the base case. In this case, solid biomass import potential is lowered by 50% in ADAPT and 25% in TRANSFORM in 2050. This case is also described in section 5.3. In this variant, limited availability of biomass consequently limits the availability of biogenic CO_2, which is one of the main carbon sources for the synthetic MTO process. The other variant looks at a case where availability of biomass, in the form of bio-naphtha, is larger than in the base case. In this second case, bio-naphtha imports are introduced.

Bio-naphtha is one of the by-products of the biorefineries, and therefore, their supply potential depends on the demand for advanced biofuels. Bio-naphtha is emerging as a tradable commodity. According to industry sources, there have been some spot bio-naphtha trades in Northwest Europe. In 2019, about 0.3% of the total consumption of naphtha in Europe was from bio-naphtha (Nova Institute[27]) – which corresponds to around 100-150 kt – and demand for bio-naphtha is expected to grow in the future. For the purpose of this scenario variant, bio-naphtha import potentials are estimated using the sustainable aviation fuel targets introduced in the draft proposal ReFuel Aviation Initiative (COM/2021/561 final, 2021). The total bio-naphtha production potential in Europe is calculated on the basis of the sustainable aviation fuel targets proposed in this document. In the variant, around 50% of this potential is assumed to be available for the Dutch petrochemical industry, with an indicative price of 21.5 €/GJ (865 €/tonne[28]). Table 5.3 specifies the assumption about the bio-naphtha import potential in the Netherlands.

Table 5.3 Bio-naphtha import potential in the Netherlands according to the ADAPT and TRANSFORM scenarios.

	ADAPT			TRANSFORM*		
	2030	2040	2050	2030	2040	2050
Bio-naphtha (PJ)	0	45	60	0	70	150

*In TRANSFORM the bio-naphta can be higher than in ADAPT because more aviation fuels will be produced in the EU.

Figure 5.16 illustrates the results of the two scenario variants in comparison to the base case scenarios for 2040 and 2050. Results show that restrictions on raw biomass availability result in a slight reduction in bio-naphtha use in 2050, in both scenarios. However, limiting solid biomass import potential results in increased use of DAC to compensate for reduced bioenergy capture and storage (BECCS) that created negative emissions and to compensate for the reduced availability of biogenic CO_2. Thus, in this scenario variant, CO_2 for methanol via DAC increases from 33% of the total CO_2 used for methanol synthesis to 50%, when compared with the base case scenario. In the TRANSFORM scenario, bio-naphtha import potentials are fully used both in 2040 and 2050, as bio-naphtha blending in existing steam crackers appears more cost-competitive compared to HVC production from synthetic methanol.

[27] PowerPoint-Präsentation (bioproductscentre.com)

[28] Based on (S&P Global Platts, 2021), 1000$/ton is used as the indicative import price. This is converted to €/ton.

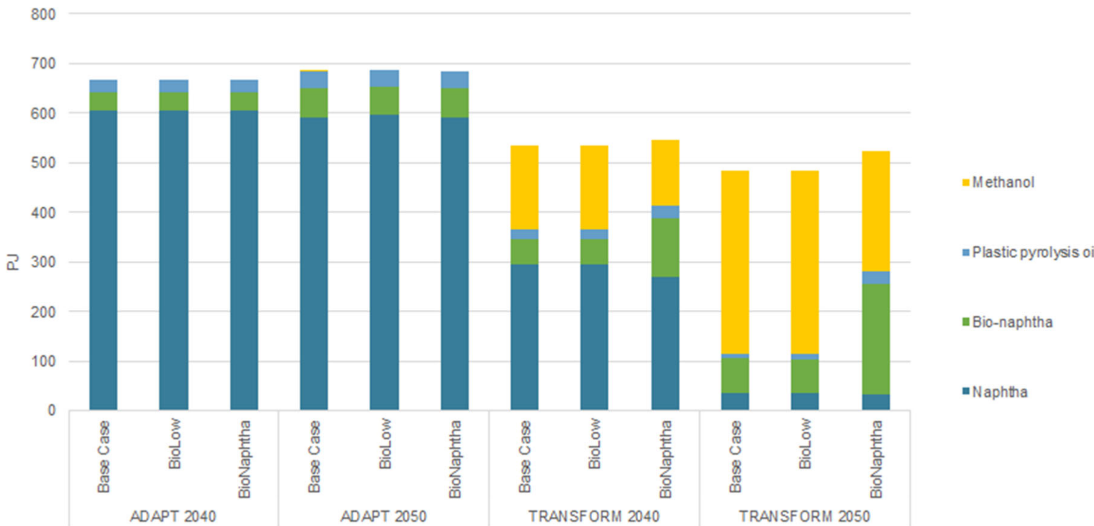

Figure 5.16 Feedstock use for HVCs production in case biomass availability is reduced and in case bio-naphtha imports are introduced compared to the base case of the ADAPT and TRANSFORM scenarios.

5.5.2 *Plastic recycling*

The base case results indicate a very limited role for chemical recycling of plastics and their use in HVCs production. The estimations of mixed plastic wastes used in the base case scenarios were low due to the limited availability of mixed plastic wastes in the Netherlands in 2050. In the scenario variant, the availability of mixed plastic waste is assumed to be 3 times larger in TRANSFORM and increased by 80% in the ADAPT scenario in 2050[29], as compared to the base runs. This implies that plastic waste imports from abroad are considered in this scenario variant. Table 5.4 shows the total volumes considered for each scenario. Figure 5.17 illustrates the scenario variant results (PlastWaste) in comparison with the base case for 2040 and 2050 for both scenarios. Results clearly show that plastic recycling via pyrolysis is a low-cost feedstock substitution option and when there is sufficient supply, it can easily be processed in steam crackers, replacing a certain amount of naphtha from virgin fossil resources.

Table 5.4 Plastic waste availability for both scenarios in the what-if plastic recycling.

Scenario	Plastic waste generated in the Netherlands in 2050 (kt/y) (base case)	Plastic waste imported (kt/y)	Total plastic waste availability (kt/y)
ADAPT	1640	1376	3016
TRANSFORM	1640	4863	6503

[29] The amount of extra plastic waste needed was based on the target of 10% of the total ethylene production coming from pyrolysis oil in ADAPT (2050) and 30% for TRANSFORM (2050).

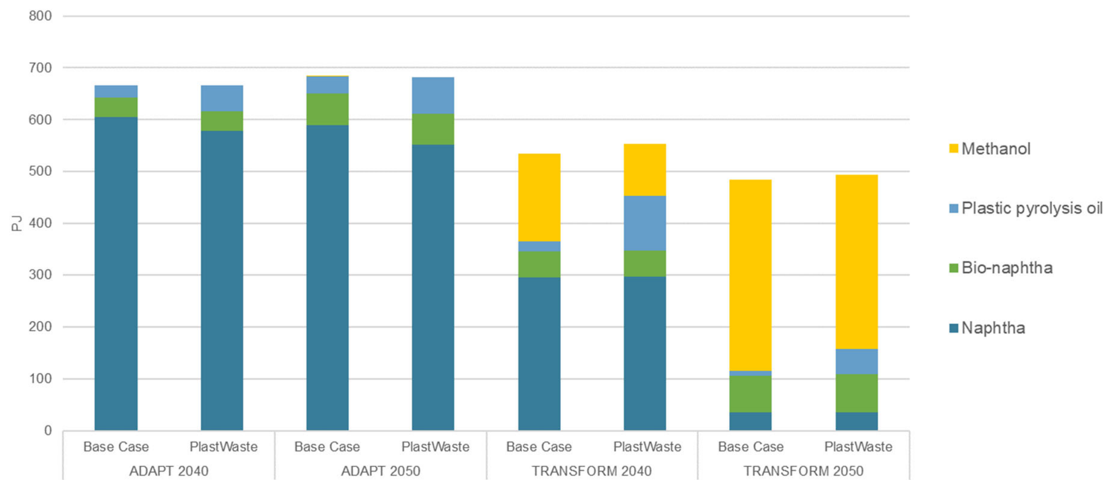

Figure 5.17 Feedstock use for HVCs production in case plastic recycling is increased compared to base case ADAPT and TRANSFORM scenarios.

5.5.3 *Impacts on the total energy system*

In both scenarios, expanding the import options for renewable feedstocks (i.e. bio-naphtha and plastic waste) only results in marginal changes in the demand for electricity and hydrogen in the total energy system. Relatively speaking, bio-naphtha imports have the greatest effect on the hydrogen demand in the TRANSFORM scenario, reducing it by 2% compared to the base case scenario. It is remarkable that in the two variants of this scenario the methanol production does not fall, but the methanol use shifts to fuel use for maritime shipping: the methanol use by international shipping increases by more than a factor of two with bio-naphtha imports and with plastic waste imports a factor of two and a half.

Hydrogen imports do not significantly change the use of methanol for the production of HVC, but, in the TRANSFORM scenario, do lead to higher methanol use in international shipping. More CO_2 is needed for this extra production of synthetic methanol. Since the biomass potential is already fully exploited in the TRANSFORM scenario, this is obtained with more CO_2 capture from the air. In the TRANSFORM scenario, limiting the maximum available biomass import also leads to more CO_2 capture from the air. This is necessary on the one hand to compensate for the lower availability of biogenic CO_2 for the production of HVCs and on the other hand because of less biogenic CO_2 storage (BECCS) to achieve negative emissions.

Although not further explored in this study, biofuel imports are expected to have also a significant effect on HVC production. Since bio-naphtha is a by-product of bio-refining, less bio-naphtha would be available, which would lead to reduced use of recycled plastics especially in TRANSFORM due to the ratio between pyrolysis oil and naphtha. For the production of synthetic methanol, the import of biofuels also means less availability of biogenic CO_2, which must be compensated by more CO_2 capture from the air.

6 Heat supply for industry, built environment and agriculture sector

This chapter takes a closer look at the heat supply for industry, the built environment and the agricultural sector. The industrial heat demand is divided into different temperature levels. How this industrial heat demand is met by different heat supply options is discussed in Section 6.1. In Section 6.2 and 6.3 first the total energy demand of the built environment and the agricultural sector is discussed, followed by discussion of the heat supply for both sectors. Heat supply through heat networks is one of the options to meet the heat demand of the built environment and agricultural sector. Section 6.4 discusses the position of heat networks in the scenarios. In order to investigate the robustness of the results with regard to the heat supply, some parameters in the scenarios have been changed. The effect of these changes on the scenario outcomes are also discussed in this chapter.

6.1 Industrial heat demand and supply

For the heat demand in industry, a distinction is made for heat supply into four different temperature levels: <100 ºC, 100-200 ºC, 200-400 ºC and >400 ºC. In addition, for the third level (200-400 ºC) a distinction is also made between steam and direct firing. For industrial processes only the net external heat demand that must be supplied by utilities is considered, i.e. heat that is supplied by combustion of reagents in a process is not considered (intrinsic heat). This applies, for example, to steel production using coal, production of high-value chemicals using naphtha or fertiliser production using natural gas. Furthermore, any surplus heat produced by industrial processes is assumed to be <100 ºC.

In both scenarios, the total external heat demand decreases in 2040 (see Figure 6.1). This decrease continues in 2050 for the ADAPT scenario, but in TRANSFORM the total external heat demand increases slightly in 2050. The decrease in the external energy demand in the ADAPT scenario mainly occurs with the demand for high temperature steam (200-400 ºC). Figure 6.2 shows that this applies especially to refineries and steel production where conventional processes disappear (refineries) or get replaced by modernised versions (steel). In TRANSFORM, there is an increase in 100-200°C heat demand due to the shift in the manufacturing of high value chemicals by the conventional naphtha-based process to the methanol-based route.

Figure 6.3 shows how the external industrial heat demand is covered. Between 2030 and 2050, the use of natural gas decreases and that of electricity increases in both scenarios. In the ADAPT scenario, biomass and residual gases remain important energy sources for heat production in 2050, followed by geothermal energy, hydrogen and ambient heat (for heat pumps). In 2050, biomass and residual gases are hardly used for heat production in TRANSFORM. Biomass is used almost entirely for the production of chemicals and transport fuels, and residual gases are used for the production of electricity. Ambient heat is an important heat source in the TRANSFORM scenario in 2050. The ambient heat is produced at temperature levels < 100°C and then upgraded by a second heat pump to the temperature level 100-200°C.

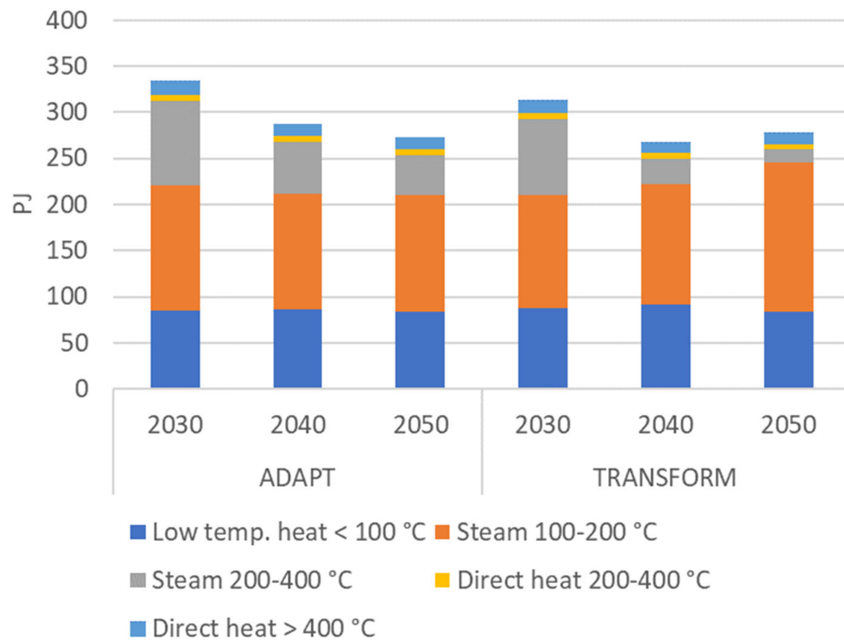

Figure 6.1 Total external heat demand for industry in the ADAPT and TRANSFORM scenarios.

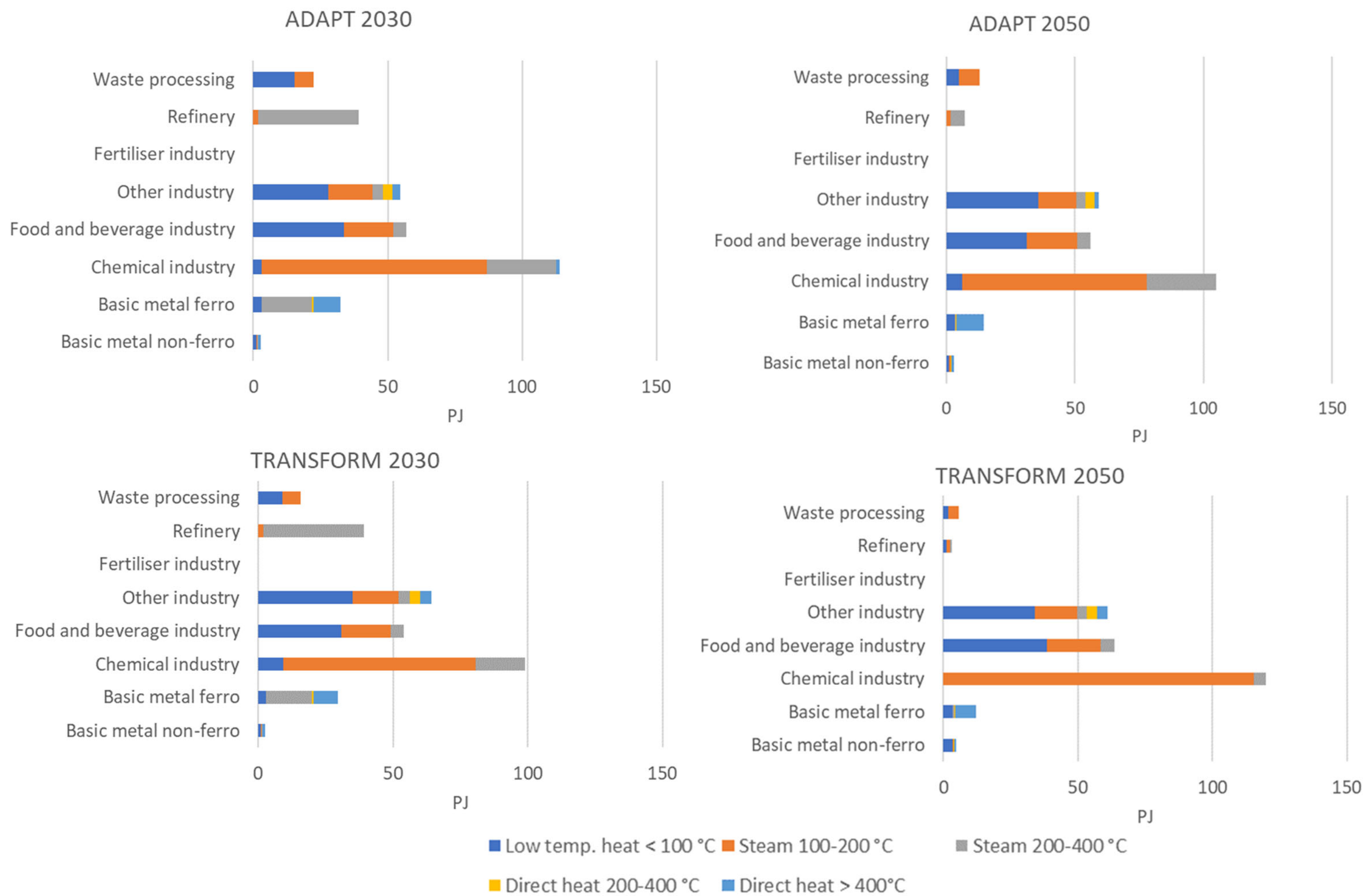

Figure 6.2 External heat demand for different industrial subsectors in the ADAPT and TRANSFORM scenarios by temperature level.

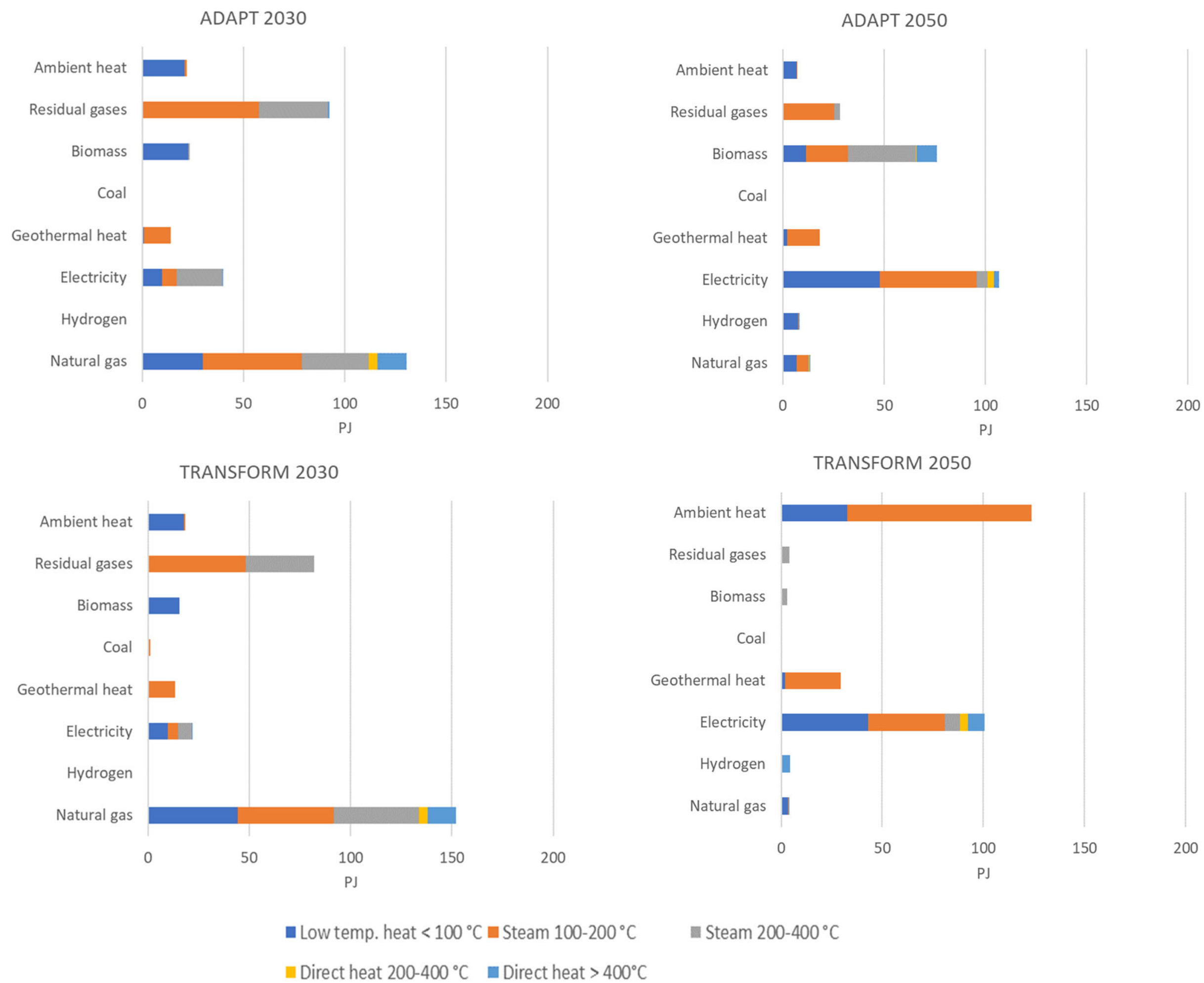

Figure 6.3 Energy supply for external heat in different industrial subsectors in the ADAPT and TRANSFORM scenarios by temperature level.

6.2 Energy demand and heat supply in the built environment

Except for some segments in the services sector (e.g. office buildings) in the TRANSFORM scenario, the number of buildings and floor area of the built environment is the same in both scenarios (see Table 3.5). Figure 6.4 shows the energy mix of the total energy consumption, i.e. heat demand and electricity for non-heat applications. This graph does not show the electricity demand for charging electric vehicles, since this is part of the transport sector and reported in Chapter 5. The electricity demand of the built environment is partly covered by local electricity production with solar panels. This share increases in the ADAPT scenario from 24% in 2030 to 39% in 2050 and in TRANSFORM from 37% in 2030 to 72% in 2050.

Just over 60% of the energy demand in the built environment concerns heat demand. This share is fairly equal for both scenarios and the different years. Figure 6.5 shows for both scenarios how the heat demand is met with different heat options. The use of gas in the built environment decreases in both scenarios: in the TRANSFORM scenario to almost nil (<10 PJ) and in ADAPT to about 150 PJ in 2050; half of this is natural gas, the other half is green gas (biogas and hydrogen). The heat supply in the built environment mainly switches to electric boilers and heat pumps in both scenarios. The latter is evidenced by the increase in the use of ambient heat that heat pumps use as a primary energy source. In the TRANSFORM scenario, this form of heat supply grows more strongly than in ADAPT. Application of hydrogen in the TRANSFORM scenario is limited to 5 PJ in 2050, although in some scenario variants this increases, i.e. when hydrogen is imported (95 PJ), when it is not needed in the chemical industry (bio-naphtha import variant 75 PJ) or when extra nuclear energy is available (57 PJ). In the ADAPT scenario, about 50 PJ hydrogen is used in the built environment, and this number is constant for all variants except when biomass imports are reduced, in which case it increases to 63 PJ. In both ADAPT and TRANSFORM a limited part of the heat demand is covered by heat networks. Solar heat is also used in both scenarios.

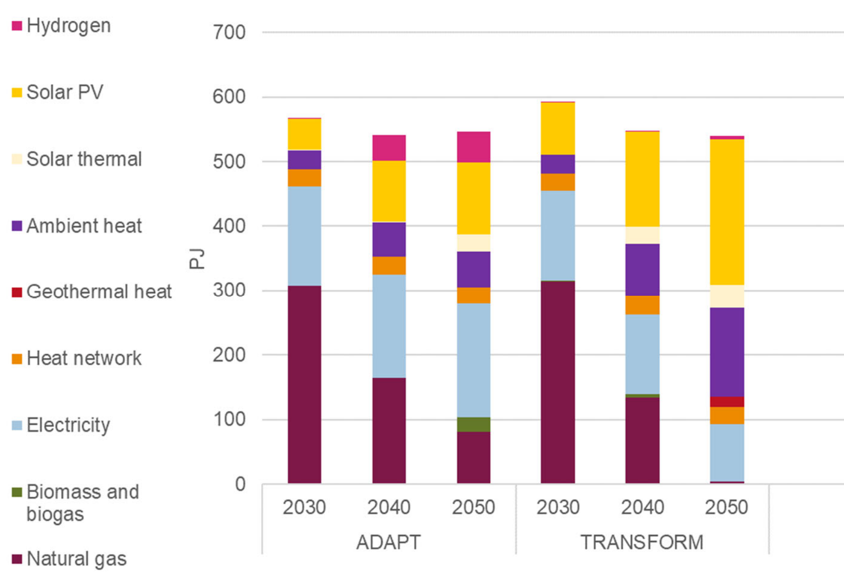

Figure 6.4 Energy consumption in the built environment in the ADAPT and TRANSFORM scenarios

Figure 6.5 Heat supply in the built environment in the ADAPT and TRANSFORM scenarios (see Section 6.4 for heat supply to heat networks)

6.3 Energy demand and heat supply in the agriculture sector

Figure 6.6 shows the total energy demand of the agricultural sector for both scenarios. The heat demand of the agriculture sector is lower in the TRANSFORM than in the ADAPT scenario and the electricity demand higher as a result of the assumed difference in consumption behavior (see Table 3.5). The electricity demand of agriculture is partially covered by local electricity production with solar panels. This share is in the ADAPT scenario 39% in 2030 and 2050. In the TRANSFORM scenario, local electricity production with solar PV is smaller in 2030 compared to ADAPT, but increases significantly to such an extent that by 2050 70 PJ (net) of the 120 PJ electricity produced by solar PV in this sector is delivered to other sectors.

The heat demand in the agricultural sector comes mainly from greenhouse horticulture. In ADAPT, 65% of the energy demand consists of heat demand. This ratio remains constant in this scenario. In TRANSFORM, a smaller greenhouse horticulture sector is assumed, so that the heat demand in 2030 is 56% of the total energy demand and in 2050 this decreases to 43%. The total heat demand of the agriculture sector decreases in both scenarios. Natural gas used for heating greenhouses is replaced by geothermal energy, biogas and biomass. In the ADAPT scenario, heat is also obtained from heat networks; also in TRANSFORM in 2030, but in 2040 and 2050 this is negligible. In the TRANSFORM scenario in 2050, heat pumps are used with ambient heat as a heat source.

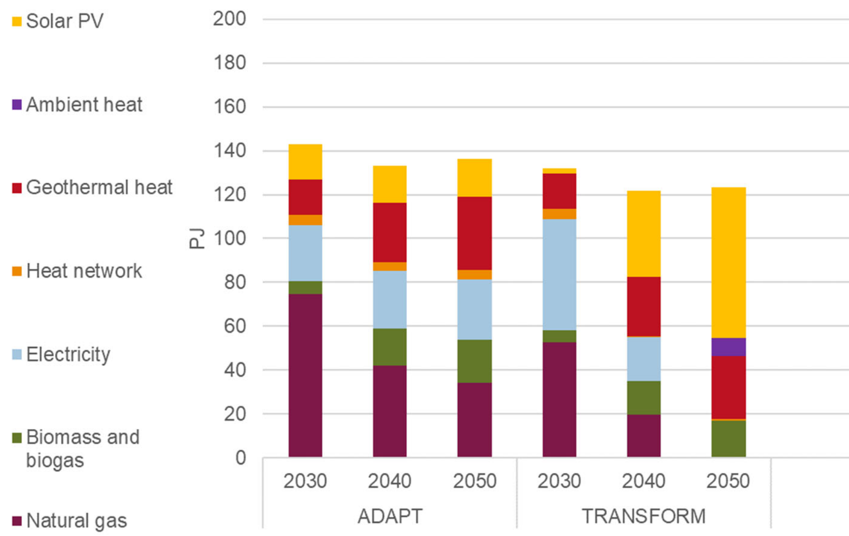

Figure 6.6 Energy consumption in the agriculture sector in the ADAPT and TRANSFORM scenarios. In TRANSFORM 2050 the solar PV production is 122 PJ, i.e. 53 PJ is exported by the agriculture sector and not shown in this graph.

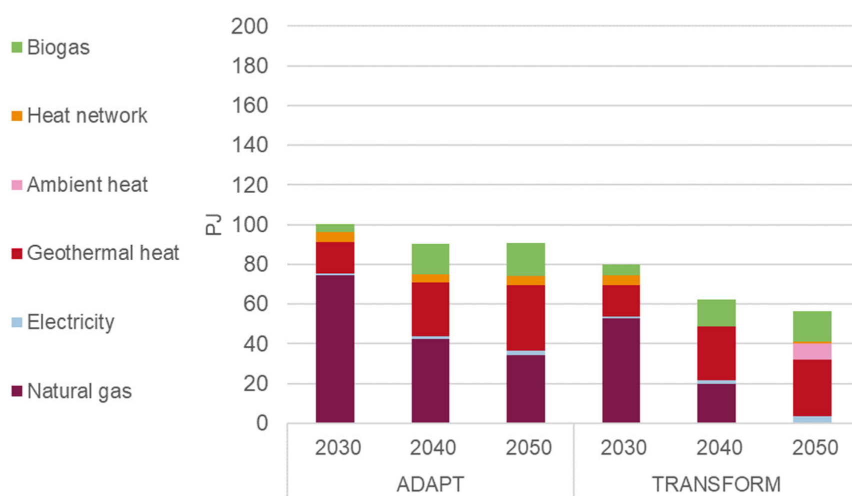

Figure 6.7 Heat supply for the agriculture sector in the ADAPT and TRANSFORM scenarios.

6.4 Heat supply to heat networks

Parts of the built environment and agriculture sectors are also supplied with heat from heat networks. The heat supply for these heat networks is shown in Figure 6.8. Compared to 2019, the heat supply via heat networks doubles in 2030 in both scenarios. After that, the heat networks are not expanded further and the heat supply even decreases slightly, both for the built environment and the horticulture greenhouses. Besides dedicated biomass plants, most of the heat is supplied currently by coal-fired power stations (with biomass co-firing), natural gas power stations and waste incineration plants. According to the scenario's, the energy mix changes in 2030 to heat supply from biomass, waste incineration and residual heat from industry. In 2030, some heat is also generated with electric boilers and, in the ADAPT scenario, supplied from geothermal wells. In 2050, biomass disappears from the energy mix in both scenarios, because other heat supply options become more attractive (in ADAPT) and biomass is used for production of transport fuels and chemicals (in TRANSFORM, see Chapter 5).

In 2050, geothermal heat increases in the ADAPT scenario and also appears in TRANSFORM. Furthermore, new forms of heat generation appear: hydrogen boilers in ADAPT and solar thermal in TRANSFORM. In the ADAPT scenario heat supply from electric boilers increases. In both scenarios, the amount of residual heat supplied to heat networks decreases between 2040 and 2050. This decline can only be compensated for to a limited extent by other sustainable heat sources. In the ADAPT scenario, this is done by geothermal energy and electric boilers. In the TRANSFORM scenario, less electricity is available for heat production since a large amount of electricity is needed in industry for production of chemicals and fuels. The heat supply from waste incineration shows a decline because less waste is incinerated and carbon capture is applied at the incinerator, which reduces the residual heat.

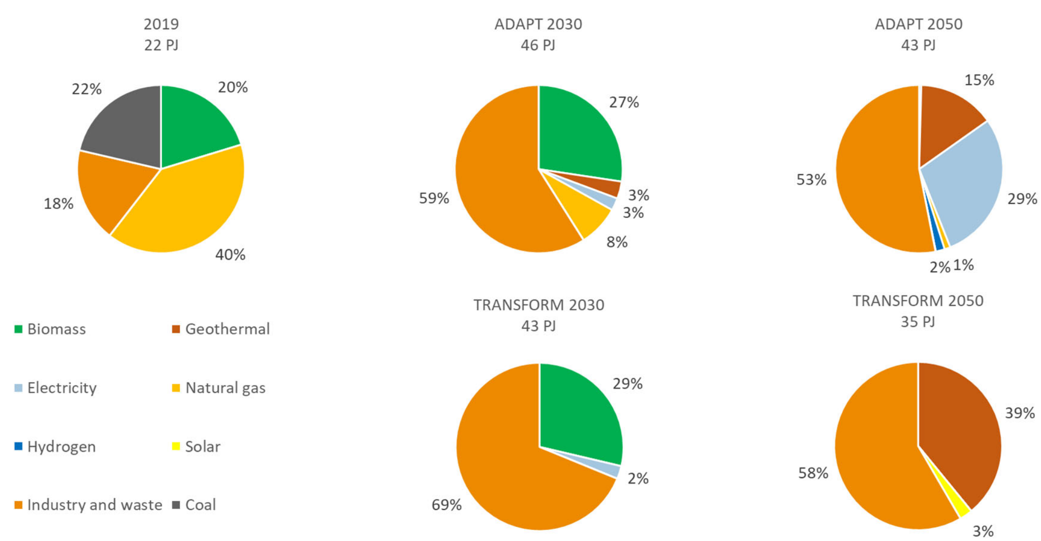

Figure 6.8 Heat production and energy mix for heat networks for 2019 (CBS, 2021) and the ADAPT and TRANSFORM scenarios

Effect of lower costs and better performance

The sensitivity to assumed techno-economic parameters of heat networks and geothermal energy has been investigated in a scenario variant. In this scenario variant, the investment costs for heat networks have been reduced by 30% and it is assumed that the heat losses are 20% instead of 25% as in the base case (e g. heat distribution systems with low-temperature heat). In addition, in the scenario variant, the investment costs for geothermal energy have been reduced by 20%.The effect of these parameter changes is small for the ADAPT scenario (see Figure 6.9). The contribution of heat networks to the heat supply of the built environment does not change and a small increase can be seen for the agricultural sector. Due to the smaller heat losses, the total heat supply decreases. The same effect can be seen in the TRANSFORM scenario in 2030 (and also in 2040, but not shown in Figure 6.9). However, in 2050, the heat supply to the built environment and the agricultural sector increases by 75%. This increase can be attributed to a greater heat production from geothermal wells.

Geothermal energy is also applied to supply heat to industrial processes. Reducing investment costs for geothermal energy does not significantly change the use of geothermal energy in industry in either scenario.

Residual heat supply
In both scenarios, residual heat from industry, waste processing and electricity generation is supplied to heat networks (see Figure 6.10). The heat supply in 2030 is greater in the TRANSFORM scenario than in ADAPT, but in 2050 the heat supply to heat networks is approximately the same. Residual heat is supplied from waste processing and the chemical industry in both scenarios, both in 2030 and 2050, but for reasons explained above the contribution from the waste sector is much reduced in 2050. Residual heat from electricity generation (i.e. cogeneration) only contributes in 2030 and then disappears because the use of natural gas for electricity production is strongly reduced (ADAPT) or disappears completely (TRANSFORM). The residual heat supplied from other industry sectors differs per scenario. In ADAPT, heat is also supplied to the heat networks from the fertiliser industry, the food and beverage industry (both in 2030) and other industry (only in 2050). In the TRANSFORM scenario, in addition to the chemical industry, the food and beverage and basic metals sectors account for a large share of the residual heat supply to the heat networks in 2050. This not only involves residual heat from processes but also from residual capacity of utilities in those industries. The shift between the industrial sectors is related to the availability of residual heat, and the possibilities to use this heat within the industry itself.

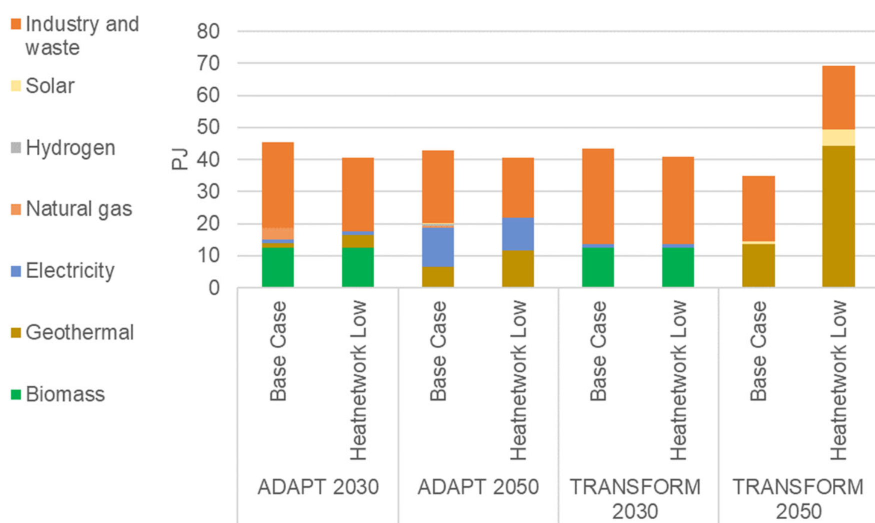

Figure 6.9 Heat supply to heat networks in the base scenarios and a scenario variant with changed techno-economic parameters for heat networks and geothermal energy.

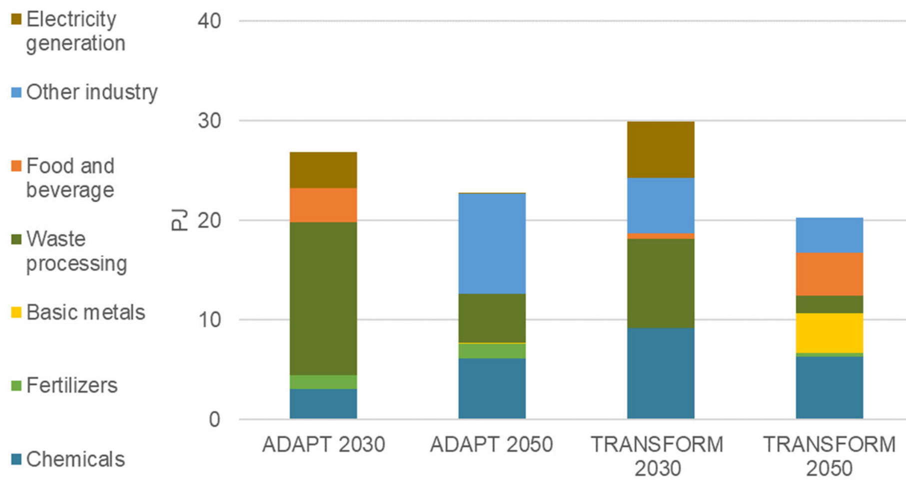

Figure 6.10 Residual heat supply from industry, waste processing and electricity generation to the heat networks for the ADAPT and TRANSFORM scenarios.

7 Key observations and conclusions

This new scenario study is an update of a previously published scenario study by TNO (Scheepers, Faaij, & Van den Brink, White paper, 2020), (Scheepers, et al., 2020). As in the previous study, the two scenarios ADAPT and TRANSFORM form the basis of the analyses. The update relates to new GHG reduction targets, updates of techno-economic parameters, updates of projections for energy demand and industrial production, model adjustments to industrial sectors and processes and an additional target for sustainable carbon in the production of chemicals and plastics.

Text Box B summarizes the main differences in results of the new scenario study compared to the previous one. In this text box, the results for ADAPT and TRANSFORM of this study are also compared with the results of the II3050 study, a scenario study for the Dutch energy system in 2050.

In this new study, extra focus has been placed on the industrial processes for producing chemicals and transport fuels. For both scenarios, the impact on the energy system of Dutch industrial production that meets the full demand for chemicals and transport fuels (i.e. without the import of semi-finished products or import of transport fuels) was examined. A larger potential for biomass import is assumed than in the previous study, but for the TRANSFORM scenario this is still more limited than in ADAPT. While in the ADAPT scenario fossil feedstocks can still be used for chemical production, in the updated TRANSFORM scenario chemicals are produced from sustainable and recycled feedstocks.

This study has also analysed the heat supply from industry and the residual heat supply from industry to the built environment and agricultural sector in more detail. In order to analyse the production of chemicals and transport fuels and the heat supply, the representation of industrial processes in the energy system model OPERA has been modified and updated, including the addition of new technical pathways.

7.1 General observations

Tightening the GHG reduction targets and changes in industry affect other sectors, in particular the electricity production, the demand for various transport fuels (both domestic and international transport) and the supply of heat to the built environment and agricultural sector. This study shows that in both scenarios the Dutch energy system can meet the energy demand of all sectors and feedstock demand of the industrial sector while achieving net zero GHG emissions. This will require significant amount of (renewable) electricity (including import/export with neighbouring countries) and biomass import. Since no other imports are considered (e.g. biofuels, hydrogen bio-naphtha, methanol), the scenarios assume de facto a future in which the international prices for semi-manufactured products (or energy carriers) are higher than the costs of production in the Netherlands. This assumption was made for this study to assess how limitations in biomass availability can affect the total Dutch energy system compared to the other sustainable supply options available to the Netherlands (e.g. wind energy). However, it is likely that at least some of these semi-finished products and energy carriers could be imported at prices below the Dutch production costs. This would reduce the effort for the Dutch energy system to reduce the GHG emissions.

New insights for the TRANSFORM scenario
Compared with the previous study, most of the new insights in this scenario study arise from the TRANSFORM scenario:

- Realising GHG neutrality in 2050 proved impossible without the use of CO_2 storage. For that reason, limited application (max. 15 Mt) of CO_2 capture and storage (CCS) was allowed in the TRANSFORM scenario, a deviation from the previous study where this option was excluded in TRANSFORM. CO_2 storage is used to realise negative emissions from biomass and CO_2 air capture to offset non-CO_2 and LULUCF emissions.
- In the new TRANSFORM scenario, electricity demand has increased by 43% compared to the previous study. The increase can mainly be attributed to a significantly higher hydrogen demand. Electricity production from wind and solar reaches the maximum potentials in 2050.
- In the new TRANSFORM scenario, in addition to electricity from wind and solar, 5 GW of nuclear energy is used. If no nuclear power stations are used in TRANSFORM (because they are too expensive or socially undesirable), it is still possible to cover the energy demand and to achieve the objective of a GHG neutral energy system. This does not lead to more electricity production, but is compensated for by more renewable heat sources (ambient heat and geothermal energy) and more efficient use of electricity (e.g. more heat pumps, less hydrogen production). In the base scenario, nuclear energy is used to supply base load electricity. In the no-nuclear variant this base load production is absent and the demand for flexibility increases. The extra flexibility is provided by more electricity and hydrogen storage. In the previous scenario study no nuclear power was deployed because of a less ambitious GHG reduction target in 2050 (95%) and lower electricity demand.
- In new the TRANSFORM scenario, there is much higher demand for hydrogen than in the previous study. In 2050, hydrogen is produced entirely from electricity. The high hydrogen demand is the result of the increased demand for synthetic methanol to be used as transport fuel and for production of chemicals. The conventional route of HVC production from naphtha becomes less favourable due to the zero GHG targets, the limited CCS potential and the limited biomass import potential (preferably used for production of transport fuels).
- In the new TRANSFORM scenario, a greater potential for biomass imports is used than in the previous study, but no biofuels are imported. The total biomass potential (domestic and import) is almost fully utilised. A large share of the biogenic CO_2 produced in bio-refineries is captured and used for synthetic methanol production.

New insights for the ADAPT scenario
The new ADAPT scenario also offers some interesting insights:

- Nuclear power is not used in the ADAPT base case. Because of the greater availability of biomass import and CO_2 storage, the full available potential for wind and solar energy is not needed for electricity production. Only when the biomass potential or CO_2 storage potential is substantially limited, such that the demand for electricity increases and the wind capacity reaches its limits, does the use of nuclear power stations become cost-effective. In fact, by limiting

biomass imports and CO_2 storage, the ADAPT scenario moves in the direction of the TRANSFORM scenario. This leads to an increase in costs, making the use of nuclear energy competitive, comparable with what can be observed from the TRANSFORM scenario.
- The demand for hydrogen in the updated ADAPT scenario is comparable to the scenario from the previous study. However, the main difference with the previous study is that in 2050 hydrogen in this new study is produced entirely from electricity. As a result of an update of CO_2 storage costs, the production of blue hydrogen becomes less cost-effective.
- Although the availability of biomass (both domestic and import) has increased in this study compared to the previous study, this potential is not fully exploited in ADAPT. The use of biomass is comparable to the previous study, with the difference that the biofuels in the updated scenario are produced entirely within the Netherlands and are not imported, as was the case in the previous study.

Carbon balance shows origin and destination of the carbon
The modified OPERA model calculates a carbon balance. This carbon balance provides insight into the origin and destination of carbon in energy supply and demand flows and carbon use for the production of chemicals:
- The carbon flow in the TRANSFORM scenario is significantly smaller in 2050 than in 2030. In ADAPT this reduction is much smaller. This relatively small carbon reduction in the ADAPT, scenario is the result of the continuation of fossil fuel use in combination with an increase in the use of biomass as a sustainable carbon source. In the TRANSFORM scenario, the amount of carbon decreases sharply because hardly any fossil fuels are used in 2050.
- In both scenarios, approximately the same amount of CO_2 is captured in 2050. In the ADAPT scenario, this mainly concerns fossil CO_2 that is almost entirely stored in empty gas fields under the North Sea bed. In TRANSFORM, 35 Mt of the 50 Mt captured CO_2 - of biogenic origin and from the atmosphere - is used for the production of chemicals and transport fuels. The remaining captured CO_2 is stored in empty gas fields.
- Due to the sustainability ambitions of the TRANSFORM scenario, in particular the 95% GHG reduction for bunker fuels and a renewable carbon target for chemicals, the demand for carbon by 2050 exceeds the amounts that can be covered with biomass. The shortage is supplemented by CO_2 direct air capture.

Total system costs
The total system costs are more or less the same as in the previous study. However, the cost differences between the scenarios and the changes between 2030 and 2050 are considerably larger (varying from a few percent to more than 17%). Whereas in the previous study the total system costs in the TRANSFORM scenario still decreased in 2050, the total system costs now increase compared to 2030 for both scenarios. In the updated scenarios more and higher cost options are being applied to achieve net-zero GHG emissions. Despite the higher GHG reductions for bunker fuels and a target for renewable carbon for chemicals, the total system costs in the TRANSFORM scenario are lower than in ADAPT. This is mainly due to scenario assumptions related to lower energy demand and industrial production. As shown in the previous study, the total system costs increase when the possibilities for cost-effective options are reduced (e.g. less CO_2 storage in ADAPT or nuclear energy in TRANSFORM). But the reverse is also true: total system costs fall if (more) options with low costs become available, e.g. cost

reductions of technologies due to learning effects or hydrogen imports with a lower price than domestic production costs.

Box B

Comparison with the previous scenario study and other energy scenarios for the Netherlands

New and previous scenario study
Various adjustments in the new scenario study lead to changes in the energy production mix, the energy mix in final energy consumption, application of technology and the emission of greenhouse gases for the ADAPT and TRANSFORM scenarios. The most notable differences in the results compared to the previous scenario study are:

- *Total system costs:* As in the previous study, the annual costs of the total energy system in the new study for the TRANSFORM scenario are lower than those for ADAPT. However, the cost difference is smaller in 2050 than in the previous scenario study. The TRANSFORM scenario has been made more sustainable by making the feedstocks sustainable. This translates into an increase in total system costs.
- *Electricity:* In the TRANSFORM scenario, the total electricity generation in the new study in 2050 is 38% higher than in the previous study. This is partly due to a significantly higher electricity demand for hydrogen production. For the ADAPT scenario, the electricity production is at approximately the same level. Electricity imports and exports are sensitive to the changes. For TRANSFORM, imports are lower in 2050, but exports will be comparable to the previous study, which leads to higher net exports in the new study. In the ADAPT scenario, the electricity exports are lower, while imports have increased. In the new study, this leads to a net import of electricity for ADAPT in 2050.
- *Hydrogen:* Compared to the previous scenario study, the demand for hydrogen for the scenarios in the new study has increased. This is due to the assumption that all transport fuels are produced in the Netherlands; the previous scenario study still involved imports of biofuels. In addition, under the TRANSFORM scenario in the new study, there is more demand for hydrogen for production of synthetic methanol as a transport fuel and feedstock for chemical and plastic production. In the ADAPT scenario of the new study, more than twice as much hydrogen will be produced in 2050 in hydrogen plants as in the previous scenario study; for TRANSFORM this is more than by a factor of four. In the previous study, in the ADAPT scenario, blue hydrogen was produced from natural gas with CCS. In the new study, hydrogen is mainly produced with electrolysers in both scenarios. This is due to higher cost parameters for CO_2 storage, making the production of blue hydrogen less cost-effective than green hydrogen.
- *Biomass:* For the new scenario study it is assumed that more biomass is available to compensate for the no-biofuels import constrain. In the ADAPT scenario, this leads to shifts in use (less biomass for heat production in industry, more biofuels), but the total amount of biomass remains approximately the same. In the new study, the biomass use for the TRANSFORM scenario is about 50% higher. This is mainly due to increased biofuel production.

Box B (continued)

- *CO_2 and residual greenhouse gas emissions:* In the previous scenario study, there were still residual greenhouse gas emissions in 2050, including LULUCF emissions. In the new study, the net emissions are zero in both scenarios. Furthermore, in the previous study, hardly any CO_2 was captured in the TRANSFORM scenario. In the new study CO_2 capture is used (from biomass processes and from the atmosphere) for the production of synthetic fuels and methanol. Also, in the new study, a limited amount of CO_2 is stored in depleted gas fields in the TRANSFORM scenario. This creates negative emissions that compensate for remaining greenhouse gas emissions. In the ADAPT scenario, the same amount of CO_2 is stored in the new study as in the previous scenario study. In the ADAPT scenario, with regard to CO_2 capture, there are shifts between the various industrial processes.
- *Heat:* The supply of residual heat from industry to the built environment and horticulture greenhouses is considerably smaller in the new scenario study than in the previous study. This is because residual heat is better specified in the model and more residual heat is also reused within industry, so that less residual heat in industry is available for supply to other sectors. As a result, the heat supply to the built environment via heat networks in 2050 will be much smaller. This amounts to about 30% of the heat supply in the previous scenario study. The production of heat from geothermal energy is greater in the new scenarios: 35% more in ADAPT and more than twice as much in TRANSFORM.

New ADAPT and TRANSFORM scenarios compared to the II3050 scenarios
For the Integrated Infrastructure Outlook 2030-2050 (II3050)[a], climate-neutral energy scenarios have been drawn up for 2050 for four future scenarios. Compared to the ADAPT and TRANSFORM scenarios, there are a few important differences in scope and approach. Three notable differences are:

- The II3050 scenarios cover all energy sectors and non-energy use as feedstock, but not fuel use for international aviation and shipping (bunker fuels). The ADAPT and TRANSFORM scenarios do take into account the demand for bunker fuels.
- The production capacities for, among other things, wind and solar, the amount of hydrogen and biomass (in the form of green gas) are used as input data for the II3050, while this is the result of cost optimization in the ADAPT and TRANSFORM scenarios.
- Climate neutral means no net CO_2 emissions for the II3050 scenarios. ADAPT and TRANSFORM are net zero greenhouse gases, i.e. including other greenhouse gases in addition to CO_2, such as methane (CH_4) and nitrous oxide (N_2O) within the target.
- The table below compares a number of results from both scenario studies for 2050. To make the scenarios somewhat comparable, the production of offshore wind in the II3050 scenarios has been increased for the production of synthetic bunker fuels[b]. Compared to the II3050 scenario's the ADAPT scenario use more biomass and fossil fuels and more CO_2 is stored in empty gas fields in the Northsea. For the TRANSFORM scenario, the higher production from offshore wind, the production of nuclear energy[c] and the relatively low consumption of fossil fuels stand out. For TRANSFORM, the differences can in particular be explained by the greening of the hydrocarbons used as raw materials. More biomass and hydrogen are being used instead of fossil fuels, with hydrogen being produced from electricity generated in the Netherlands.

Box B (continued)

		II3050				TNO	
		Regional	National	European	Inter-national	ADAPT	TRANS-FORM
Electricity production[b]	TWh	312	403	228	211	315	621
o.w. offshore wind[b]	TWh	162	269	157	144	192	386
o.w. onshore wind	TWh	45	45	23	23	33	54
o.w. solar PV	TWh	105	89	48	44	51	120
o.w. nuclear energy	TWh	0	0	0	0	0	43
Electricity imports	TWh	12	10	21	22	53	8
Hydrogen	PJ	342	518	500	1048	257	738
Biomass	PJ	310	194	947	443	945	854
Geothermal energy	PJ	108	47	4	4	58	88
Fossil fuels	PJ	374	511	1073	734	1415	125
CO_2 storage	Mton	5	6	27	26	50	15

[a] Netbeheer Nederland, The Energy System of the Future - Integrated Infrastructure Outlook 2030 -2050 (II3050), April 2021
[b] The impact of fuel delivery to international aviation and maritime shipping has been examined separately for the II3050 study. This requires 40% extra wind power at sea. The figures for offshore wind have been adjusted in the table above.
[c] The impact of nuclear energy on the II3050 scenarios has been investigated by Berenschot/Kalavasta in 'System effects of nuclear power plants in Climate Neutral Energy Scenarios 2050,' 2020

7.2 Production and use of transport fuels

Transport fuel mix
Compared to the current use of biomass, biomass use shifts to the transport sector, mainly for aviation and shipping in both scenarios. Road transport consists in 2050 of zero emission vehicles, such as battery electric vehicles and fuel-cell electric vehicles. Among the domestic transport modes, biofuels are used in inland shipping and non-road machinery.

Aviation fuels
Biokerosene appears as the main renewable fuel supply option for aviation in both scenarios. This is due to the limited sustainable aviation fuel options and the higher production costs of synthetic kerosene. Even when biomass potential is limited the available biomass is used to meet the emission reductions in the aviation sector.

Another important reason for biokerosene use relates to the multi-product feature of the biorefineries. For instance, a biorefinery with biokerosene as its main product contributes to reducing emissions in aviation and re-carbonising the feedstock use for HVCs. Bio-naphtha, one of the by-products of this biorefinery is used in the chemical industry. The other important by-product is the captured biogenic CO_2. In

2050, CO_2 becomes an important feedstock both for the chemical industry and production of synthetic fuels for the shipping sector. Furthermore, electricity produced from residual gases contributes to the renewable electricity supply pool.

Marine fuels
Model results in this study show that LNG can play an important role as marine fuel, especially when the GHG emission reduction targets for this sector are moderate (i.e. 50% in ADAPT). However, there is downstream methane slip from LNG that may paralyse the use of LNG. Depending on the level of this slip, LNG may even disappear and be replaced by synthetic and bio-methanol. So, this role is highly dependent on the life cycle GHG emissions of LNG.

A high GHG emission reduction target in the shipping sector in the TRANSFORM scenario indicates a fuel supply mix of biofuels and synthetic fuels. Among the different supply options, bio and synthetic methanol appears to be the two low cost renewable supply options when the methane slip issue is considered. Limitations to the available biomass result in lower biofuels use in the shipping sector. This reduction is compensated for by synthetic fuels.

7.3 Sustainable feedstock use in the petrochemical industry

Industrial policies focus on measures to reduce direct chimney emissions of companies (scope 1 emissions) and emissions related to the heat and electricity supply (scope 2 emissions). Indirect emissions, upstream and downstream (scope 3), can be reduced by using renewable feedstocks. The ADAPT scenario continues to use fossil fuels as feedstock for the production of chemicals, which leads to scope 3 GHG emissions. The new TRANSFORM scenario introduces a dedicated target for the use of renewable feedstocks and also promotes the use of recycled plastics (via pyrolysis) in the petrochemical industry. This allows a better understanding of the main pressure points of re-carbonising the petrochemical industry as part of an integrated, GHG emission neutral energy system.

The main conclusions based on this modelling analysis are as follows:
- Reducing scope 1 emissions and meeting carbon neutrality becomes very challenging for the petrochemical industry in the TRANSFORM scenario, because CCS and biomass imports are limited. As a consequence, the sector shifts towards the methanol-to-olefin production route.
- A large part of the CO_2 is derived from biogenic CO_2, captured from bioenergy systems, mainly biomass gasification, followed by Fischer-Tropsch (FT) synthesis. Thus, the relatively low carbon conversion of biomass to biofuels is compensated for by the capture and use of this carbon in the chemical industry. CO_2 obtained via direct air capture (DAC) also contributes to meeting the renewable carbon target.
- Bio-naphtha, which is a low-cost substitution option, is also utilised in the chemical industry, however the availability was limited. Thus, any increase in bio-naphtha potential (e.g. by import) reduces the role of the synthetic methanol route in this sector and this synthetic methanol shifts to shipping sector.
- Pyrolysis oil, produced from recycled plastics, is another low-cost option to replace fossil naphtha. The main limitation to its use relates to the extent to which it can replace virgin naphtha. In the analyses of this study a maximum of 30% blending with fossil naphtha is introduced. As the fossil naphtha use was

limited in 2050 in TRANSFORM, the use of recycled pyrolysis oil is relatively small but can be increased with plastic waste imports.
- Analysis of chemical recycling was limited to only one technology option. In future studies other chemical recycling technologies that are at different stages of development could be included to better assess the future role of chemical recycling.
- All above results relate to the scenario analysis, where both synthetic fuels and biofuels for domestic transport and bunkers are assumed to be produced in the Netherlands. Thus, results reflect a future where the multi-product biorefineries serve many different sectors. When for instance biofuels are imported there is a shortage of (biogenic) carbon. This can be compensated by direct air capture of CO_2, which is a more expensive and also a more energy-intensive renewable carbon supply option.

7.4 Heat supply and demand of industry, built environment and agriculture sector

By adapting to the OPERA model, this new scenario study provides much better insights into the external heat demand of industrial processes. Four temperature levels are now distinguished, as well as a distinction between steam demand and demand for direct heating. Compared to the previous study, these adjustments lead to different results with regard to the heat demand in industry and the supply of residual heat from industry to the built environment and the agricultural sector.

Industrial heat demand
The new scenario results show that for both scenarios the total external heat demand decreases after 2030. In the ADAPT scenario, the external heat demand for high temperatures decreases in refineries and steel production, but increases in the chemical sector. In the TRANSFORM scenario there is a shift towards external heat demand at lower temperatures due to changes in the manufacturing of high value chemicals.

Heat supply to heat networks
In the previous scenario study, the supply of residual heat from industry to the built environment and the agricultural sector was relatively large. In the new scenario analysis the heat supply from industry is only 30% of the heat supply in the previous study (see text box B for explanation). In the new scenario's the heat supply via heat networks doubles in 2030 compared to 2019, but decreases slightly in 2050. In both scenarios, residual heat from industry is the most important heat source for these heat networks. In 2030, biomass is still used for heat production in both scenarios, but this is replaced by geothermal energy in 2050.

Heat supply built environment and agriculture sector
In addition to the modest role of heat networks in covering the heat demand in the built environment, the electric heat pump is the most important option for heating homes and buildings. In ADAPT there is also room for a gas network that distributes natural gas, hydrogen, green gas or a mixture. In the agricultural sector, geothermal energy is an important source of heat in both scenarios.

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