Towards a sustainable energy system for the Netherlands in 2050

Scenario update and scenario variants for industry

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Contents

Executive summary

This report presents the results of a new scenario study into a future sustainable energy system for the Netherlands. In 2020, TNO presented energy scenarios based on two different storylines. These scenarios were adjusted in 2022 to expectations of economic developments, new policy goals, new technological insights and improved data. Two years later, there is again reason to update the scenarios and base them on new, more ambitious national and European policy targets and their implementation policies (e.g. Dutch Climate Act, EU's Fit-for-55 and REPowerEU programs). In addition to the scenario update, this scenario study focuses on the uncertain future of the Dutch energy-intensive industry. Three possible future developments are explored in scenario variants.

ADAPT and TRANSFORM scenarios
The scenarios are based on two storylines for the Netherlands for the period 2030-2050: ADAPT and TRANSFORM. These storylines have also been used in the two previous TNO scenario studies. In both scenarios, CO_2 emissions will decrease and the climate objectives will be achieved. The way this happens varies. In ADAPT, Dutch society strives to maintain the current lifestyle and preserve the economic structure, including a strong industrial sector. Fossil fuels can continue to be used, but less than is currently the case. These fuels are made climate neutral by using CO_2 storage. Sustainability of hydrocarbon feedstocks is not pursued. There are also limited ambitions to make fuels for international aviation and shipping (whose emissions fall outside the Dutch climate objective) more sustainable.

Motivated to reduce their carbon footprint, Dutch and European citizens in TRANSFORM are willing to change their behaviour. As a result of this lifestyle change, the demand for mobility changes (e.g. less flying, more use of public transport and bicycle) and the demand for industrial and agricultural products reduces (e.g. less demand for meat). In this storyline, companies invest in transformation and innovation of production processes based on renewable energy and sustainable and recycled feedstocks. CO_2 storage is limited to what is necessary to compensate for greenhouse gases that are difficult to reduce with negative emissions (i.e. capture and storage of non-fossil CO_2). In addition, in TRANSFORM the fuels for international aviation and shipping are fully sustainable so that no greenhouse gas emissions can arise.

Scenario variants for energy-intensive industry
Industrial companies are currently responsible for more than 40% of Dutch energy demand and more than 30% of Dutch greenhouse gas emissions. The ADAPT scenario assumes that the Dutch energy-intensive industry retains a strong competitive position. This is different for the TRANSFORM scenario and that is why three variants have been explored with a different development of the energy-intensive industry. This involves four types of industry: refineries, production of high value chemicals (olefins, such as ethylene, propylene, etc. and aromatics), steel production and fertiliser production. These industries may face two forms of international competition: competition for the final products they make or competition in making (energy-intensive) semi-finished products. The TRANSFORM scenario assumes that the Dutch energy-intensive industry can compete internationally and that production takes place on the basis of imported primary feedstocks. In the Less Competitive variant, the industry experiences a lot of international competition, which leads to a reduction in production, but the products are still made from primary feedstocks. In the Competitive &

Import variant, the Dutch energy-intensive industry is internationally competitive, but it is more cost-effective to convert primary feedstocks into semi-finished products abroad and import them to the Netherlands. The Less Competitive & Import variant is a combination of the two previous variants: a lot of international competition resulting in a reduction of production volume and import of semi-finished products instead of primary feedstocks. The variants were used to investigate the impact of various developments for energy-intensive industry on the Dutch energy system, in particular with regard to electricity and hydrogen production and the use of biomass.

Calculating the energy system
For the scenarios and industry variants, an energy system for the Netherlands has been calculated in five-year steps for the period 2030-2050, using the OPERA energy system model. The OPERA model calculates an energy system for a given year that can meet energy, mobility and product demands while meeting the greenhouse gas emissions target. The model chooses the technologies and energy sources that lead to the lowest social costs of the energy system.

Transition paths for the Dutch energy system are described for the scenarios and industry variants based on the changing composition of the energy supply and energy demand. The assumptions and preconditions used for the scenario analyses are explained. A number of these assumptions have been investigated to what extent they influence the results. For those interested, an interactive website is available with the quantitative results of the scenarios in the form of graphs and tables, see www.energy.nl. A Dutch summary (Scheepers M. , Whitepaper: Toekomst van het Nederlandse energiesysteem, 2024) has also been published together with this report.

Main results of the scenario analyses
The results of the scenario analyses provide insight into the possible developments of the future Dutch energy system and its implications. These insights are summarized below.

- *Energy-intensive industry and fuels for international transport determine future energy demand of the Dutch energy system*
  The future development of energy-intensive industry (refineries, high value chemicals, steel industry and fertiliser industry) and the demand for fuels produced in the Netherlands for international aviation and shipping determine the development of a climate-neutral energy system for the Netherlands. If the production volume of energy-intensive industry remains virtually the same, in the future 40 to 50% of Dutch energy demand will come from industry (energetic and non-energy consumption), about the same as today. However, if this industry experiences more competition, resulting in reduced production in the Netherlands and/or the energetically intensive part of the production chain is moved abroad (with the import of semi-finished products), then this study shows that the share may drop to just above 30%. The energy volume of fuels supplied from the Netherlands for international aviation and shipping (600 PJ) is approximately comparable to the heat and electricity demand of all buildings in the Netherlands. This could remain the case in the future, but it is also possible that this will be almost halved if seagoing vessels also get their fuel from foreign ports.

- *Electrification and demand for green hydrogen will result in significant growth in electricity demand*
  Due to electrification of the energy demand for heat and mobility, the demand for electricity is increasing significantly. Compared to current electricity consumption, domestic electricity demand will therefore grow by a factor of approximately 2.5.

Because electricity will also be used for the production of green hydrogen in the future, this will result in a further increase in electricity demand. The domestic electricity demand will then increase by approximately a factor of 3. More than 90% of the hydrogen is intended for industry (including for sustainable production of steel and fertilizer) and the production of synthetic fuels (including for aviation). If energy-intensive industry shrinks and/or the energy-intensive part of the production process is moved abroad, electricity demand will grow by a factor of more than 2 to 2.5 instead of a factor of 3. If that development takes place, the demand for hydrogen will not have to decrease. It may then become attractive for the built environment to use hydrogen as a heating fuel (up to about 14%), especially if the import price for hydrogen is competitive with the costs of domestic hydrogen production. Hydrogen production can also contribute cost-effectively to absorbing excess wind and solar power for which there is no demand. Electricity exports also contribute to keeping the electricity system in balance. The size of that contribution does depend on the capacity expansion of the electricity networks.

- *Nuclear energy can supplement renewable electricity production from solar and wind*
  Wind and solar energy are the main energy sources from which electricity will be produced in the future. In 2030, the share of wind and solar will be between 73% and 85% and in 2050 this could grow to 90%. Compared to 2022, total production capacity in 2050 will grow by a factor of 3 to 4, stronger than electricity demand because wind turbines and solar panels cannot produce electricity all hours of the year. Nuclear energy can also become part of the electricity production mix (with a share of 7% to 9% in 2050) if the plans for two new nuclear power stations (3 GW) are realized and small modular reactors with heat supply to industry (SMRs) are also applied (in total 2 GW). A future sustainable energy system without nuclear power is also possible, but the social costs for the energy system will then be higher because more costs will have to be incurred for flexibility options to meet baseload demand with wind and solar power alone. With a shrinking industry and/or import of semi-finished products from abroad, electricity production in the Netherlands does not have to grow as strongly. Because the base load demand is smaller, the production of electricity from nuclear power plants grows relatively less compared to that from wind and solar power.

- *Carbon continues to play an important role in a climate-neutral energy system*
  Depending on the scenario, the total amount of carbon (as hydrocarbons) in the energy system will remain almost the same or up to 40% lower than it is now. In a greenhouse gas-neutral energy system, carbon remains necessary for the production of fuels (including aviation and shipping fuels) and the production of chemicals and plastics. The energy transition makes it necessary to replace fossil carbon by sustainable carbon, such as biomass and recycled plastics. But a significant reduction requires additional policy. With a shrinking industry, the amount of carbon drops by almost 50%. Nevertheless, fossil carbon can remain present in the system and GHG-reduction target can be achieved. For instance, refineries will still export fossil fuels and some fossil carbon will be used in the production of chemicals. Fossil carbon is also stored as CO_2 in depleted gas fields under the North Sea and fossil CO_2 emissions are compensated with negative emissions (captured and stored non-fossil CO_2). Completely eliminating the use of fossil fuels can lead to high system costs. In addition, it is cost-effective to capture and store CO_2 when converting biomass into fuels and chemicals. Biogenic carbon capture and storage can compensate for CO_2 emissions released by fossil applications that are difficult to make sustainable. Carbon removal or negative emissions is also needed to compensate for difficult-to-reduce non-CO_2 greenhouse gas emissions, such as methane emissions from agriculture.

- *Primary energy consumption increases due to application of sustainable technologies* In 2030, the energy system can meet the target for final energy consumption from the Energy Efficiency Directive (EED) of 1609 PJ, but achieving the (indicative) target for total primary energy consumption of 1935 PJ is difficult. After 2030, without an explicit efficiency target, final energy consumption will be, depending on the scenario, 4% to 10% above the target for 2030. Many efficiency measures are also used to achieve the greenhouse gas emissions reduction target. In addition, lifestyle changes can also contribute to both emission reduction and lower energy consumption. Primary energy consumption will continue to increase and will be well above the indicative target of 2030. This is due to the introduction of (new) technologies for energy conversion that lead to additional energy losses (e.g. electrolysers for hydrogen production, nuclear power plants, processes that convert biomass into fuels) and new energy demand (e.g. CO_2 capture). A shrinking industry and/or relocation of energy-intensive part of the production chain abroad results in lower final and primary energy consumption.

- *Major investments are required, but system costs do not need to increase significantly* Achieving the energy transition requires significant investments that will increase in the coming decades. The increase in investments is dampened by technology learning, i.e. a decrease in costs as a result of innovation and implementation of new technologies. The annual social costs for the entire energy system will increase, especially if fossil fuels continue to be used and consumers do not change their lifestyle. If this does happen and the use of fossil fuels decreases, the increase of annual costs of the energy system will be significantly less. The annual system costs are shifting from energy purchasing costs to capital costs, especially if the energy system is made more sustainable. However, the annual system costs for industry continue to consist largely of energy purchasing costs, although these may decline somewhat relatively. In a scenario with far-reaching sustainability, the system costs for the industry will be much lower than in a scenario with less far-reaching sustainability and where a substantial amount of fossil fuels continues to be used.

1 Introduction

New energy scenarios
Reports about melting ice caps and weather extremes make us realize that measures to combat climate change are urgently needed. This leads to new, stricter policy goals that aim to accelerate the energy transition. The European Commission has introduced the European Green Deal/Fit-for-55 package[1] and the REPowerEU[2] plan. The Dutch government has responded with an amendment to the Climate Act (Dutch Govermenent, 2023), stricter greenhouse gas (GHG) reduction targets for 2030 (EZK, 26 april 2023), and the GHG reduction path thereafter (VVD, D66, CDA en ChristenUnie, 2021). This is the motivation for updating previously published TNO scenario studies (in 2020 (Scheepers M. , et al., 2020) and 2022 (Scheepers M. , et al., 2022)). Similar to the previous studies this new scenario study examines possible long-term development paths for the Dutch energy system, taking the achievement of the greenhouse gas reduction targets as a starting point. The focus is on the period 2030-2050. The two scenarios in this study are based on the same storylines as those in the previous two studies (ADAPT and TRANSFORM), with minor adjustments. In addition to new policy targets, the scenario update also takes into account new energy price projections, new energy demand forecasts, updates of techno-economic parameters and an expansion of available technology options.

Focus on industry development
New in this scenario study are alternative developments for Dutch industry. The industrial sector has a significant share in Dutch greenhouse gas emissions (32% in 2022) and energy use (47% in 2022) if the use of hydrocarbons as feedstock are also taken into account (Klimaat en Energieverkenning 2023, 2023). Previous TNO scenario studies have assumed that the future structure of Dutch industrial production will not fundamentally change or that the production volume will decline as a result of changes in consumer behaviour. Other long-term scenarios drawn up for the Netherlands assume no major changes for the industry (such as in the TVKN 2050 scenario study (Daniels & Strengers, 2024)) or the size of the industry decreases in some scenarios (II3050 scenario study (Het energiesysteem van de toekomst: Secenarios energiesysteem 203-2050 - Integralte energiesysteemverkenning 2030-2050, 2023)). But so far no scenario study has explicitly examined the effect of different developments in Dutch industry. In this scenario study, changes in development in the energy-intensive industry are compared with a scenario in which these changes do not take place and is the effect on the Dutch energy system analysed.

Factories of energy-intensive industry are often part of international companies and investment decisions that are necessary to make current industrial processes more sustainable are taken in an international context. It is therefore conceivable that investments in sustainable production facilities do not take place at the same location of current production plants. Such possible developments are outlined in studies of Guidehouse (Guidehouse, 2023) and PWC (PWC, 2024). The Guidehouse study models the industrial energy demand for various development paths. The PWC study argues that energy-intensive

[1] https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/delivering-european-green-deal/fit-55-delivering-proposals_en
[2] https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/repowereu-affordable-secure-and-sustainable-energy-europe_en

industries in north-west Europe will have higher energy costs than in other regions of the world. This scenario study goes a step further by also investigating the consequences of alternative developments for Dutch industry for the transition of the entire Dutch energy system.

Providing insights for government policy and business strategy
This scenario study explores possible transition paths to a sustainable energy system against the background of geopolitical and market developments that are beyond the influence of Dutch policymakers and companies. The insights obtained from the scenario study are relevant for government policymaking and strategic decisions of companies. These insights provide starting points for action perspectives. The scenario results can also guide the development of innovative technological solutions and provide a reference basis for technology implementation studies and business case analyses.

This scenario study builds on insights from previous studies and adds new insights. The scenario results are also compared with results from previously published scenario studies.

About this study
This study was carried out within TNO's Energy Transition Studies research program 2023, funded by the Ministry of Economic Affairs and Climate Policy. A research project on the future of the Dutch energy-intensive industry is also part of this programme. Input was provided to the scenario study from this research project (Lamboo, Eblé, Uslu, & Weeda, 2024) (Uslu & Oliveira, 2024). The outcome of this scenario study are two publications. This report contains an extensive description of the results, describes the research methodology and provides an overview and substantiation of assumptions and input data used for the analyses. In addition, a separate publication (in Dutch) summarizes the results and highlights the most important insights (Scheepers M. , Whitepaper: Toekomst van het Nederlandse energiesysteem, 2024). Furthermore, quantitative scenario results in the form of graphs and tables are also available on an interactive website, see www.energy.nl.

Reading guide
This report has the following structure:
- Chapter 2 explains the research methodology used. It is explained how storylines form the basis for scenario development and how an energy system model is used to quantify the scenarios.
- Chapter 3 describes the scenarios used: two base scenarios (ADAPT and TRANSFORM) and three scenario variants for industry.
- Chapter 4 discusses the parameterization of the base scenarios and industry variants.
- The results of the ADAPT and TRANSFORM scenarios are described in Chapter 5.
- Chapter 6 presents the results of the industry variants compared to the TRANSFORM scenario.
- Finally, Chapter 7 lists the most important insights and conclusions.

2 Methodology

2.1 Dutch energy system

This scenario study examines possible transition pathways to a sustainable energy system for the Netherlands between 2030 and 2050. An energy system is a subsystem of the economy and has a geographical demarcation. The energy system overlaps with other subsystems, such as the environmental system (e.g. GHG emissions), the system of feedstocks and materials (e.g. hydrocarbons), the spatial system (e.g. space for wind turbines, solar panels), see Figure 2.1. The scenario study considers all greenhouse gases: in addition to CO_2, this also includes CH_4, N_2O and F-gasses. Although greenhouse gas emissions from part of the agricultural sector (e.g. livestock farming) and land use do not belong to the energy system, these greenhouse gas emissions are also included in the scenario analyses.

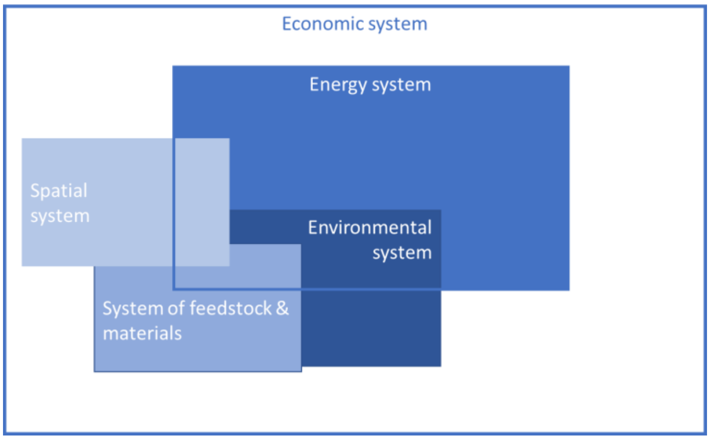


Figure 2.1: The energy system and relationships with other systems

This study examines the Dutch energy system, including energy production and CO_2 storage on the Dutch part of the North Sea. The energy system considered is schematically shown in Figure 2.2. This energy system includes energy production (e.g. electricity and fuel production), but not the extraction of fossil fuels. Fossil fuels are sourced externally from domestic and foreign sources. Various end-use sectors are distinguished within the energy system: industry, built environment, agricultural and transport. The energy system also includes the demand for hydrocarbon feedstock, as well as bunker fuels used for international aviation and shipping. All techniques used for production, conversion, transport & storage and use of energy, such as industrial production installations, heating installations and transport vehicles, but also CO_2 pipelines and energy saving technology are part of the energy system. However, aircraft and seagoing vessels for international aviation and shipping are not included as technologies within the system boundary; only their fuel demands are considered. The Netherlands can import various hydro carbon feedstocks and commodities via seaports, such as fossil fuels, biomass[3], plastic waste, biofuels and bio-

[3] In this report, the term 'biomass' is used for primary energy and in case of direct energy use, the term 'biofuel' is used when biomass is converted into a liquid fuel and the term 'bio-feedstock' when biomass is used for production of chemicals and plastics.

naphtha. Energy imports and exports are also possible from neighbouring countries via pipelines and interconnectors of the electricity network. Fossil fuels, biomass and electricity are used for the production of hydrocarbons and hydrogen which are ultimately utilized as feedstocks in manufacturing fertilisers, chemicals and plastics. It should be noted that the Dutch energy system produces liquid fuels for international aviation and shipping that are refuelled in the Netherlands (bunker fuels) and for export to other countries within and outside Europe. Based on international agreements, the Netherlands is responsible for greenhouse gases from the subsectors within the energy system and those from land use, but not for greenhouse gases from international aviation and shipping to and from the Netherlands.

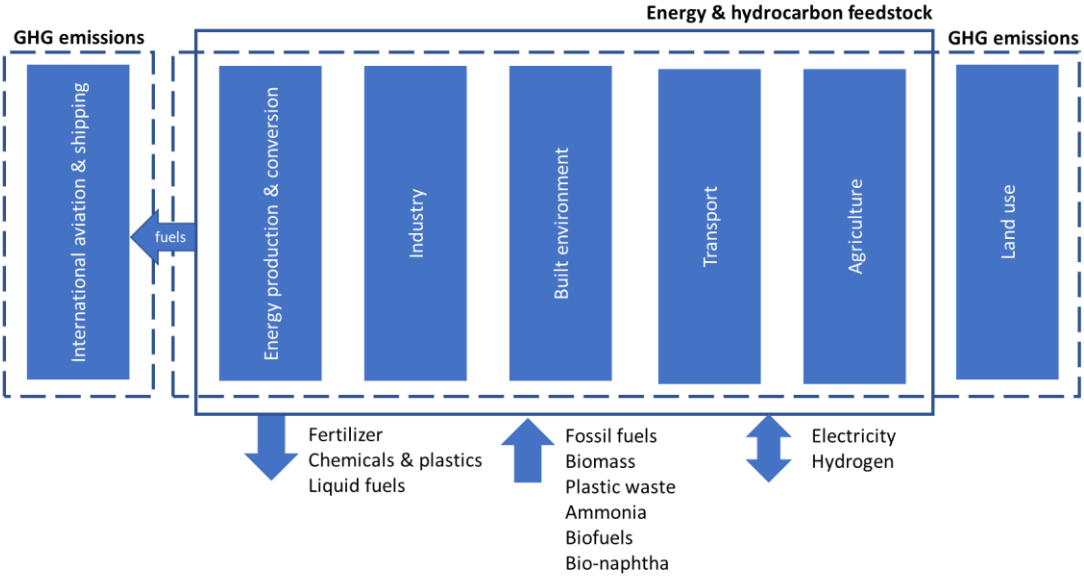


Figure 2.2: The energy and GHG system with subsectors and the exchange across the system boundaries

2.2 Storylines and scenarios

Future transition pathways to a sustainable energy system can be investigated using scenarios. Scenarios are essentially a mutually coherent set of realistic assumptions and preconditions that can change over the period under consideration. These assumptions and preconditions describe the external uncertainties of the energy system that cannot or are difficult to be influenced by policy makers and market agents (e.g. economic and demographic, societal and (geo)political developments). Scenarios are based on storylines that provide a qualitative description of possible future developments. By providing scenarios with quantitative parameters, it is possible to calculate a future energy system with an energy system model, see Figure 2.3. For this study the OPERA model has been used. Insights into the implications of the scenarios are obtained by analysing the model results.

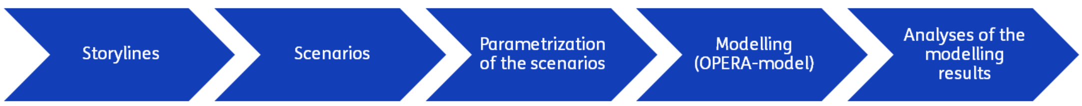


Figure 2.3: Schematic representation of the scenario analyses methodology

2.3 OPERA model

The OPERA model is shown schematically in Figure 2.4. The OPERA model calculates an energy system for a given year with which the energy demand can be met and industrial production can be realized while at the same time certain preconditions are met (e.g. maximum GHG emissions). An important feature of the model is that the technology deployment and energy mix (both supply and demand mix) are determined by the model's optimization algorithm (i.e. endogenous). The model chooses the technologies and energy sources that lead to the lowest cost of the energy system The model uses social costs based on investment and operating costs for the entire energy system (excluding subsidies and taxes) and the cost balance of energy imports and exports[4]. Input parameters that the OPERA model uses are (see also Section 4.1):

- Scenario objectives: maximum greenhouse gas emissions (total and per sector) and maximum energy use.
- Demand for energy, demand for mobility and production of certain industrial products.
- Techno-economic data.
- Price of imported feedstocks and commodities.
- Certain restrictions on the use of technologies.

The model is a representation of the energy system as described in Section 2.1. The model distinguishes different regions in the Netherlands: 7 regions on land (each industry cluster falls in a separate region) and 7 regions on the North Sea with distinctive wind regimes and distances to the coast. The model also takes into account fluctuations in energy demand and supply. For each subsequent year for which an energy system is calculated, the model takes into account the assets already present from the previous period based on the technical lifetime of these assets. The model determines whether additional capacity needs to be invested to meet demand[5].

The model results of the calculated energy system can be categorized into physical and economic aspects:

- Physical aspects: energy supply and demand mixes (total and per sector), technologies used (e.g. installed capacities, full load hours), import and export of energy (e.g. fossil energy, biomass, electricity, hydrogen), residual greenhouse gas emissions.
- Economic aspects: shadow prices (CO_2, electricity, hydrogen), annual system costs and annual investments (total and per sector).

A more detailed description of the OPERA model can be found in (Stralen, Dalla Longa, Daniëls, Smekens, & Zwaan, 2021). Compared to the 2022 scenario study, a number of adjustments have been made to the model, see Appendix A.

The exchange of electricity and hydrogen with eight countries in Northwest Europe (Belgium, Denmark, France, Germany, Ireland, Sweden, Norway and UK) is determined with the I-ELGAS model (Koirala, et al., 2021). For this purpose, the hourly demand for electricity and hydrogen, and the production capacity of relevant options have been taken over by I-ELGAS

[4] In practice, market parties will want to pursue their own maximum benefit when making investment and operational decisions and not the desired optimum for society as a whole. Good market design, regulation and policy can provide guidance, but there will never be perfect information and coordination. As a result, the energy system that has been calculated for the lowest social costs will be difficult to realize in practice.

[5] It is possible to have investments determined by the OPERA model at the lowest social costs over the entire period (i.e. 2030-2050), i.e. with perfect foresight. However, in practice, the future for investors is uncertain. In this study, the energy system is optimized per year and not over the entire period. In principle, this will lead to higher system costs.

from OPERA. Subsequently, I-ELGAS determined the import and export flows and border prices for electricity and hydrogen, which then have been used in the OPERA model.

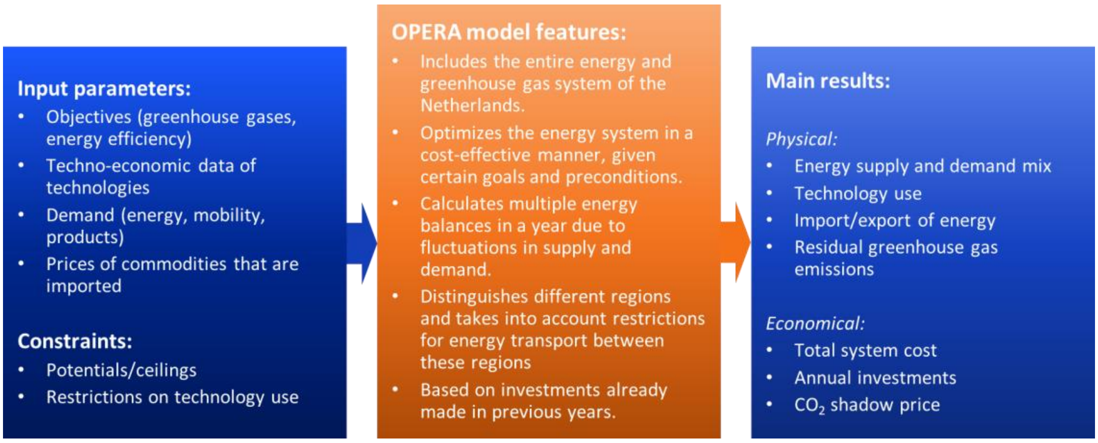


Figure 2.4: OPERA: Integral energy system model for the Netherlands

2.4 Analysing the energy system

Possible transition paths to a sustainable Dutch energy system have been analysed as follows:

- First base scenarios are analysed. These scenarios are an update of the same scenarios from the study published in 2022 (Scheepers M. , et al., 2022).
- Various scenario variants were subsequently analysed. In this study these are scenario variants focus on industry.
- After this, what-if analyses were carried out. This involved examining the extent to which changes in assumptions or preconditions influence the results.

3 Scenarios

This Chapter describes the construction of the ADAPT and TRANSFORM scenarios (Section 3.1), the development of the energy-intensive industry therein (Section 3.2) and the scenario variants for the energy-intensive industry (Section 3.3). The parameterisation of the scenarios and scenario variants is discussed in Chapter 4.

3.1 ADAPT and TRANSFORM

The same base storylines (ADAPT and TRANSFORM) were used for this study as in the scenario studies published by TNO in 2020 (Scheepers M. , et al., 2020) and 2022 (Scheepers M. , et al., 2022). Storylines have been drawn up for the 2020 study that describe two possible visions on the future (see box 1). These two visions are still relevant to the current study. However, political choices have been made for a more concrete and ambitious climate policy. This has resulted in new policy objectives for the European Union (Green Deal, Fit-for-55, REPowerEU) and the Netherlands (revision of the Climate Act 2023 (Dutch Govermenent, 2023)). The two base scenarios have been adjusted accordingly, addressing key factors such as greenhouse gas emissions and energy use, while maintaining similar policy goals for both scenarios. The more ambitious scenario (TRANSFORM) now corresponds more closely with the desired transition path based on the 'Nationaal Plan Energiesysteem' (EZK, 2023). To realize this transition path, by 2035 a scale jump is required in four chains: electricity, green hydrogen, sustainable heat and non-fossil carbon. If this jump in scale is not sufficiently achieved, fossil energy will have to continue to play a role in the Dutch energy system and the GHG reduction can only be achieved with the application of CO_2 storage (Afman, et al., 2023). The ADAPT scenario presents such a transition path in which the policy goals are achievable, but where a fully sustainable energy system is not yet realized. In both scenarios economic growth (GDP growth of 1.5% per year) and demographic development are assumed to be the same, as well as the prices for energy commodities on the world market.

Box 1 – Visions on the future (storylines)

ADAPT
- *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.*
- *Planning for structural change post 2050.*
- *To abate CO_2 emissions, fossil fuels are expected to be utilised in combination with carbon capture and storage (CCS).*

TRANSFORM
- *The 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.*

3.2 Industry in ADAPT and TRANSFORM

This scenario study takes a closer look at possible alternative developments for four energy-intensive sectors in the industry: refineries, high value chemicals industry[6], steel industry and fertiliser industry. The base scenarios serve as a reference. Table 3.1 describes the assumptions associated with the two base scenarios for the four industry sectors. The TRANSFORM scenario assumes behavioural changes in society, as a result of which the demand for mobility and products is lower than the ADAPT scenario. This applies to all four industrial sectors considered:
- Due to fewer flights and more local production (results in less international shipping), the demand for bunker fuels is lower.
- Due to sustainable design, less packaging material, etc., the demand for plastics is lower.
- Due to sustainable design (longer lifetime, reuse) there is less demand for steel.
- Sustainable agriculture leads to a reduction in the demand for fertiliser.

[6] High value chemicals (HVCs) refer to olefins (e.g. ethylene, propylene and butadiene) and aromatics (e.g. benzene, xylene and toluene) currently produced via steam cracking in the organic chemical industry.

Table 3.1: Representation of four industries in ADAPT and TRANSFORM in 2050

	ADAPT	TRANSFORM
Overall GHG emission reduction targets	• Climate neutrality by 2050 • EU ETS implementation resulting in zero emissions at industry before 2050 • For international bunkering 50% GHG emissions reduction (tank-to-wheel)	• Climate neutrality by 2050 • EU ETS implementation resulting in zero emissions at industry in 2040. • Also climate neutrality for the international bunkering (tank-to-wheel).
Refineries	• Meet 10% of the EU fuel market demand • Reduce fossil refining by 50% due to transport policies and the decreased demand for fossil fuels; demand relates mainly to diesel, kerosene and marine fuels • Renewable fuel refineries meeting the 10% EU 27 demand • Import biomass wood chips/pellets • No or limited imports of renewable fuels	• Meet 10% of the EU fuel market demand • Reduce fossil refining capacity by 80% due to decreased demand for fossil fuels; demand relates mainly to kerosene (for export) and marine diesel oil (both for export and to meet the demand in the Netherlands) • Renewable refineries meeting the 10% EU 27 demand. • Import biomass wood chips/pellets • No or limited imports of renewable fuels
High value chemicals	• Production of HVCs continue to grow as the demand for plastics grow • Circularity plays a limited role, thus overall recycling is limited • Plastics recycling limited by the available Dutch waste mix • Non-fossil carbon feedstock demand/supply is driven by the refinery transition in the NL • Limited import of aromatics	• Circularity plays an important role, as a result demand for plastics reduced by 40% compared to ADAPT • Chemical recycling plays an important role • Plastics recycling is limited by the available Dutch waste mix • A target for non-virgin fossil carbon content is set at 80% for the year 2050 • Limited import of aromatics
Fertilisers	• Fertilisers demand grows, so is the production in the Netherlands • Limited import of ammonia	• Production will be lower than ADAPT in 2050 • Limited import of ammonia
Steel industry	• Production will continue to increase up to 2030 and will be constant afterwards • Hisarna iron production process with CCS	• Production volume is reduced by 25% compared to ADAPT • There will be no CCS • DRI based on natural gas is implemented by 2030/2035 shifting gradually to green hydrogen in 2050 • Switch to electric arc furnace (EAF)

3.3 Scenario variants for industry

The Dutch energy-intensive industry faces a major challenge in making their production more sustainable in the coming decades. The energy-intensive industrial production in the Netherlands grew because feedstocks for industry, including oil, could easily be supplied from all over the world via seaports and products could be exported via the same seaports or transported further into Europe via good road, rail and waterway infrastructure. In addition, the Netherlands had access to a large amount of relatively cheap natural gas. Some of these comparative advantages continue to exist (sea ports, transport infrastructure, sales markets), others will disappear (e.g. natural gas) and new ones arise (e.g. wind energy production and CO_2 storage in depleted gas fields under the North Sea). Making production more sustainable requires major investments. It is not taken for granted that companies with existing factories in the Netherlands will build their new production facilities in the Netherlands as well. Companies can build their new factories in places where sustainable energy (e.g. electricity, hydrogen) and sustainable feedstocks (e.g. biomass) are available in sufficient quantities and at relatively low prices (i.e. relative to the costs of renewable energy in the Netherlands). In that case, the products will be produced with lower volumes in the Netherlands or production will totally disappear. Companies with production outside the EU may be faced with import duties as a result of the Carbon Border Adjustment Mechanism (CBAM (European Commisson)) if they ship the products to the EU. It is also possible that part of the production chain takes place abroad, i.e. close to available sustainable energy and feedstocks, and semi-finished products (e.g. hydrogen, ammonia, pyrolysis oil, bio-ethanol, bio-naphtha, hot briquetted iron, etc.) are transported to be converted into final products in the Netherlands. Also recycling of materials (e.g. in the production of steel, plastics) can be a reason to have production taking place closer to the end-user markets.

In the transition to sustainable production, companies of the four energy-intensive industrial sectors have three choices:

1) Continue the production in the Netherlands with transformation to a sustainable production.
2) Moving the energy-intensive part of the production chain to a location outside the Netherlands where sufficient sustainable energy and feedstocks are available at low prices, shipping the semi-finished products to the Netherlands (or purchase the semi-finished products from the world market) and maintaining the production of the final product in the Netherlands.
3) Moving the production to a location outside the Netherlands where sufficient sustainable energy and feedstocks are available at lower prices and shipping the final product to the Netherlands and Europe.

The Expertteam Energiesysteem 2050 states that it is unlikely that the Dutch economy will become sustainable without structural changes, that the comparative advantages of the Netherlands will change and suggests that this should be taken into account in scenario studies (Discussiepaper Economie, 2022). The Guidehouse study for the sustainable industry roadmap (Guidehouse, 2023) identifies three different future scenarios for the Dutch energy-intensive industry that lead to different development paths. The visions on the future for the Dutch industry differ in the scale of production and exports and the amount imported (feedstocks and/or semi-finished products).

The changes in comparative advantages lead to uncertainties about the future competitive position of the four energy-intensive industrial sectors. This concerns the competitive position with regard to the energy/feedstock intensive part of production and the competitive position with regard to the end products. This is investigated in this study with scenario variants in which production volume and imports are changed. Figure 3.1 shows a matrix in which the competitive position for the entire production varies between competitive (left) and less competitive (right) on the X-axis. The Y-axis shows the competitive position for the semi-finished products, also between competitive (top) and less competitive (bottom). The matrix creates four quadrants. In the two left-hand quadrants the volume of production of the end products does not change significantly, while in the right-hand quadrants there is a considerably lower production. In the top two quadrants, the energy-intensive part of production takes place in the Netherlands, while in the two bottom quadrants this production is (partially) moved outside the Netherlands and semi-finished products are imported. One of the base scenarios has been chosen for the scenario in the top left quadrant that serves as a reference against which the scenario variants are compared. The TRANSFORM scenario fits best here because in this scenario the sustainability of industrial production is implemented to a larger extent than in ADAPT. Moreover, ADAPT assumes that the structure of the Dutch industry will not change, i.e. this storyline does not match with de assumptions in the variants. Note that the production volume in TRANSFORM is lower than in ADAPT, because it is assumed that a more sustainable production process goes hand in hand with a societal change in the use of products (see Section 3.1).

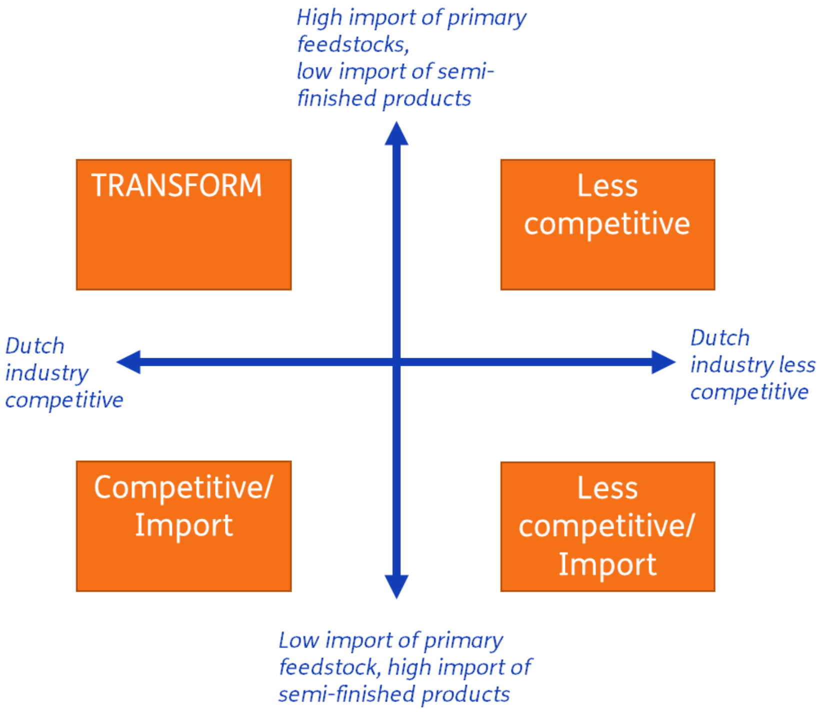


Figure 3.1: Matrix for the industry variants

Scenario variants have been drawn up for the three other quadrants. These three industry variants will be compared with the TRANSFORM scenario. It is assumed that the competitive position changes in the same way for all four sectors. Although there are parallels (iron, ammonia and synthetic fuel production require electricity/hydrogen; biofuels and bioplastics are based on biomass), future developments may be quite different for each of the four sectors. There are only dependencies to consider between refineries and organic chemicals industry. A comparable development in all four sectors could have significant consequences for the entire Dutch energy system. For this reason, it has been decided to limit the shifts somewhat (to lower production volume, to import semi-finished products). This study is primarily concerned with gaining insights into the extent to which developments in industry can influence the Dutch energy system, and not with a precise quantification. A description of the current situation for the four industry sectors and sustainable production alternatives can be found in Appendix B.

Refineries

The TRANSFORM scenario is based on a storyline, where the Dutch refineries will continue to serve to the European market. While fossil refineries will shrink, renewable refineries will be built. The future of (renewable) refineries will depend, among others, on their cost-competitiveness. The future contribution of Dutch refineries may become lower due to limited availability of renewable resources and the wish to build these new refineries close to the resources. In addition, the demand for renewable fuels will depend on the fuel demand for international bunkering. Maritime bunkering in the Netherlands and in Europe appears as one of the sectors prone to competition. Different studies indicate that certain policy measures introduced in the Fit-for-55 package (i.e. REDIII targets, ETD, FuelEU Maritime proposal) may result in international maritime bunkering shifting to other regions in the world (Patrahau, van Geuns, Faber, & van den Toon, 2023) (Faber, Meijer, Nelisen, & van der Toorn, 2022) (Faber, van den Berg, & Leestemaker, 2021). Given that the international maritime bunkering in the Netherlands is very large, the analysis of a future scenario with lower bunkering demand appears as important.

The TRANSFORM scenario considers imports of primary solid biomass (in the form of wood chips and pellets) to the Netherlands to produce transport fuels. This means large quantities of solid biomass will be needed. There have been many discussions around the sustainability and availability of biomass (Strengers & Elzenga, 2020) (SER, 2020) (Panoutsou & Maniatis, 2021) (Faaij, 2018). In addition to how much biomass can be imported (fair share versus other discussions), the land requirements to store wood chips and wood pellets for further processing resulted in questions around primary biomass versus semi-finished or finished products. Therefore, analysis of primary biomass import versus import of semi-finished and finished products deemed necessary.

High value chemicals
The TRANSFORM scenario considers substantial changes in the demand for and use of plastics. Circular strategies have the potential to significantly reduce the demand for new plastics. These material demand reductions are the result of changes in consumption patterns, policy measures (e.g. bans, right to repair), changes in product design (design for longer life, repair, recycling) and new business models (sharing economy, repair services, reuse systems). Based on these considerations, the TRANSFORM scenario assumes a 40%[7] reduction in plastic demand, which can translates to 40% reduction in the production of HVCs, compared to the ADAPT scenario.

While in TRANSFORM and the Less competitive variant recycled plastics are limited to the supply available in the Netherlands, availability increases in the two other variants due to the import of plastic waste. The TRANSFORM scenario assumes a mixture of plastic streams to be comparable to the current mix. As alternative a more substantial change in product design (more mono-materials) and in collection and separation of plastic waste (deposit systems, more separate collection) can be considered. This allows for a substantial increase in mechanical recycling of the separated plastic streams and uptake of polymer specific chemical recycling technologies such as glycolysis in the variants Competitive & Import and Less Competitive & Import. However, the latter technology falls outside the scope of the OPERA model.

Steel
For the TRANSFORM scenario a decreasing production volume is assumed in line with the storyline. The TRANSFORM scenario includes the use of innovative technology, i.e. a gradual transition to direct reduced iron (DRI) production, first with natural gas and from 2040 onwards with hydrogen. TRANSFORM assumes that the Netherlands can produce sufficient hydrogen at prices that are competitive with hydrogen imports. This gives steel production in the Netherlands a competitive advantage compared to steel production abroad. An electric arc furnace (EAF) will be used for steel production.

In the industry variants, two developments are possible for the Dutch steel industry that can be considered in combination or independently:

- The enormous challenge of achieving sustainable steel production in the Netherlands may result in less steel being produced locally. This may be due to technical (e.g. upscaling) challenges or a loss of competitive position against foreign producers of high-

[7] This reduction share assumption is described in Appendix D

quality sustainable steel. For example, DRI production could be cheaper elsewhere (due to the availability of relative cheap hydrogen) or because of implemented the technology on large scale earlier.

- For technical and/or economic reasons, it may be decided to produce no or only a part of the pig iron in the Netherlands from iron ore and to import hot briquetted iron (HBI) for the production of high-quality steel in electric arc furnaces (EAF). Increasing the use of scrap iron can limit the demand for HBI and can be part of a strategy to increase recycling flows. However, this development was not investigated in the model analysis.

Fertilisers

In line with the storyline the ammonia production in the TRANSFORM scenario is decreasing over time. A limited amount is imported (15%), partly as green ammonia. TRANSFORM assumes that the Netherlands can produce sufficient hydrogen at prices that are competitive with hydrogen imports. This will ensure that Dutch fertiliser manufacturers remain competitive in future. However, the Dutch fertiliser industry may face a loss of competitive position in future, for example because ammonia production based on green hydrogen is cheaper in places with a wide supply of sustainable electricity. This could lead to decrease Dutch fertiliser production and the closure of one of the fertiliser plants (assumed in variants Less competitive and Less competitive & Import). If hydrogen import is cheaper than hydrogen production in the Netherlands, green hydrogen can be imported or fertilisers can be produced from imported green ammonia (assumed in variants Competitive & Import and Less competitive & Import).

Summary

Table 3.2 summarizes the industry variants defined for the four basic industry subsectors in the Netherlands. The described industry variants focus on the situation around 2050. However, the scenario analyses will be carried out for the period 2030-2050 (including the transition towards 2050). Recycle streams (e.g. plastic waste, scrap) are expected to increase. These streams are considered as semi-finished products in the scenarios.

Table 3.2: Scenarios variants for industry

	Variant Less competitive • Dutch industry less competitive • No import of semi-finished products[a]	Variant Competitive & Import • Dutch industry stays competitive • Import of semi-finished products[a]	Variant Less competitive & Import • Dutch industry less competitive • Import of semi-finished products[a]
Refineries	• Due to high competition refineries serve only 5% of the EU's demand • Import of wood chips and pellets to produce transport fuels • High competition in fuels result in refinery product slate shifting to production of naphtha and aromatics/reformate	• Continue to serve the EU market (10%) • Renewable refineries are based on import of renewable-intermediates (biooil, ethanol, renewable H_2 carriers) • 50% of the renewable fuel demand is to be met by (semi-) finished product imports → bio oil, ethanol + H_2 import	• Due to high competition refineries serve only 5% of the EU's demand • Renewable refineries are based on import of renewable-intermediates (biooil, ethanol, renewable H_2 carriers) • 50% of the renewable fuel demand to be met by (semi-) finished product imports → bio oil, ethanol + H_2 import
HVCs	• Further reduction of HVCs production in the Netherlands (-40% compared to 2019) • Plastic waste availability is kept to national plastic waste • Plastic waste composition is comparable with the current composition	• Production of HVCs (-20% compared to 2019) • Plastic waste import from the EU is possible • Due to broader circularity implementation substantial change in product design, as a result higher mechanical recycling	• Further reduction of HVCs production in the Netherlands (-40% compared to 2019) • Plastic waste import from the EU is possible • Due to broader circularity implementation substantial change in product design, as a result higher mechanical recycling
Steel	• Production volume is 50% of production in TRANSFORM • In 2030/35 DRI on natural gas, no CCS; from 2040 DRI on hydrogen • For steel production switch to electric arc furnace (EAF)	• Production volume same as in TRANSFORM. • Limited iron production, instead import HBI. • Increase scrap iron content to 30% without decreasing the quality of the steel.	• Production is 50% of production in TRANSFORM • No iron production. instead import of HBI. • Increase scrap iron content to 30% without decreasing the quality of the steel.
Fertiliser	• Fertiliser production in the Netherlands is concentrated in one plant. • Limited import of ammonia (15%), ammonia mainly produced by the fertiliser plant.	• The two Dutch fertiliser plants remain in operation. One fertiliser plant shifts completely to ammonia import, whereas thee other fertiliser plant produces ammonia from imported hydrogen.	• Fertiliser production in the Netherlands is concentrated in one plant and based on imported ammonia.

[a] Semi-finished products refer to:

- Refineries: bio-intermediates, such as bio oil, ethanol, hydrogen
- HVCs: bio/renewable-naphtha, bio oil, ethanol, bio/renewable methanol, plastic waste, hydrogen
- Fertilisers: green ammonia, hydrogen
- Steel: hot briquetted iron (HBI), hydrogen

4 Scenario parameters

To quantify the scenarios with the OPERA model, the scenarios must be provided with input parameters. The parameterization of the base scenarios is explained in Section 4.1 and of the scenario variants for the energy-intensive industry in Section 4.2.

4.1 ADAPT and TRANSFORM

The basic scenarios have been updated to reflect the most recent policy targets. This involves adjustments of existing policy targets and new policy targets decided by the Dutch government and adjustments that arise from European policy. In addition, adjustments have been made with regard to preconditions for technology options, in particular restrictions on maximum technology use (potentials).

Policy targets

The following policy targets are applied to the base scenarios (see also Table 4.1):

- A GHG reduction target of 55% applies for 2030 and by 2050 no net greenhouse gas emissions may be emitted (Dutch Govermenent, 2023), i.e. GHG neutral. A recent correction for 1990 greenhouse gas emissions has been included, i.e. an increase of 1.6 Mtonne for the 1990 emissions (Klimaat en Energieverkenning 2023, 2023).
- Sectoral GHG reduction targets have been set in 2030 (Brief aan Tweede Kamer - Voorjaarsbesluitvorming Klimaat, 26 april 2023). The sectoral policy targets add up to a higher GHG reduction than 55% (a reserve margin has been built in). In the base scenarios, the sectoral targets apply for 2030, but in order to achieve an integral target of 55%, these targets have been slightly adjusted (i.e. without reserve margin). No sectoral GHG reduction targets apply in the base scenarios beyond 2030.
- Also GHG reduction targets for 2035, 2040 and 2045 of 70%, 80% and 90% GHG reduction apply (VVD, D66, CDA en ChristenUnie, 2021).
- In the TRANSFORM scenario the GHG emissions of the Dutch ETS sector is zero in 2040 and following years as a result of the tightening of allowances proposed by the European Commission (Fit for 55 package). For ADAPT no specific target is applied for the ETS sector.
- GHG emissions from international aviation and shipping fall outside the Dutch reduction target. To which extent sustainable fuels are part of bunker fuels in the Netherlands are influenced by GHG reduction measures for these sectors. The TRANSFORM scenario assumes that GHG emissions in 2050 for international aviation and shipping are reduced by 100%, with a 2040 reduction target of 53% for international aviation and 70% for maritime shipping. The ADAPT scenario assumes a less ambitious GHG reduction: 50% in 2050 and a reduction target in 2040 of 30% for international aviation and 45% for maritime shipping.
- In addition to GHG reduction targets, both scenarios also take into account the target for maximum final energy use in 2030. Following the European Energy Efficiency Directive (EED) (European Commission) the energy saving target for the Netherlands for 2030 is -11.0% for final and -11.7% for primary energy use (Gerdes & Menkveld, 2023). This results in a maximum energy use in 2030 of 1609 PJ for final and 1935 PJ for primary

energy consumption. Because the reduction of final energy demand is a binding target and the reduction of primary energy use is indicative, the maximum final energy demand of 1609 PJ is used as an additional target for 2030.
- In both the ADAPT and the TRANSFORM scenarios it is assumed that the policy target of 1.6 billion cubic meters (bcm) (50 PJ) of biomethane use in the built environment will be achieved in 2030. This is based on the policy target for a blending obligation of 1.6 bcm in 2030 (Brief aan Tweede Kamer - Bijmengverplichting groen gas, 4 juli 2022). The target has now been adjusted downwards to 1.1 bcm (Kamerbrief aanpassing bijmengingverplichting groe gas, 9 februari 2024). No target for biomethane use is applied in the years after 2030. Furthermore, in 2030, the use of biomass will be limited to 7.8 PJ for district heating and 4.8 PJ for horticulture greenhouses, because biomass for heat applications in no longer supported (Brief aan Tweede Kamer - Beleidsinzet biogrondstoffen, 22 april 2022).
- From 2030, coal-fired power plants can no longer be used (Wet verbod op kolen bij elektriciteitsproductie, 2019).

Demand
An important driver for the model analysis is the demand that the energy system must meet. The applied input parameters for demand assume an equal demographic development of the Dutch population in both scenarios. Also for economic development the same development (an annual GDP growth of 1.7%) is assumed for both scenarios, and recessions are not taken into account within the time period studied. Demographic development and economic growth are reflected in the development of input demand parameters (see Table 4.2) for industry (production volumes for largest sectors and additional energy demand), built environment (numbers for houses, square meters for services), the agricultural sector (energy demand) and transport sector (passenger and freight kilometres and fuel demand for international transport). The values for these demand developments for the ADAPT scenario have been taken from the Climate and Energy Outlook 2022 (Klimaat en Energieverkenning, 2022). To reflect the assumed behavioural changes 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 are assumed compared to ADAPT. To compensate for lower industrial production, TRANSFORM assumes that the service sector will become larger than in the ADAPT scenario.

Technology
From a set of approximately 600 technology options, the model analysis selects those techniques that result in an energy system that can meet demand, meet policy goals and lead to a system with the lowest social costs. Technology options include techniques for production, conversion, transport and use of energy, techniques for capturing, transporting and storing CO_2 and other CO_2 sequestration technologies, and energy saving options. The techno-economic data for these options are retrieved from a database containing current data and projections for parameter values in 2030 and 2050, see Appendix E. In addition, a number of techniques are described in data sheets[8]. The performance and cost parameters for 2030 and 2050 take into account technology learning, i.e. cost reduction and performance improvement as a result of R&D and technology deployment. For technologies with learning potential for which the learning rate is unknown, an investment cost reduction of 20% is assumed between 2030 and 2050. It is assumed that the technology development and the costs of the technology are the same in both scenarios.

[8] See: https://energy.nl/datasheets/

Table 4.1: GHG reduction targets

	Unit	ADAPT					TRANSFORM				
		2030	2035	2040	2045	2050	2030	2035	2040	2045	2050
GHG reduction target (wrt 1990)[a]	%	55%	70%	80%	90%	GHG neutral	55%	70%	80%	90%	GHG neutral
GHG emissions per sector[b]	Mtonne CO_2eq	103.0	68.6	45.7	22.9	0	103.0	68.6	**45.7**	**22.9**	**0**
Built environment		14.1					14.1				
Agriculture		19.1					19.1				
Land use		1.9					1.9				
Mobility		22.4					22.4				
Industry		31.6					31.6				
Power sector		13.9					13.9				
ETS sector[c]								23.65	**0**	**0**	**0**
GHG emissions international transport	Mtonne CO_2eq										
Aviation (% reduction wrt 2005)		10.7[d]	9.4	8.1	6.2	5.5 (50%)	9.2[d]	6.9	4.6	2.3	0 (100%)
Shipping (% reduction wrt 2008)		34.4[d]	32.5	30.5	28.6	26.7 (50%)	31.2[d]	23.4	15.6	7.8	0 (100%)
Final energy use	PJ	1609					1609				
Circular carbon target for production of chemicals	%	5%[e]	0%	0%	0%	0%	5%[e]	20%	40%	60%	80%

[a] Climate Act 2023

[b] Letter to Parliament of 26 April 2023

[c] In TRANSFORM the GHG emissions of the Dutch ETS sector is zero in 2040 according to the tightening of allowances proposed by the European Commission (Fit for 55 package. For ADAPT no specific target will be applied

[d] Based on a 6% renewable and low-carbon fuels share (European Commission, 2023), (European Commission, 2021)

[e] This non-fossil criterium is added in line with policy described in (Ministerie van Infrastructuur en Waterstaat, 2023)

Table 4.2: Demand input parameters

Sector	Unit	ADAPT					TRANSFORM				
		2030	2035	2040	2045[a]	2050[a]	2030	2035	2040	2045[a]	2050[a]
Industry											
Steel production	Mtonne	7.2	7.2	7.2	7.2	7.2	6.48	6.21	5.94	5.67	5.4
Ammonia production	Mtonne	2.83	2.92	3.01	3.1	3.2	2.38	2.14	1.9	1.63	1.34
Olefine production	Mtonne	5.50	5.76	6.07	6.40	6.72	4.95	4.75	4.56	4.32	4.03
Aromatics production	Mtonne	4.37	4.57	4.82	5.08	5.34	3.98	3.81	3.64	3.44	3.20
Methanol production	Mtonne	0.51	0.53	0.55	0.57	0.59	0.46	0.44	0.41	0.39	0.36
Chlorine production	Mtonne	1.14	1.2	1.27	1.34	1.41	1.03	0.99	0.95	0.9	0.84
Salt production	Mtonne	8.22	8.6	9.09	9.6	10.11	7.39	7.09	6.82	6.48	6.06
Glass production	Mtonne	0.97	1	1.02	1.05	1.07	0.87	0.86	0.84	0.84	0.85
Ceramic production	Mtonne	3.04	3.04	3.05	3.05	3.06	2.73	2.62	2.51	2.46	2.41
Non-energetic use other industries	PJ	19.00	19.35	19.75	20.15	20.57	19.00	19.35	19.75	20.15	20.57
Waste incineration	PJ	29.37	29.37	29.35	29.37	29.37	62.49	54.68	46.87	29.29	15.62
Mobility											
Passenger road traffic	Billion vehicle kilometres	117	122.77	128.88	134.8	140.79	111.1	112.8	114.8	116.7	119.7
Light freight traffic	Billion vehicle kilometres	21.36	22.54	23.6	24.69	25.77	21.15	22.09	22.89	23.7	24.48
Heavy freight traffic	Billion vehicle kilometres	8.63	8.94	9.28	9.6	9.93	8.54	8.76	9	9.22	9.43
Inland shipping	Billion vehicle kilometres	53.84	55.27	56.7	58.13	59.55	54.38	56.38	58.4	60.45	62.53
Bus transport	Billion vehicle kilometres	0.68	0.68	0.68	0.68	0.68	0.69	0.7	0.7	0.71	0.72
Lubricant use	PJ	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7
Energy demand for mobile equipment											
Agriculture	PJ	15	15.6	15.19	15.19	15.19	11.25	9.79	9.01	8.82	8.63
Industry	PJ	25.5	23.9	13.68	21.87	20.84	22.95	19.72	10.26	14.76	12.5
Service sector	PJ	7.09	7.09	7.09	7.09	7.09	7.99	8.42	8.85	9.27	9.7
Energy demand international transport											
International aviation	PJ	159.3	168.31	178.35	186.24	194.16	137.7	145.4	153.1	160.8	170
International shipping	PJ	472.6	472.4	474.1	476.3	469.1	429.4	408.5	387.5	364	340.6

[a] trend is extrapolated

Table 4.2: Demand input parameters (continued)

Sector	Unit	ADAPT					TRANSFORM				
		2030	2035	2040	2045[a]	2050[a]	2030	2035	2040	2045[a]	2050[a]
Building stock											
Number of apartments	Million	2.97	3.09	3.14	3.18	3.23	2.97	3.09	3.14	3.18	3.23
Number of terraced houses	Million	2.43	2.52	2.57	2.6	2.64	2.43	2.52	2.57	2.6	2.64
Number of other homes	Million	2.84	2.95	3	3.05	3.09	2.84	2.95	3	3.05	3.09
Gross floor area education	Million m^2	32.19	31.5	30.83	30.16	29.5	32.19	31.5	30.83	30.16	29.5
Gross floor area hospitals	Million m^2	21.24	23.38	25.86	28.48	31.1	21.24	23.38	25.86	28.48	31.1
Gross floor area commercial buildings	Million m^2	173.9	184.19	195.14	206.42	217.7	173.9	184.2	195.1	206.4	217.7
Gross floor area offices	Million m^2	68.89	69.56	70.01	70.77	71.45	72.34	74.78	77.11	79.62	82.16
Gross floor area data centres	Million m2	1.62	2.05	2.59	3.30	4.19	1.62	2.05	2.59	3.30	4.19
Gross floor area other service sector buildings	Million m^2	134.8	136.99	138.64	139.83	141.02	134.8	137	138.6	139.8	141
Other heat demand											
Agriculture	PJ	70.66	66.46	71.65	71.65	71.65	56.53	53.36	50.18	46.59	42.99
Base metal – ferro	PJ	10.22	19.01	9.218	9.06	8.901	8.41	8.08	7.61	7.13	6.67
Base metal – non-ferro	PJ	1.42	1.4	1.45	1.44	1.44	1.46	1.21	1.25	1.44	1.24
Fertiliser industry	PJ	6.24	12.02	12.81	12.16	13.78	10.25	8.6	9.19	7.04	6.33
Chemical industry	PJ	94.38	95.47	111.32	104.66	131.52	86.23	80.36	92.78	91.32	95.76
Food and beverage industry	PJ	40.6	37.65	38.55	37.95	38.26	40.6	34.97	38.68	34.97	38.03
Other industry	PJ	36.69	40.76	40.53	41.97	36.97	43.65	45.96	52.17	45.03	43.79
Waste processing industry	PJ	62.49	62.49	62.49	63.49	64.49	6.4	5.78	5.17	4.58	3.84
Other fuel demand Transport	PJ	23.98	23.65	23.29	22.66	22.86	37.79	34.43	27.29	30.91	28.68

[a] trend is extrapolated

Table 4.2: Demand input parameters (continued)

Sector	Unit	ADAPT					TRANSFORM				
		2030	2035	2040	2045[a]	2050[a]	2030	2035	2040	2045[a]	2050[a]
(Other[a]) electricity demand											
Households	TWh	19.58	20.14	20.65	21.23	21.83	19.58	20.14	20.65	21.23	21.83
Service sector (incl. data centres)	TWh	26.75	27.63	28.86	30.15	31.00	29.79	31.68	34.12	36.80	39.18
Agriculture	TWh	7.03	7.19	7.65	7.65	7.65	9.14	9.71	10.71	11.09	11.47
Basis metal – ferro	TWh	2.11	2.11	2.11	2.11	2.11	1.90	1.82	1.74	1.66	1.59
Basis metal – non-ferro	TWh	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Fertiliser industry	TWh	0.36	0.10	0.0	0.0	0.0	0.30	0.07	0.0	0.0	0.0
Chemical industry	TWh	12.01	12.35	12.33	13.02	13.64	10.98	10.32	9.34	8.83	8.18
Food and beverage industry	TWh	10.57	10.21	10.52	10.38	10.35	10.57	10.21	10.52	10.38	10.35
Other industry	TWh	10.35	10.49	10.93	11.16	11.31	11.39	11.86	12.69	13.29	13.82
Waste processing industry	TWh	1.94	1.94	2.08	2.13	2.20	1.94	1.70	1.56	1.33	1.10
Transport[b]	TWh	1.95	2.01	2.07	2.13	2.20	1.97	2.05	2.14	2.22	2.31

[a] Electricity demand in addition to electrification of heat appliances and industrial processes, e.g. lighting, mechanical drives, etc.
[b] This concerns electricity demand for trains and trams.

There are deployment restrictions for a number of technologies. These limitations relate to when technology becomes available, the growth of the technology that is realistic, and physical or policy limitations. The maximum deployment possible (potentials) for different technology options is shown in Table 4.3. In line with current Dutch energy policy in the scenarios it is not allowed to operate coal-fired power plants after 2030. The existing Borssele nuclear power plant will be in operation until 2043, i.e. an extended service lifetime of 10 years proposed and under investigation by the Dutch government. 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).

Energy prices

The prices for fossil fuels are based on advice from the European Commission (Recommended parameters for reporting on GHG projections in 2023, unpublished document shared with Member States, 2022), with the middle price scenario used for natural gas. These prices are the same as used in the Climate and Energy Outlook 2022 (Klimaat en Energieverkenning, 2022). The prices used for biofuels (biodiesel and bioethanol) are assumed to be constant over the period considered and correspond to figures from the AdvanceFuel project[9]. Prices for green hydrogen, green ammonia and e-methanol are derived from a HyDelta study (Hajonides van der Meuelen, Scaric, Tyraskis, & Verstraten, 2022).

Non-GHG and indirect CO_2 emissions

The model analysis takes into account non-GHG and indirect CO_2 emissions that arise outside the energy system. For this purpose, a baseline projection is used as input in the model, see Table 4.5. For CH_4, N_2O, F-gases and land use (i.e. LULUCF: Land Use, Land Use Change and Forestry), emission levels have been assumed per scenario in line with the underlying storylines. There are a number of technology options available in the OPERA model to reduce non-GHG emissions to meet the overall GHG target.

[9] See: http://www.advancefuel.eu/

Table 4.3: Potentials for technology options

	Unit	ADAPT					TRANSFORM				
		2030	2035	2040	2045	2050	2030	2035	2040	2045	2050
Wind energy potential	GW										
Onshore		7.8	7.8	7.8	7.8	7.8	7.8	8.9	10	11	12
Offshore		16[a]	26	36	38	40	16[b]	30.5	45	57.5	70[c]
Solar energy potential (PV)	GW	36.6[b]	52.7	68.6	88.8	109.0	42.9[a]	64.7	83.6	107.7	132.1
Nuclear capacity	GW										
Borssele[d]		0.5	0.5	0.5			0.5	0.5	0.5		
New nuclear power potential											
Gen III			1.5	3	3	3		1.5	3	3	3
SMR				0.45	0.9	2			0.45	0.9	2
Gen IV						0.2					0.2
CO_2 storage potential	Mtonne										
Industry		9.7[e]	24	35	40[f]	40[f]	9.7[e]	12.7	12.7	12.7	15[g]
Power generation		3[e]					3[e]				
Geothermal potential[h]	PJ	50	88	125	163	200	50	88	125	163	200
Biomass potential	PJ										
Domestic		164	183	202	221	241	164	175	186	198	209
Import[i]		83.4	225	366	508	650	83.4	225	366	508	650

[a] 6 GW additional to Climate agreement

[b] Monitor RES 1.0 (PBL, 2021)

[c] 70 GW wind offshore is based on (Matthijsen, Dammers, & Elzinga, 2018). An other study by Taminiau and Van der Zwaan calculates a potential of 99 GW (Taminiau & van der Zwaan, 2022).

[d] For Borssele an extended service life time of 10 years is assumed after 2033;

[e] Climate agreement, 2.5 Mtonne additional for industry (2022). However, the subsidy ceiling in the SDE++ will expire in 2023, i.e de facto there is no maximum.

[f] The potential is derived from the total available storage capacity of 1,600 to 1,700 Mt in the Dutch part of the North Sea (Joint Fact Finding CO_2-afvang en -opslag, Klimaattafel, 2018).

[g] Potential needed for sufficient negative emissions

[h] Based on (Platform Geothermie, 2018).

[i] TNO own assessment based on the recent DG RTD study (EC, 2024). The assessment approach can be found in annex C.

Table 4.4: Energy prices

		ADAPT and TRANSFORM				
	Unit	2030	2035	2040	2045	2050
Natural gas	€2015/GJ	10.7	10.7	10.7	10.7	11.2
Oil	€2015/GJ	14.6	14.6	15.4	16.6	18.6
Coal	€2015/GJ	2.9	2.9	3.1	3.3	3.5
Biomass, used cooking oil (UCO)	€2015/GJ	16.2	16.2	16.2	16.2	16.2
Biomass, woody, domestic	€2015/GJ	5.4	5.4	5.4	5.4	5.4
Biomass, woody, import, cheap	€2015/GJ	9.7	9.7	9.7	9.7	9.7
Biomass, woody, import, expensive[a]	€2015/GJ	12.7	12.7	12.7	12.7	12.7
Bio-oil	€2015/GJ	8	8	8	8	8
Bio-methanol	€2015/GJ	27.3	25.4	45.9	35.7	66.4
Bio-ethanol	€2015/GJ	34.3	32.8	56.8	61.7	118.9
Bio-kerosine	€2015/GJ	33.8	29.9	41.1	23.2	45.8
E-methanol	€2015/GJ	230.8	218.0	205.3	192.5	179.8
E-kerosine	€2015/GJ	36.5	22.8	41.1	23.2	23.2
Hydrogen	€2015/GJ	24.7	20.7	16.7	12.7	8.7
Ammonia	€2015/GJ	167.2	149.0	130.8	112.7	94.5

[a] 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 4.5: Non-GHG and indirect CO_2 emissions

	Unit	ADAPT					TRANSFORM				
		2030	2035	2040	2045	2050	2030	2035	2040	2045	2050
CH_4											
Built environment	Mt CO_2-eq	0.39	0.37	0.36	0.34	0.32	0.39	0.37	0.36	0.34	0.32
Agriculture	Mt CO_2-eq	10.49	10.31	10.72	10.75	10.76	7.87	6.47	6.37	6.24	6.11
Industry	Mt CO_2-eq	2.64	2.22	1.93	1.64	1.35	2.64	2.22	1.93	1.64	1.35
Energy	Mt CO_2-eq	0.10	0.00	0.00	0.00	0.00	0.10	0.00	0.00	0.00	0.00
Transport	Mt CO_2-eq	0.07	0.06	0.05	0.03	0.02	0.06	0.05	0.03	0.02	0.01
N_2O											
Agriculture	Mt CO_2-eq	4.75	4.68	4.61	4.57	4.54	3.56	2.94	2.74	2.66	2.58
Industry	Mt CO_2-eq	0.43	0.43	0.44	0.44	0.44	0.38	0.37	0.37	0.36	0.36
Energy	Mt CO_2-eq	0.11	0.00	0.00	0.00	0.00	0.11	0.00	0.00	0.00	0.00
Transport	Mt CO_2-eq	0.22	0.20	0.18	0.16	0.15	0.18	0.15	0.13	0.10	0.08
F-gases											
Other industry	Mt CO_2-eq	0.87	0.77	0.73	0.70	0.66	0.77	0.66	0.62	0.58	0.54
Transport	Mt CO_2-eq	0.13	0.03	0.02	0.00	0.00	0.11	0.02	0.01	0.00	0.00
Indirect CO_2 emissions											
Households	Mt CO_2-eq	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
Agriculture	Mt CO_2-eq	0.28	0.28	0.28	0.29	0.29	0.21	0.18	0.17	0.17	0.17
Chemical sector	Mt CO_2-eq	0.88	0.91	0.93	0.97	1.00	0.90	0.75	0.70	0.66	0.60
Other industry	Mt CO_2-eq	0.67	0.68	0.69	0.69	0.70	0.67	0.68	0.69	0.69	0.70
LULUCF	Mt CO_2-eq	3.66	3.08	2.92	2.80	2.66	3.66	3.08	2.92	2.80	2.66

Industry
In this scenario study, a number of specific assumptions apply to the four industry sectors in the base scenarios ADAPT and TRANSFORM, see Section 3.2. Table 4.6 shows the input parameters that apply to these four industry sectors. In the base scenarios no imports of (energy) commodities are assumed (hydrogen, biofuels, methanol, fossil/renewable naphtha, LPG and HVO), except for ammonia. In both scenarios it is assumed that part of the imported ammonia is produced from green hydrogen. Importing green hydrogen (produced from renewable energy) by ship in the form of ammonia is expected to be possible sooner than importing green hydrogen by ship or pipeline. This ammonia is used for fertiliser production and is not converted back to hydrogen. With domestically produced hydrogen and imported green hydrogen, the Netherlands can meet the RFNBO objective outlined in the Renewable Energy Directive (RED III).

Recycled plastics are used via chemical recycling for the production of high-value chemicals. In 2030, in the TRANSFORM scenario, the assumption is that 5% of the recycled plastics available in the Dutch market will be used as feedstock for HVC production. This percentage increase by 16.25% in 2035, 27.5% by 2040, 38.75% by 2045 and 50% by 2050. In the ADAPT scenario, recycled plastics are also used as feedstock for HVC production, but in smaller quantities: 0% in 2030, 3.25% in 2035, 7.5% in 2040, 15% in 2045 and 16.25% in 2050.

For steel production, the TRANSFORM scenario assumes the introduction of Direct Reduction Iron (DRI), with proportions of 10% in 2030, 20% in 2035, 40% in 2040, 80% in 2045 and 100% in 2050, starting with natural gas, switching to green hydrogen in 2040. In the ADAPT scenario, no technology choice is imposed.

4.2 Scenarios variants for industry

The input parameters for industry sectors used in the industry variants are shown in Table 4.7. The selected parameters correspond to the descriptions from Section 3.3. While Section 3.3 mainly describes the situation in 2050, this section also provides insight into the assumed change in the parameters over the period 2030-2050.

Table 4.6: Input parameters for industry sectors in ADAPT and TRANSFORM base scenarios

	Unit	ADAPT					TRANSFORM				
		2030	2035	2040	2045	2050	2030	2035	2040	2045	2050
Refineries											
Total production	PJ	1802	1652	1502	1352	1201	1442	1171	901	631	360
High value chemicals											
Olefins production	Mtonne	5.50	5.76	6.07	6.39	6.72	4.95	4.75	4.56	4.32	4.03
Aromatics production[a]	Mtonne	4.37	4.57	4.82	5.08	5.34	3.98	3.81	3.64	3.44	3.20
Plastic recyling (chemical)[b]	ktonne	0	54	108	162	216	43	140	237	334	431
Steel											
Total production	Mtonne	7.20	7.20	7.20	7.20	7.20	6.48[c]	6.21[c]	5.94[d]	5.67[d]	5.40[d]
Fertiliser											
Total production	Mtonne	2.84	2.92	3.01	3.10	3.20	2.38	2.14	1.90	1.63	1.34
Ammonia import[e]	Mtonne	0.43	0.44	0.45	0.47	0.48	0.36	0.32	0.29	0.24	0.20

[a] Instead of production, a maximum of 1.1 Mtonne of fossil aromatics can be imported at a price of 14.6 €/GJ.

[b] In ADAPT, 0% and TRANSFORM 5% of plastic waste will be used as feedstock through chemical recycling in 2030. This increases linearly to 15% for ADAPT and 50% for TRANSFORM in 2050.

[c] In 2030 50% DRI and in 2035 on natural gas.

[d] From 2040 onwards 100% DRI on hydrogen.

[e] 15% green NH_3 import.

Table 4.7: Input parameters for industry sectors in TRANSFORM and industry variants

		TRANSFORM					Competitive & Import					Less Competitive					Less Competitive & Import				
		2030	2035	2040	2045	2050	2030	2035	2040	2045	2050	2030	2035	2040	2045	2050	2030	2035	2040	2045	2050
Refineries																					
Total production	PJ	1442	1171	901	631	360	1442	1171	91	631	360	721	586	451	315	180	721	586	451	315	180
Import bio-intermediates[a]	%						50%	50%	50%	50%	50%						50%	50%	50%	50%	50%
High value chemicals																					
Olefins production	Mt	4.95	4.75	4.56	4.32	4.03	4.95	4.72	4.49	4.26	4.03	4.95	4.50	4.05	3.59	3.14	4.95	4.50	4..05	3.59	3.14
Aromatics production	Mt	3.98	3.81	3.64	3.44	3.20	3.98	3.81	3.64	3.44	3.20	3.98	3.61	3.32	2.86	2.49	3.98	3.61	3.32	2.86	2.49
Plastic input (chem. recycling)b	Kt	43	140	237	334	431	43	536	1029	1522	2015	43	140	237	334	431	43	425	807	1188	1570
Steel																					
Total production	Mt	6.48[c]	6.21[c]	5.94[d]	5.67[d]	5.40[d]	6.48[c]	6.21[c]	5.94[d]	5.67[d]	5.40[d]	3.24[c]	3.11[c]	2.97[d]	2.83[d]	2.70[d]	3.24[c]	3.11[c]	2.97[d]	2.83[d]	2.70[d]
Pig iron import	%						50%	50%	50%	50%	50%						100%	100%	100%	100%	100%
Scrap	%						30%	30%	30%	30%	30%	20%	20%	20%	20%	20%	30%	30%	30%	30%	30%
Fertiliser																					
Total NH_3 production[e]	Mt	2.38	2.14	1.90	1.63	1.34	2.38	2.14	1.90	1.63	1.34	1.43	1.28	1.14	0.98	0.80	1.43	1.28	1.14	0.98	0.80
Ammonia import	Mt	0.36	0.32	0.29	0.24	0.20	1.43	1.28	1.14	0.98	0.80	0.21	0.19	0.17	0.15	0.12	1.43	1.28	1.14	0.98	0.80
Hydrogen importf							8.9	8.0	28.5	24.5	20.1										

[a] Bio-intermediates are bio pyrolysis oil and bioethanol; In variants Competitive & Import and Less Competitive & Import, hydrogen used for synthetic fuel production is also imported. Amounts depend on H_2 import price.

[b] In variants Competitive & Import and Less Competitive & Import, plastic input in 2030 is comparable to TRANSFORM base case, with a linear increase thereafter to 50% in 2050.

[c] In 2030 50% DRI and in 2035 on natural gas.

[d] From 2040 onwards 100% DRI on hydrogen.

[e] Ammonia production in the Netherlands is divided over two production facilities, one of which accounts for 60% and the other 40%. In variants Less Competitive and Less Competitive & Import the one that accounts for 60% will continue.

[f] In 2030 and 2035 only 25% of ammonia production from H_2, from 2040 onwards 100%; 1 Mtonne NH_3 requires 0.3 Mtonne H_2; calorific value H_2 125 MJ/kg.

5 Results for ADAPT and TRANSFORM

In this chapter the results of the ADAPT and TRANSFORM scenarios are presented. Section 5.1 shows an integrated picture of the future energy system in terms of primary energy supply and final energy consumption. Sankey diagrams, which can be found in Appendix F, also provide an overview of the future Dutch energy system according to ADAPT and TRANSFORM. Section 5.2 takes a closer look at the energy supply and Section 5.3 at the energy consumption in different sectors. The reduction of GHG emissions and CO_2 capture, storage and use is discussed in Section 5.4. Carbon balances of the two scenarios are also shown in that section. Section 5.5 shows results for electricity, hydrogen and CO_2 transport. Investments required for the energy transition and the costs of the future energy system are discussed in Section 5.5. Finally, results from a number of what-if analyses are discussed in Section 5.6.

5.1 Energy supply and consumption

5.1.1 Primary energy supply

Total primary energy supply encompasses the sum of all primary energy sources available within the Netherlands, both produced domestically and imported. It essentially reflects the total amount of energy available from primary energy sources before undergoing any conversion or transformation process. Total primary energy supply includes raw energy forms such as crude oil, natural gas, coal, uranium and renewable sources (e.g. wind and solar energy) along with imported energy in its various forms. This metric is fundamental in providing a holistic overview of the energy sources for the Netherlands, as is illustrated in Figure 5.1.

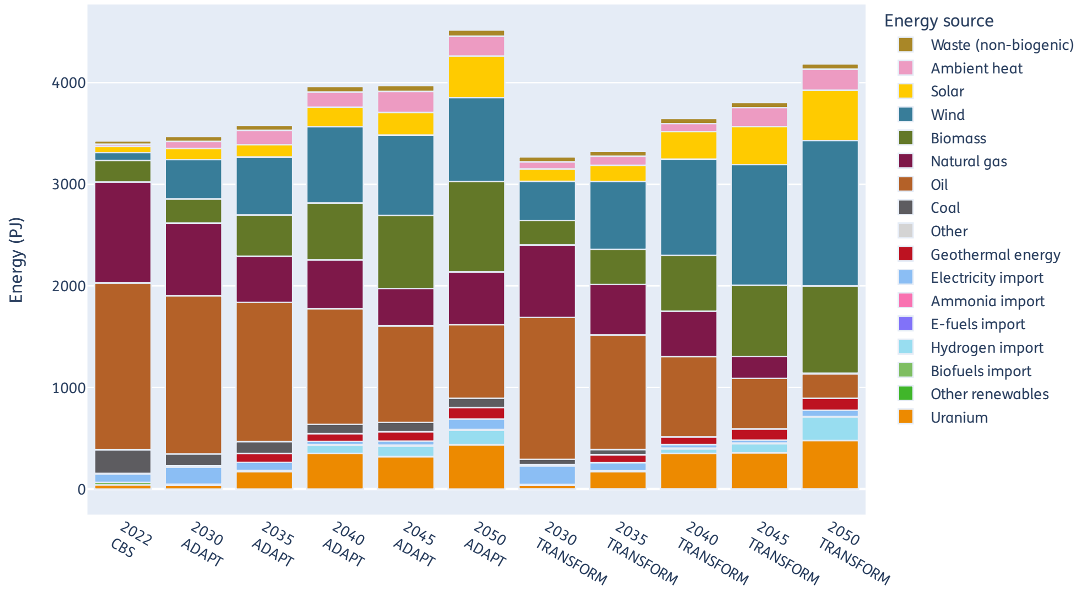


Figure 5.1: Total primary energy supply in 2022 and in ADAPT and TRANSFORM (2030 to 2050), including non-energy use and energy for international aviation and shipping (bunker fuels)

ADAPT shows a steady, albeit slower, increase in renewables compared to TRANSFORM. This slower pace aligns with ADAPT's approach of balancing current technological realities with future ambitions without drastic shifts. TRANSFORM, with its focus on a more aggressive reduction of fossil fuel use, use of innovative technologies, and application of efficient options, exhibits a rapid decline in conventional energy sources and a faster shift towards renewable energy sources, which can be also observed in energy imports, as exemplified by hydrogen imports. Moreover, ETS regulations will ensure that no greenhouse gases are emitted in industry from 2040 onwards. This will accelerate changes in industrial production, such as the introduction of direct reduced iron in steel production in the TRANSFORM scenario replacing coal by green hydrogen. ADAPT, on the other hand, maintains a relatively stable use of coal, although this is lower than 2019 levels because of the phase-out of coal fired power plants. As industry switches to cleaner processes and other end-use sectors start using different energy carriers, the energy profile changes, increasing the share of renewable energy sources in the energy mix.

A key observation in the TRANSFORM scenario is the more moderate increase for the total primary energy supply over time, compared to ADAPT. This trend is driven by TRANSFORM's strategy for reduced energy demand and industrial production, leading to less demand for feedstocks, i.e. non-energetic energy use. TRANSFORM also assumes larger reductions in GHG emissions from international aviation and shipping sectors by 2050 and more use of circular carbon compared to ADAPT, which directly impacts the energy mix.

The specifics of this transition is reflected in the variations in energy sources, such as solar, wind, and fossil fuels, across both scenarios. The role of nuclear energy increases significantly in both scenarios, thus contributing to a CO_2-free energy mix.

Besides, solar and wind energy, both scenarios also reveal a rising trend in the use of ambient heat and biomass, which underscores their integral role in the future energy landscape. Figure 5.2 shows primary energy supply, but only for domestic energy, excluding non-energy use and bunker fuels. While the primary energy supply excluding bunker fuels and non-energetic use of TRANSFORM is initially still below the level of ADAPT, from 2040 this primary energy use in TRANSFORM will be higher. This is caused by the application of more energy techniques with significant conversion losses, such as electrolysers. The primary energy mix for domestic energy use in Figure 5.2 is comparable to the energy mix in Figure 5.1. Overall, the trends depicted in Figure 5.1 and Figure 5.2 clearly portray the contrasting approaches of ADAPT and TRANSFORM in steering towards a sustainable energy future, each marked by its own set of priorities and pace. This report dig into the specific drivers behind these trends in the following sections.

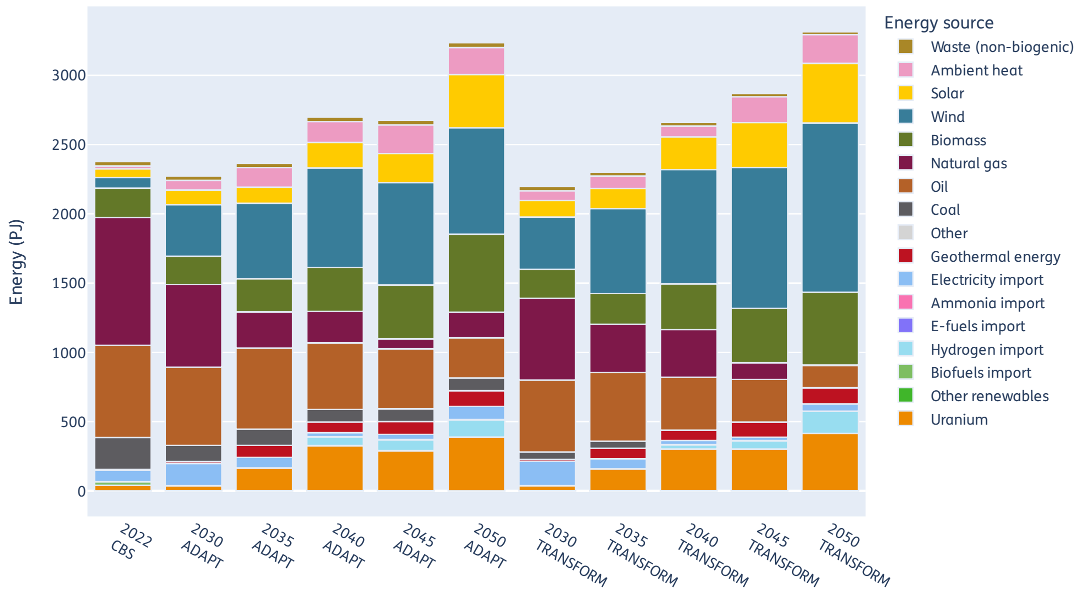


Figure 5.2: Total primary energy supply for ADAPT and TRANSFORM scenarios for domestic energy use, excluding non-energy use and energy for international aviation and shipping (bunker fuels)

5.1.2 Final energy consumption

Final energy consumption represents the amount of energy utilized by end-users in sectors such as the built environment, industry, agriculture and transportation (domestic and international). This amount is based on total primary energy supply after subtracting energy lost during transmission, distribution, and conversion. Figure 5.3 presents the total final energy consumption under two scenarios, ADAPT and TRANSFORM, from 2030 to 2050. For ADAPT, the final energy consumption experiences a steady growth over the entire period. In contrast, the final energy consumption in TRANSFORM is lower and shows a slightly decreasing trend. This is the result of a lower demand for energy and mobility and smaller industrial production compared to ADAPT as a result of the assumption on behavioural change in TRANSFORM, see scenario parameters in Table 4.2. Figure 5.4 shows the total final energy domestic consumption, i.e. excluding non-energy use and bunker fuels. It should be noted that the final consumption shown in this figure deviates from the definitions used in the Energy Efficiency Directive (EED) (European Commission). In the EED, ambient heat is excluded from final energy consumption, but fuels for aviation are included. The EED target for final energy consumption of 1609 PJ has been applied for 2030, but not for the following years. See Section 5.7 for further discussion on final and primary energy consumption.

In the scenarios, no target has been imposed for the share of renewable energy for 2030. The revised Renewable Energy Directive (REDIII) (European Commission, 2023) sets a binding target to increase the share of renewable energy in total European gross final consumption to at least 42.5% in 2030, with the ambition to aim for 45%. The Dutch contribution to this target is 39% renewable energy in 2030. The model results show that the ADAPT and TRANSFORM scenarios with a renewable energy share of 43% in 2030 meet this target.

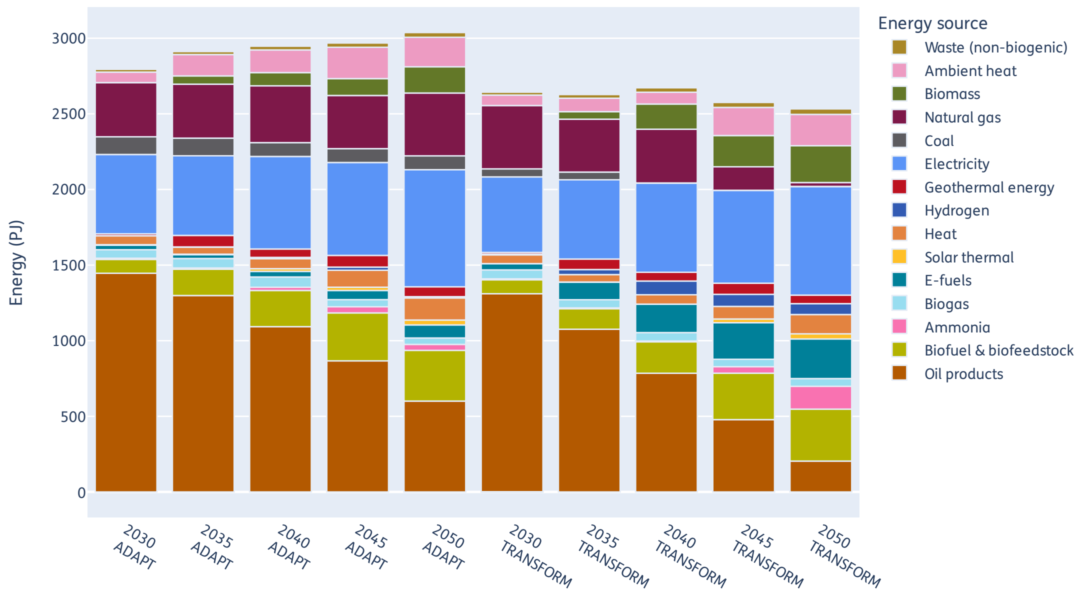


Figure 5.3: Final energy consumption for ADAPT and TRANSFORM scenarios, including non-energy use and energy for international aviation and shipping (bunker fuels) 5.

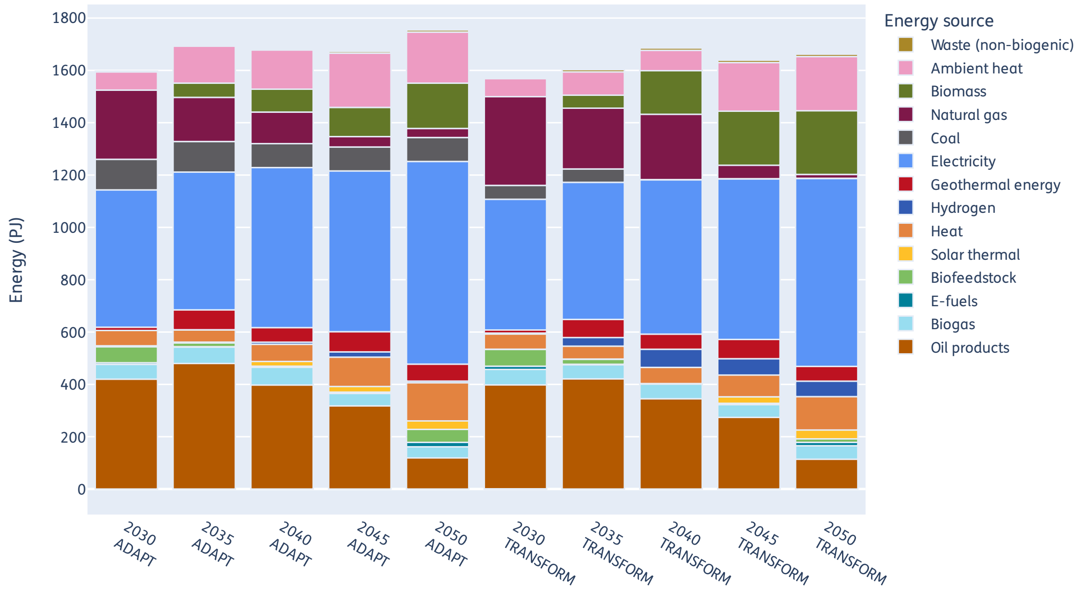


Figure 5.4: Final energy consumption for ADAPT and TRANSFORM scenarios, excluding non-energy use and energy for international aviation and shipping (bunker fuels)

5.2 Energy supply

5.2.1 Electricity

Electricity consumption

Both scenarios expect an increase in electricity consumption (see Figure 5.5). This growth in demand is the result of electrification of energy demand in all sectors, which mainly concerns shifts from fuels to electricity for heat production (e.g. electric boilers and heat pumps) and mobility (e.g. electric vehicles), see also Sections 5.3.2 and 5.3.4. In addition, the increase in electricity consumption is the result of the strong growth in hydrogen production with electrolysers (see Section 5.2.2). In 2050, excluding exports, the electricity consumption in ADAPT will be more than 2.7 times larger than that in 2022 (108.5 TWh according to CBS) and in TRANSFORM this will be almost 3.2 times. In 2050, 29% of domestic electricity consumption is used for hydrogen production in both scenarios. If electricity demand for hydrogen is ignored (and also exports), the electricity demand will increase with a factor 2.3 in 2050 compared to 2022 in ADAPT and with a factor 2.7 in TRANSFORM.

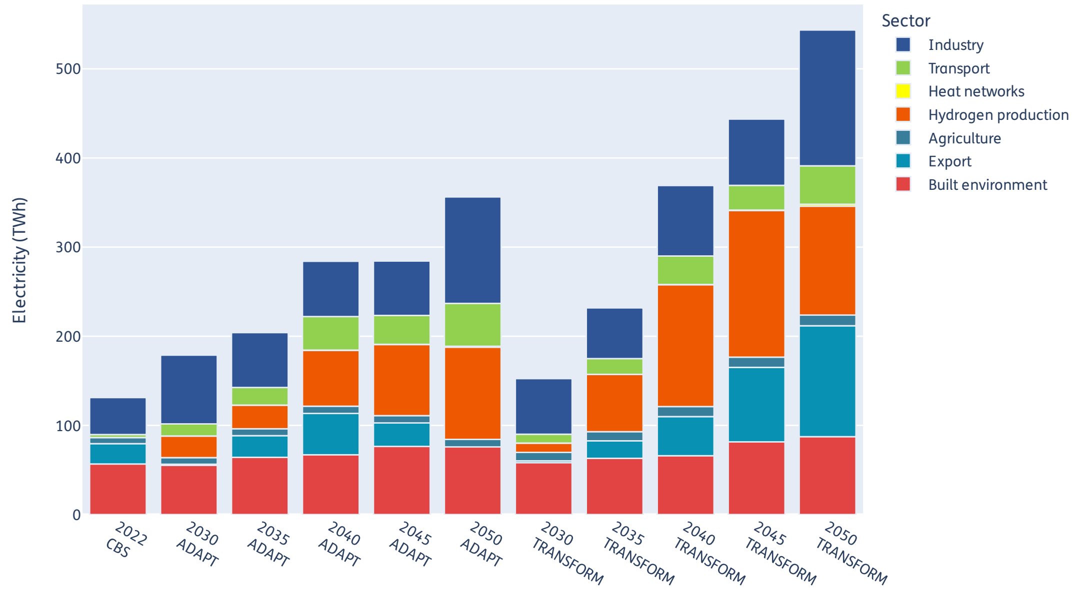


Figure 5.5: Electricity consumption in 2022 and in ADAPT and TRANSFORM (2030 to 2050)[10]

Electricity supply

As a result of growing electricity consumption, electricity supply is also increasing. The electricity supply consists of electricity production in the Netherlands supplemented with imports (see for discussion on electricity import and export below). The scenarios envisage a threefold increase of Dutch electricity production (i.e. without imports) in 2050 for ADAPT compared to 2022 and an almost fivefold increase in TRANSFORM (see Figure 5.6). The scenarios also show that electricity production is becoming more sustainable. This is happening under pressure from GHG emission reduction targets. The share of fossil fuels in electricity production (about 73% in 2019) is decreasing rapidly: in 2030 this share has fallen to 24% in ADAPT and 11% in TRANSFORM and in 2035 this is less than 3% in both scenarios. Electricity production is shifting to wind and solar energy, of which offshore wind accounts for the largest share. While the share of solar and wind energy was already 33% in 2022, this share will further increases in ADAPT to 73% in 2030 and 89% in 2050 and in TRANSFORM this share increases to even higher values: 85% and 91% respectively. In 2022, the Borssele nuclear power plant produced 4.1 TWh of electricity (a share of 3.5%). In both scenarios electricity production from nuclear energy will gradually increase from 2035 onwards by expanding the number of nuclear power plants resulting in 2050 in the production of 34.3 TWh (9.2%) in ADAPT and 40.7 TWh (7.1%) in TRANSFORM. A small part of the electricity in 2050 will be produced from waste incineration, residual gases from biomass conversion processes and from hydrogen.

[10] Unlike other graphs that show energy volumes in Petajoules (PJ), the electricity graphs show volumes in Terrawatt hour (TWh). 1 TWh is equal to 3.6 PJ.

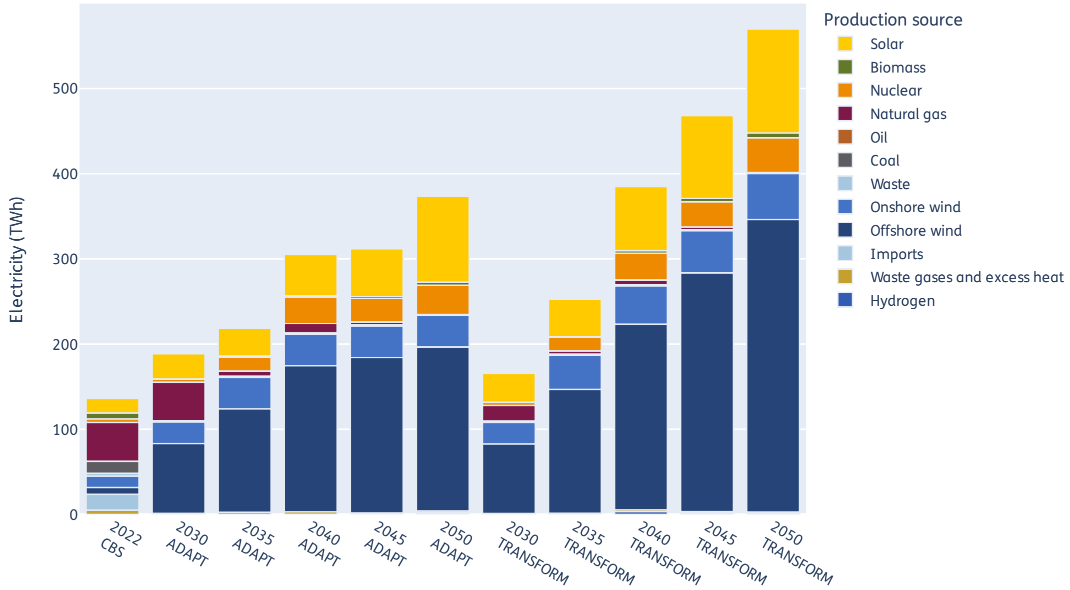


Figure 5.6: Electricity supply in 2022 and in ADAPT and TRANSFORM (2030 to 2050)

Electricity generation capacity

The development of the installed capacity for electricity production for ADAPT and TRANSFORM is shown in Table 5.1. For comparison, the installed capacity in 2022 is also shown. The total installed capacity increases significantly, even more strongly in TRANSFORM than in ADAPT. Compared to 2022, the total installed capacity in ADAPT increases with a factor 3.4 in 2050 and becomes in TRANSFORM 4.5 times larger. This is not only the result of growing electricity production, but also due to the type of electricity generation[11]. Electricity is only generated with wind and solar when the wind blows and the sun shines. For wind and solar power more capacity is needed for the same electricity production in comparison to a gas fired or nuclear power plant. The table also lists the potentials, i.e. the maximum installed capacity for solar, wind and nuclear energy that can be used in the model calculations (see explanation in Table 4.3). The maximum potentials are reached for onshore and offshore wind in all years in ADAPT. In TRANSFORM the potentials for onshore and offshore wind energy are assumed to be higher than in ADAPT, but also fully used because of higher electricity demand. In 2050, the potential for solar energy will also be fully utilized in both scenarios, with this potential also being larger in TRANSFORM than in ADAPT. The maximum capacity for the different types of nuclear power plants is fully utilized in TRANSFORM in all years but not in ADAPT (see Box 2).

[11] Strong growth in capacity is already visible in the figures for 2022. Compared to 2019, electricity production capacity in the Netherlands has since grown by almost 50% due to an increase in wind and solar capacity.

Table 5.1: Electricity production capacity (in GW) for the ADAPT and TRANSFORM scenarios

Type	2022	ADAPT									
		2030		2035		2040		2045		2050	
	Installed	Installed	Potential	Installed	Potential	Installed	Potential	Installed	Potential	Installed	Potential
Coal	4.1	**0**	0	0	0	0	0	0	0	0	0
Natural gas	18.9	12.7		11		15.5		15.5		0	
Nuclear	0.5	0.5	0.5	2.0	2.0	3.9	3.9	3.5	3.9	4.8	5.2
Solar	19.6	34.4	36.6	37.2	52.7	53.7	68.8	61.3	88.8	109.0	109.0
Onshore wind	6.2	7.8	7.8	7.8	7.8	7.8	7.8	7.8	7.8	7.8	7.8
Offshore wind	2.6	16	16	26	26	36	36	38	38	40	40
Biomass	0.3	0.7		7.1		12.5		17.7		18.8	
Hydrogen		0		0.1		0.6		0.6		6.5	
Other	1.5	3.4		3.4		0.7		0.1		0	
Total	53.7	75.6		94.4		130.7		144.4		186.7	

Type	2022	TRANSFORM									
		2030		2035		2040		2045		2050	
	Installed	Installed	Potential	Installed	Potential	Installed	Potential	Installed	Potential	Installed	Potential
Coal	4.1	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0
Natural gas	18.9	9.5		9.6		11.2		9.9		4.5	
Nuclear	0.5	0.5	0.5	2.0	2.0	3.9	3.9	3.9	3.9	5.2	5.2
Solar	19.6	39.0	49.6	45.5	64.7	83.6	83.6	106.7	107.7	132.1	132.1
Onshore wind	6.2	7.8	7.8	8.9	8.9	10	10	11	11	12	12
Offshore wind	2.6	16	16	30.5	30.5	45	45	57.5	57.5	70	70
Biomass	0.3	1.0		5.6		8.7		13.5		15.5	
Hydrogen		0		0.7		6.0		6.1		6.6	
Other	1.5	4.6		3.7		3.3		2.9		2.3	
Total	53.7	78.5		110.2		171.2		210.9		247.7	

Import and export of electricity

The modelling of the scenarios includes import and export of electricity through trade with neighbouring countries. At any time of the year, demand for electricity in the Netherlands can exceed supply, or the opposite occurs when domestic supply exceeds demand. The demand is then supplemented with electricity imports from abroad or the surplus is exported abroad. Figure 5.7 shows the total amount of imported and exported electricity per year and the balance thereof for both scenarios. There is a net export in all years that increases to 46 TWh in ADAPT and to 124 TWh in TRANSFORM (also visible in Figure 5.6), with the exception of ADAPT 2050, which shows a net import of 2 TWh (also visible in Figure 5.5). The changes in the total import and export volumes per year arise from the development of electricity demand and supply in the Netherlands and in neighbouring countries. In TRANSFORM in particular, electricity surplus from offshore wind is exported in addition to conversion into hydrogen.

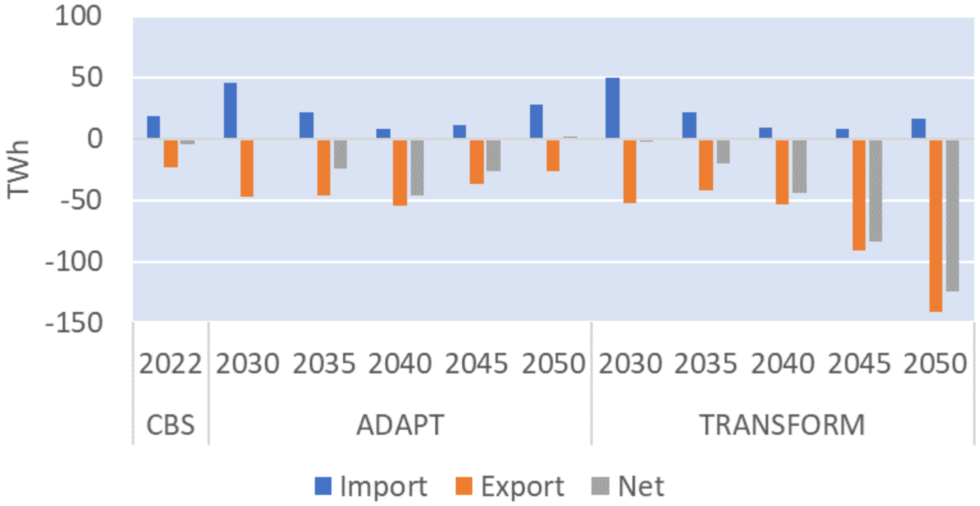
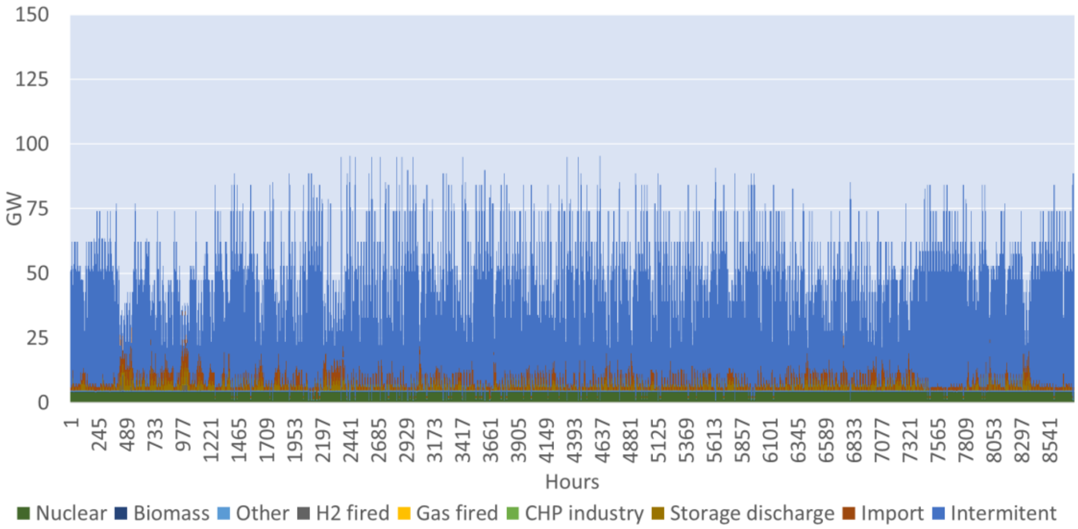


Figure 5.7: Total electricity import and export in 2022 (source: CBS) and in ADAPT and TRANSFORM

Balancing the electricity system

The OPERA model creates an energy balance for every hour of the year using supply profiles for wind and solar energy and a demand profile. This explains how the scenario calculations take fluctuating supply and demand of electricity into account. Figure 5.8 and Figure 5.9 show the results for 2050 for ADAPT and TRANSFORM respectively. The peak demand in ADAPT is 95 GW and in TRANSFORM this is 136 GW. The peak of electricity demand, i.e. excluding exports, energy storage and electricity for hydrogen production, amounts to 26 GW for ADAPT and 37 GW for TRANSFORM. In both scenarios, approximately 90% of the electricity is generated from wind and solar energy (shown as intermittent in the figures). To meet the base load demand, it is cost-optimal to install a relatively large amount of intermittent power and use the surplus that is not required for the base load demand for hydrogen production with electrolysers. Therefore, most of the time the electrolysers run at partial load and hydrogen is stored in empty salt caverns on land. Energy storage and the exchange of power with surrounding countries (import and export) also contribute to maintaining the electricity balance. Nuclear energy, biomass and industrial combined-heat and power (CHP) plants are used in base load. Hydrogen power plants are used as peak units: in ADAPT 123 full load hours and in TRANSFORM 182 full load hours.



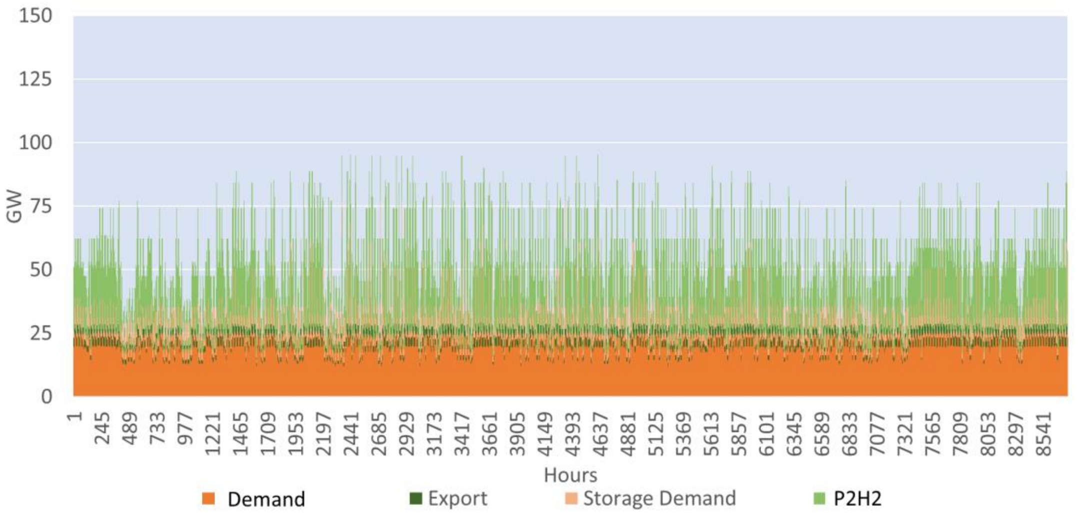


Figure 5.8: Hourly electricity supply (top) and demand (bottom) for ADAPT in 2050 (P2H2: power to hydrogen with electrolysers)

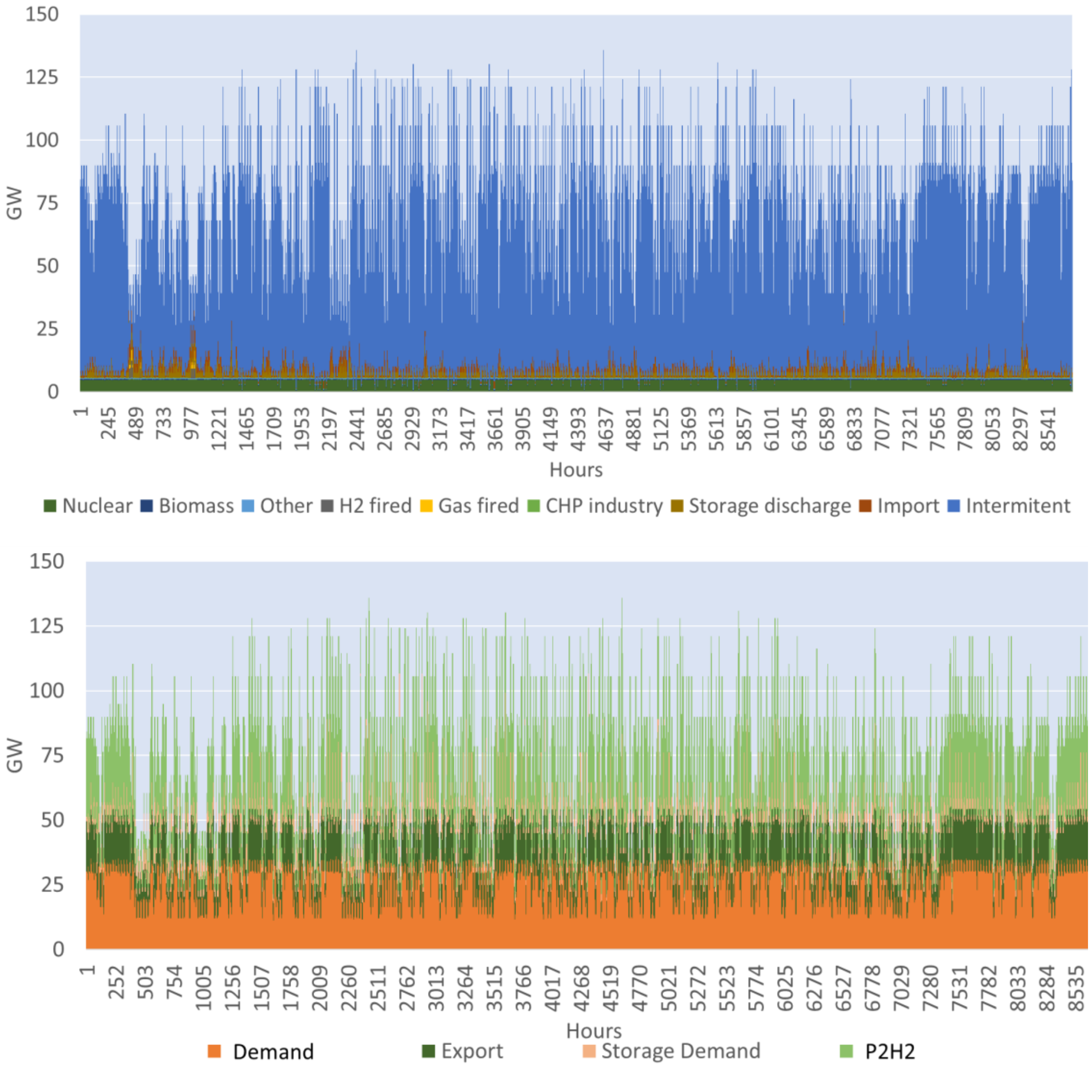


Figure 5.9: Hourly electricity supply (top) and demand (bottom) for TRANSFORM in 2050 (P2H2: power to hydrogen with electrolysers)

Box 2 - Nuclear energy

New nuclear power plants

In accordance with the proposed government policy regarding nuclear energy, the existing Borssele nuclear power plant will be kept in operation until 2043 in ADAPT and TRANSFORM. In addition new nuclear power plants are realized: large-scale nuclear power plants (generation III*), small modular nuclear power plants (small modular reactor (SMR), generation III) and , in 2050, also an advanced nuclear power plant (generation IV **). This takes into account the expected commercial availability and time to realize the nuclear reactors. **Table 5.1** shows that in TRANSFORM the nuclear energy capacity is expanded to the maximum potential, but not for ADAPT. In both scenarios the first large nuclear power plant will be put into operation in 2035, followed by a second one in 2040. Both the existing Borssele nuclear power plant and the new nuclear power plants provide base load electricity. The further expansion of nuclear energy capacity will take place with SMRs from 2040 onwards. The SMRs are located near industrial clusters and can, in addition to electricity, also supply steam to industrial processes. According to the scenario results in 2050 in TRANSFORM a total of 13 SMRs (with a size of 150 MW_e each) will be deployed near the industry clusters in South Holland, Zeeland and Limburg. In ADAPT in 2050 10 SMRs will be deployed, but only in South-Holland. In ADAPT the SMRs will deliver maximum heat production. This means that electricity production is about 40% lower compared to an SMR operated in electricity only mode. In 2045 that is also the case for TRANSFORM, but heat demand is substantially lower than in ADAPT. Because of this lower heat demand, but higher demand for electricity in TRANSFORM in 2045 and 2050, operations of most SMRs changes to lower heat and higher electricity production. The heat demand is then insufficient to operate SMRs to its full heat production capacity.

No new nuclear

In a what-if analyses of the ADAPT and TRANSFORM scenarios without new nuclear power plants no expansion of nuclear production capacity takes place. The total installed capacity will decrease because both scenarios have used the maximum potential of wind and solar energy. Both scenarios without new nuclear power plants show a lower electricity production compared to the base scenarios (changes in the exchange with foreign markets have not been considered). Lower availability of electricity leads to less hydrogen production. In ADAPT, a shift is taking place in bunker fuels, less synthetic fuels and more biofuels. In TRANSFORM, the hydrogen demand is lower, especially in the chemical sector.

In an energy system without new nuclear power plants, the total system costs in 2050 will be 1% to 2.5% higher than in a system with nuclear energy (see Section 5.6.2). Although investment costs for nuclear power plants are per kW higher than wind turbines and solar panels, the loss of base load supply by nuclear power plants must be compensated for by more use of flexibility options with relatively high costs (such as energy storage).

* Generation III reactors are further developed second generation reactors, such as those built in the 1970s and 1980s, including the Borssele nuclear power plant.

** Generation IV reactors are reactors that are still under development and are expected to perform significantly better than third generation reactors in terms of sustainability, economy, safety, and/or non-proliferation.

Nuclear energy (continued)

Industry variants
In the three industry variants, electricity production in 2050 is lower than in TRANSFORM: 9% lower in the Competitive & Import variant, 11% lower in the Less Competitive variant and 16% lower in the Less Competitive & Import variant (see Section 6.2 for explanation). The reduction for nuclear electricity production is somewhat stronger (13%, 19% and 29% respectively) and less strong for renewable electricity production. Lower industrial electricity demand in the industry variants reduces the base load, which is favorable for nuclear energy production. In the industry variants, the installed capacity for the SMRs is smaller than in TRANSFORM. This has to do with the smaller heat demand, which makes the use of SMRs in industry less attractive. The capacity for large-scale nuclear power plants in the industry variants remains the same as in TRANSFORM. The installed capacity for sustainable electricity production in the industry variants is also slightly smaller than in TRANSFORM.

The base scenario and industry variants provide a clear indication that the size of nuclear production capacity is related to the electricity demand. If electricity demand is lower, as in ADAPT and the industry variants compared to TRANSFORM, then the need for electricity production capacity is logically smaller, but this has more effect on the nuclear capacity than the capacity for renewable electricity production.

5.2.2 Hydrogen

Hydrogen demand
Hydrogen is currently mainly used in industrial processes for fertiliser production, oil refining and production of chemicals. This hydrogen is still produced from fossil fuels or produced as a by-product in chlorine production (total estimated production 180 PJ[12] per year (Weeda & Segers, 2020)). The hydrogen demand for fertiliser production and in refineries will continue to exist in the future. In addition, new hydrogen demand arises in the scenarios for steel production and for production of e-fuels (e.g. e-kerosine and ammonia as shipping fuel). Figure 5.10 shows Sankey diagrams for hydrogen consumption and supply in 2030 and in 2050 for both scenarios. The graphs show external hydrogen demand (i.e. tradable or merchant hydrogen) according to the ADAPT and TRANSFORM scenarios, i.e. excluding hydrogen that is produced and consumed within industrial production processes, such as ammonia production in fertiliser plants. Note that in addition to hydrogen production within chemical processes, chemical processes can also use merchant hydrogen.

In both scenarios, the demand for merchant hydrogen shows a strong increase in 2050 compared to 2030: from 141 PJ to 422 PJ in ADAPT and from 159 PJ to 560 PJ in TRANSFORM. Higher values in TRANSFORM can be explained from the ambitions to produce more sustainable bunker fuels and feedstocks, which, among other things, leads to a larger demand for e-fuels. In TRANSFORM, merchant hydrogen will be used from 2035 onwards for iron making (direct reduced iron) in steel production and from 2045 onwards for ammonia production in the fertiliser industry. In ADAPT no hydrogen is used for production of iron in steel manufacturing but a small amount is used for fertiliser production.

[12] 1 PJ is equal to 8,333 tonnes of hydrogen.

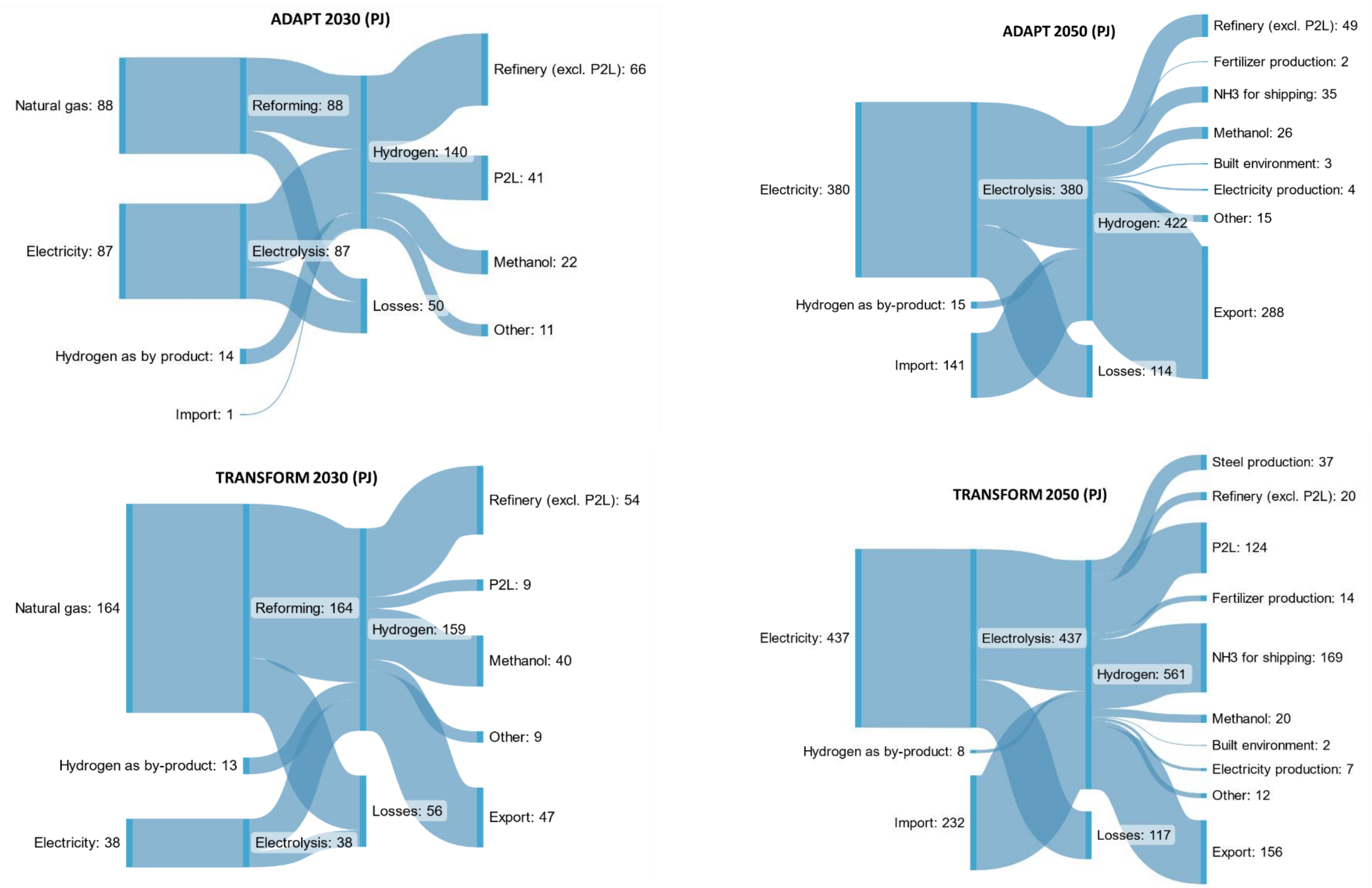


Figure 5.10: Hydrogen supply (left site of the diagrams) and consumption (right side of the diagrams) in ADAPT and TRANSFORM (P2L: power to liquid)

In both scenarios, hydrogen is also imported and exported from surrounding countries by pipeline but not by ship. In 2030 there will be hardly any imports, but TRANSFORM shows some exports. In both scenarios, export volumes will be significantly higher in 2050 and hydrogen will be imported as well. In 2050, ADAPT will have a net export of 147 PJ and TRANSFORM will have a net import of 76 PJ.

Demand for hydrogen is also emerging in other sectors: for district heating in the built environment and electricity production in both ADAPT and TRANSFORM, but in relative small amounts. In both scenarios, hydrogen is not used directly as a transport fuel for trucks. For an explanation, see Section 5.3.2.

Hydrogen supply
In both scenarios, the merchant hydrogen demand in 2030 will be met by green hydrogen produced from renewable electricity using electrolysers and blue hydrogen produced from natural gas with steam methane reforming and CO_2 capture and storage (CCS). In 2040 onwards only green hydrogen is produced with electrolysers. If green hydrogen becomes the most cost-effective way to produce CO_2-free hydrogen, the question is whether producers will invest in blue hydrogen for a relative short period. The production of green hydrogen mainly takes place offshore directly at the offshore wind farms and in particular at times when there is a surplus of wind energy (see Section 5.2.1). This hydrogen is subsequently transported to the mainland and a part of it is first stored in underground salt caverns. From there, the hydrogen is transported to the industry clusters. Building the electrolysers offshore is more cost-effective compared to electrolysers located at industry sites because transporting hydrogen through a pipeline network is cheaper than transporting electricity (Martínez-Gordón, Gusatu, Morales-Espana, Sijm, & Faaij, 2022).

Electrolyser capacity
Electrolyser capacity for producing tradable hydrogen in ADAPT and TRANSFORM in 2030 is 2 GW. This capacity increases in 2050 to 15 GW for ADAPT (of which 13.3 GW offshore) and 21 GW for TRANSFORM (of which 17.4 GW offshore)[13]. The number of full load hours for electrolysers differ per scenario: for ADAPT in 2030 and 2050 these are 7400 and 4900 respectively and for TRANSFORM 3500 and 4200. Installing such a large electrolyser capacity requires a lot of space, also if this is offshore, and building new or reusing existing pipelines offshore and onshore. In practice this may be difficult to realize. In a what-if analysis, electrolyser capacity has been reduced by 25% compared to the TRANSFORM base scenario (i.e. max. 16 GW in 2050). The model results show that limiting the capacity of the electrolysers by 25% leads to lower hydrogen production, but this is only 2% less than in the TRANSFORM base scenario. The capacity reduction is largely compensated by the fact that the number of full load hours of the electrolysers increases from 4200 to 5000 hours. In this what-if case electrolysers offer less flexibility to the electricity system. This is absorbed by an increase in the curtailment of electricity production from wind and solar and an increase in energy storage capacity. The slightly lower hydrogen supply leads to slightly lower hydrogen consumption in the chemical sector and synthetic fuel and feedstock production.

[13] In addition, electrolysers are also used in fertiliser plants for ammonia production and in refineries for the production of synthetic fuels and feedstocks. This electrolyser capacity (in 2050 6.6 GW in ADAPT and 8.7 GW in TRANSFORM) is integrated into the production processes and the hydrogen it produces is not considered tradable hydrogen.

5.2.3 Biomass

Figure 5.11 shows the use of biomass and its origin. Biomass available in the Netherlands consists of biogenic waste and residual wood. This is supplemented with biomass import: wood chips and used cooking oil (UCO). A maximum applies to the import of biomass (see Section 4.1). In 2030, about 95% of the available biomass will actually be used in both scenarios and in 2050 all available biomass will be used. The maximum biomass import is in 2050 larger than in 2030, but the available domestic biomass is slightly less in TRANSFORM because of lower biogenic waste due to behavioural change of consumers.

In 2030, the available biomass in both scenarios will be used for the production of biofuels for domestic transport, for district heating in the built environment and in the agriculture sector as biogas in combined heat and power (CHP) units and boilers. The energy and non-energy (i.e. feedstock) use of biomass in industry is relatively small in 2030. In both scenarios, biomass will be used in 2050 for the production of bunker fuels for international aviation and shipping. Compared to ADAPT, this is higher in TRANSFORM due to higher sustainability ambitions. Biofuel use for domestic transport will then have decreased compared to 2030 (see also Section 5.3.2). In both scenarios, the biomass use in industry will increase significantly in 2050, both for energy applications as for feedstock use. These volumes are larger in TRANSFORM than in ADAPT.

Note that biomass feedstocks are used in ADAPT, although no explicit sustainability target for feedstock use applies for this scenario. This is due to the demand for biofuels, in particular biokerosene in aviation (demand is higher in ADAPT than in TRANSFORM, see Section 5.3.3). In the production of biokerosene, bio-naphtha is a by-product that is used as a sustainable feedstock in the production of chemicals and plastics. As a result, by 2050 in ADAPT, 40% of the carbon in chemicals and plastics will be of biogenic origin. That is half of the circular carbon target that applies in TRANSFORM for 2050.

Part of the biomass is used for the production of methane gas (green gas). In 2030 in both scenarios 50 PJ green gas (= 1,6 BCM) is used in the built environment as a result of an imposed target (see Section 4.1). In ADAPT this increases to 73 PJ (=2,3 BCM) in 2050, but by then most of the green gas goes to industry and only 21 PJ is used in the built environment because there is no longer a specific target for this sector in 2050. In TRANSFORM the amount of green gas drops to 33 PJ of which 6 PJ is used in the built environment.

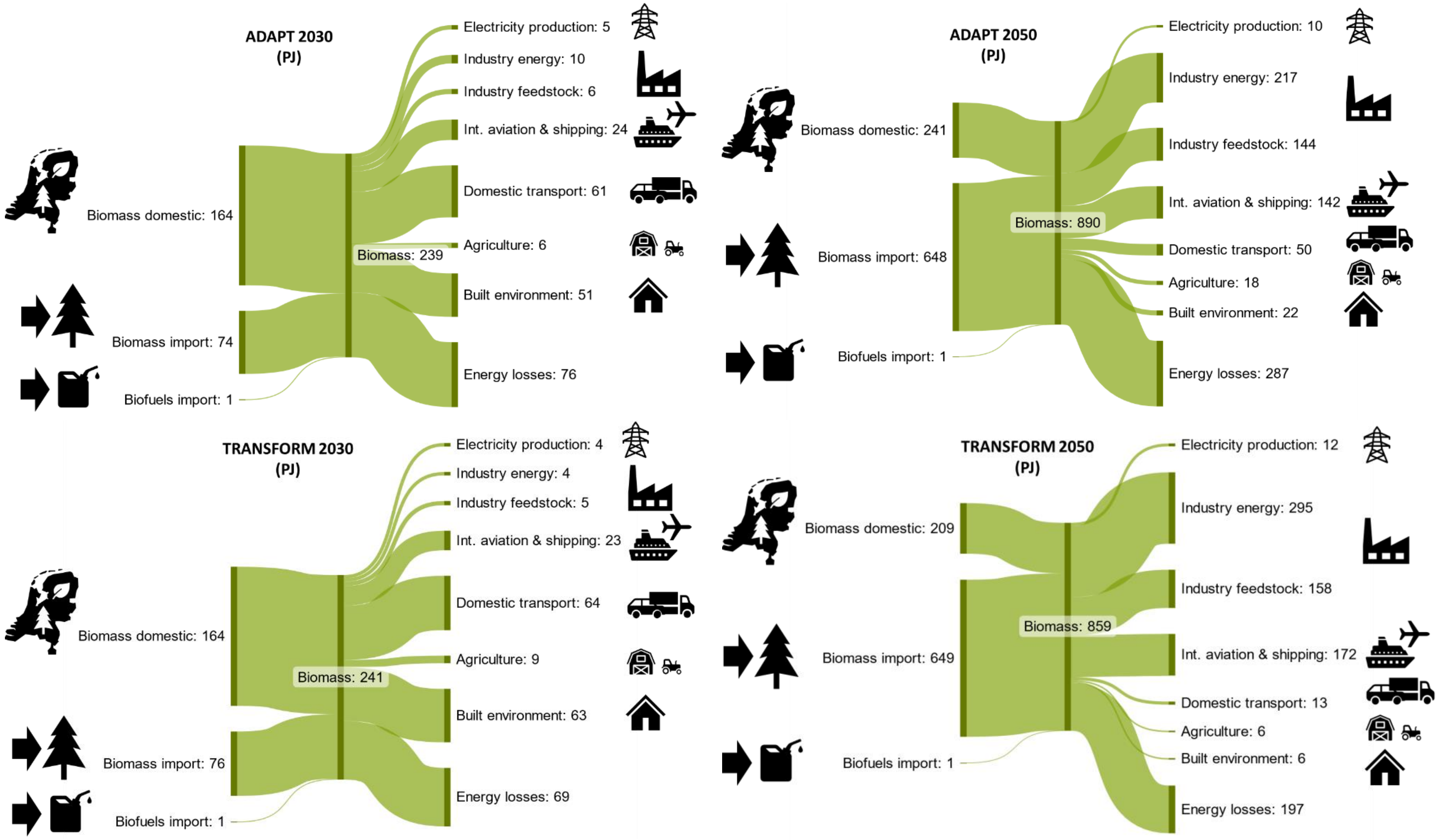


Figure 5.11: Origin and destination of biomass according to ADAPT and TRANSFORM in 2030 and 2050

5.3 Energy consumption

5.3.1 Industry

The final energy consumption (excluding non-energy use) of the industrial sector is shown in Figure 5.12. This consumption relates to a large number of industrial activities with the exception of refineries (what is not considered as end-use sector, because refineries produce fuels for domestic and international transport). The energetic and non-energetic consumption in four energy-intensive industries (refineries, high-value chemicals production, steel industry and fertiliser industry) has been examined separately in this scenario study, see Chapter 6. In addition to high value chemical, steel and fertiliser production, Figure 5.12 relates also to other industrial activities, including inorganic chemical industry, non-ferrous metal industry, food and beverage industry, glass and ceramic industry and the waste sector.

In 2030, energy consumption in industry in TRANSFORM is lower than in ADAPT, which is caused by a smaller industrial production assumed for TRANSFORM as a result of behavioural changes among consumers. In 2040, TRANSFORM shows a sharp increase in energy consumption becoming at the same level as ADAPT. This has to do with the fact that emission allowances will no longer be available for industry in 2040. More new technologies are being applied to make the industry greenhouse gas neutral, leading to additional energy consumption (such as CO_2 capture) or new process routes that are less efficient than conventional processes (such as the production of syngas from bio-feedstocks). In ADAPT, where emission allowances for industry are still available after 2040, this effect will only occur in 2050.

In 2030, fossil fuels will still provide approximately 50% of the energy demand in industry. The fossil fuel consumption in TRANSFORM will decrease sharply by 64% in 2050 compared to 2030. A much smaller decrease in ADAPT (11% in 2050 compared to 2030) can be explained by lower ambitions for sustainable fuels and feedstocks and a broader application of CO_2 storage. Yet in 2050 – also in TRANSFORM – fossil fuels will be used, especially in the chemical sector, often in the form of residual gases without CO_2 storage. These fossil CO_2 emissions are offset with negative emissions (see Section 5.4.1). CO_2 can be captured relatively cost-effectively during the production of biofuels and the use of biomass as a bio-feedstock. In TRANSFORM, more biomass will be used in industry for energy use in 2050 than in ADAPT. This is because the production of biofuels and the use of bio-feedstocks produce bio-residual gases that are used energetically.

In addition to biomass and biomass derived fuels for the production of heat, the demand for industrial heat is in both scenarios also met by electrification (electro boilers and industrial heat pumps), geothermal energy and, from 2040, by small modular nuclear reactors (SMRs) operated as CHP units (see Box 2). Coal is used for iron production but replaced by hydrogen for production of direct reduced iron in TRANSFROM, see Section 6.1.3.

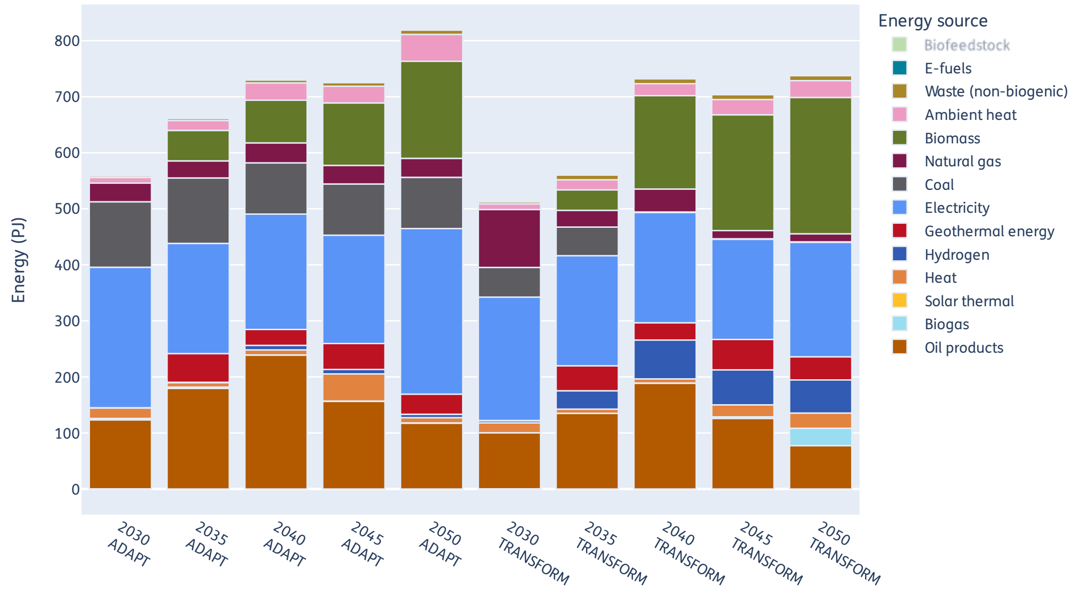


Figure 5.12: Final energy consumption for the industry sector in ADAPT and TRANSFORM, excluding non-energetic (feedstock) consumption

5.3.2 Domestic transport

Figure 5.13 illustrates the results for ADAPT and TRANSFORM for the domestic transport sector. This sector includes, next to road and rail transport, non-road mobile machinery and inland shipping. The scenario framework for 2030 is set to meet the transport sector targets introduced in the recast renewable energy directive (REDIII). That is why e-fuels appear in 2030. Biofuels and e-fuels together contribute to 15% (61 PJ) and 1.6% (6 PJ) of the total fuel demand in 2030 in ADAPT and 16% (64 PJ) and 3% (12 PJ) in TRANSFORM, respectively. According to CBS[14] the total consumption of biofuels in domestic transport was around 26 PJ in 2022. This assessment indicates a more than 2 times increase in biofuel demand for the domestic transport sector. The contribution of e-fuels in both scenarios relate to the 1% sub-target introduced in REDIII, with double counting. Thus, the data for 2030 should be read as energy content, rather than the physical supply in 2030. Nevertheless, the contribution of e-fuels, especially in TRANSFORM, seems very ambitious by 2030, considering there is no production of e-fuels in Europe at present.

Direct electrification experiences substantial growth not only up to 2030 but also beyond in both scenarios. In fact, the significant growth of battery electric vehicles (BEV) in 2040, result in achieving the necessary GHG emission reductions solely by direct electrification. The use of biofuels and e-fuels in existing internal combustion engines (ICE) appear to be very small. This relates to energy efficiency/savings due to electrification and the zero-emissions from BEVs.

In 2050, while fossil fuel use in ADAPT is almost zero, fossil fuels continue to play some limited role and contribute to around 17% of the total fuel demand in TRANSFORM, mostly for heavy duty vehicles (HDV). This can be explained by two conditions: i) Net-zero emissions/carbon neutrality has been set as the target for the Dutch energy system, and

[14] https://opendata.cbs.nl/#/CBS/nl/dataset/84714NED/table

domestic transport is integral to this system. In cost-optimal solutions, the emissions from burning this oil are offset by negative emissions in industry. ii) The bunkering emissions are set to zero in the TRANSFORM scenario in 2050. In addition, a circular carbon constrain is introduced in this scenario. This two ambitions lead to a pull of limited renewable resources to aviation and maritime bunkering, and to chemicals production, consequently continued use of fossil fuels in the domestic transport sector. Ideally, the policy would prioritise fully decarbonizing the domestic transport first. However, this model analysis is centred around cost-optimisation, and as a result, the outcomes differ somewhat from expectations.

The supply of renewable fuels, which consist of biofuels and e-fuels, appear larger in ADAPT in 2050, when compared with TRANSFORM. Among the two, biofuels contribution is larger. This can be explained by the lower demand for these biofuels in aviation and maritime, attributed to lower GHG emission reduction targets implemented (50%). Consequently, there is a larger availability of biomass to supply biofuels to the domestic transport.

In both scenarios, hydrogen is not directly used as a fuel for heavy duty vehicles. Other options, such as the use of fuels (e.g. biofuels, e-fuels, fossil diesel) in trucks with internal combustion engines (ICE) or electricity in battery electric trucks appear to be more cost-effective.

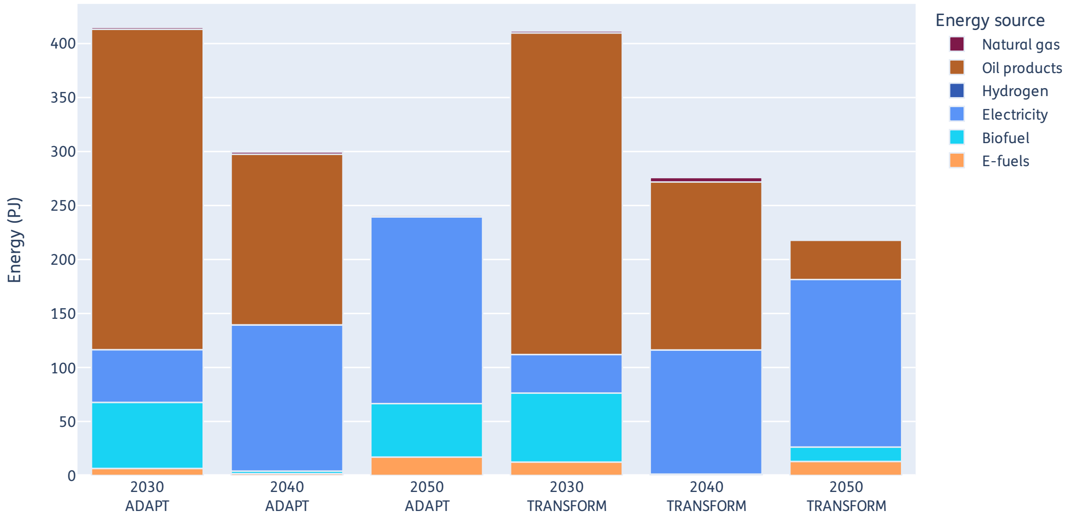


Figure 5.13: Energy mix of domestic transport in ADAPT and TRANSFORM.

Passenger cars and the light duty vehicle will almost completely make the transition from vehicles with ICE to battery electric vehicles (BEV) by 2040 both in ADAPT and TRANSFORM scenarios (see Figure 5.14). Heavy-duty transportation continues to predominately utilize vehicles with ICE up to 2040. Beyond that point, the fleet in this modality also shifts almost entirely to BEV.

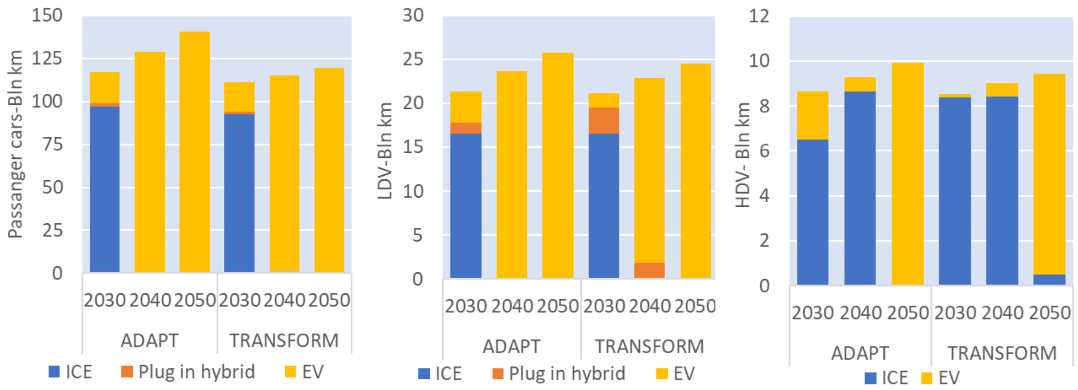


Figure 5.14: Road transport fleet development according to ADAPT and TRANSFORM in passenger cars, light duty and heavy duty vehicles (ICE: Internal Combustion Engine, EV: Electric Vehicle, LDV: Light Duty Vehicle, HDV: Heavy Duty Vehicle)

5.3.3 Bunker fuels

International aviation

In TRANSFORM, aviation activity and the fuel demand are assumed to be lower than in ADAPT. This lower demand is attributed to behavioural change and other demand-side management options. Figure 5.15 illustrates the results for this sector. In 2030, the SAF (Sustainable Aviation Fuel) target and RFNBO sub-target outlined in the are implemented (European Commission, 2023). The combined volume of biofuels and e-fuels, collectively referred to as SAF, constitutes 6% of the total fuel supply in 2030. Beyond, a GHG emission reduction of 50% by 2050 is set for ADAPT. For TRANSFORM, a zero GHG emission target applies. To attain these objectives, biofuels and e-fuels, in the form of synthetic kerosene, are projected to play a crucial role. The significance of e-kerosene is more pronounced in TRANSFORM than in ADAPT, primarily due to limited biomass resources available and competing demand from the chemical industry. In contrast to ADAPT, the TRANSFORM scenario introduces a non-fossil carbon feedstock target for the production of high-value chemicals (HVC). Because of the restricted availability of biokerosene, e-kerosene emerges as the essential SAF to achieve zero emissions in aviation.

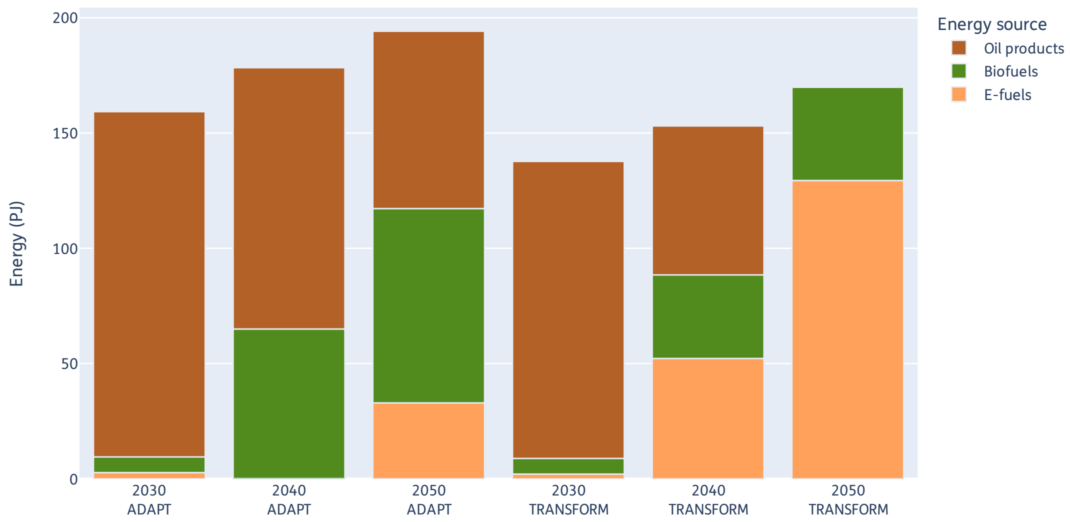


Figure 5.15: International aviation fuels (bunker fuels) in ADAPT and TRANSFORM

International shipping
The maritime bunkering in the Netherlands is large due to its strategic location, good infrastructure, and busy shipping routes. TRANSFORM considers a 30% reduction in fuel demand by 2050, compared to ADAPT. This reduction is attributed to demand side management such as efficiency improvements in vessels, speed, route and operational optimizations and behavioural changes.

The notable distinction between the ADAPT and TRANSFORM scenarios lies in the introduced GHG emission reduction objectives. The ADAPT scenario assumes a 50% GHG emission reduction, while the TRANSFOM scenario sets a target of zero emissions by 2050 to maritime shipping sector. Figure 5.16 shows the results for the two scenarios. In the ADAPT, the fossil fuels persist as the dominant component in the fuel mix, comprising more than 95% in 2030 to approximately 70% in 2050. However, the transitions from heavy fuel oil (HFO) to alternative fossil fuels, with lower emission factors such as liquified natural gas (LNG)[15] and fossil methanol. In the ADAPT, biofuels appear as the dominant renewable fuel option across the years up to 2050.

The fossil fuel use in TRANSFORM diminishes by 2050 to achieve zero emissions. The fuel mix consists of 35% biofuels that can be used in existing fleet, 22% renewable methanol, of which almost 90% relates to bio-methanol and the remaining synthetic methanol, and 43% synthetic ammonia in 2050. Thus, among the different type of synthetic fuels, ammonia appears as the preferred option, followed by renewable methanol.

[15] Emission factors that were used are: 0.0566 Mtonne CO_2/PJ and methane slip of 0.0389 CO_2-eq/PJ., in total 0.0955 Mtonne-eq CO_2-eq emissions for 1 PJ of natural gas used in shipping.

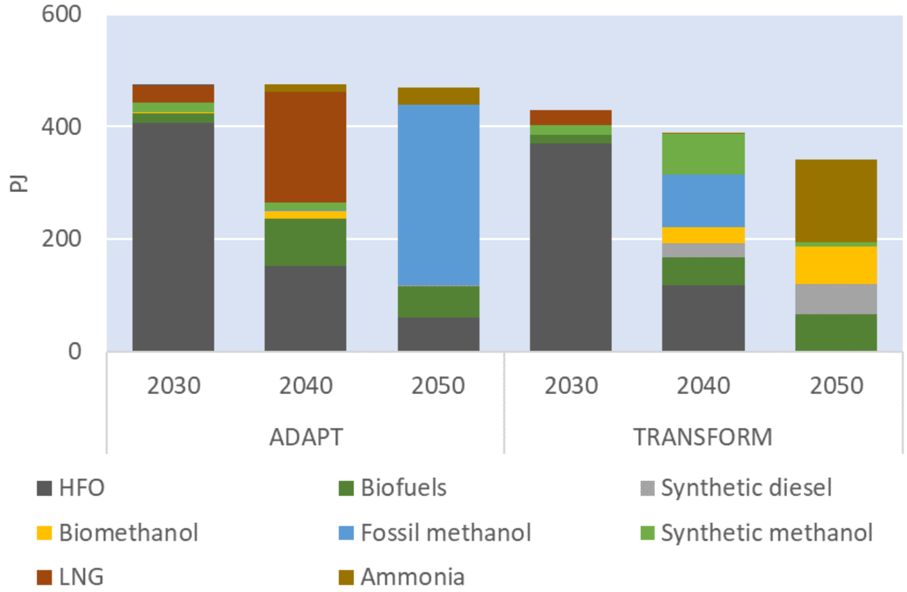


Figure 5.16: International maritime bunker fuels according to ADAPT and TRANSFORM

5.3.4 Built environment

Figure 5.17 shows the total energy consumption in the built environment for both scenarios. TRANSFORM assumes economic structural change in industrial production due to changes in consumer behaviour. At the same time, it is assumed that the service sector is growing. This does not happen in ADAPT. As a result, the energy demand for the built environment in TRANSFORM is slightly higher than in ADAPT. In both scenarios, natural gas is gradually replaced by other forms of heat supply. By 2030, boilers in some of the buildings will have been replaced by electric heat pumps (including hybrid heat pumps), which can be derived from the use of ambient heat. This replacements increase further after 2030 and also lead to an increase in electricity consumption for heating purposes. Heat networks are also expanded in both scenarios. Other sustainable forms of heat supply are biogas and solar thermal. In both scenarios, the use of biogas will decrease in 2045 and 2050 because biomass is re-directed to be used as bio-feedstock in industry and for the production of biofuels. The use of hydrogen in the built environment is very limited and only takes place in ADAPT. Figure 5.18 shows the supply mix for heat networks for the built environment. In 2030, heat production from natural gas and biomass will still account for more than half of the supply in both scenarios. In 2050, this heat production will be taken over by geothermal energy, solar thermal and expansion of industrial residual heat supply.

Energy-saving measures for the built environment are also included in both scenarios, including improving the energy labels of houses. In 2030, houses with labels G/F/E will be energetically improved to labels D/C and in 2050 to label B, but improvement to label A/A+ is not applied. In TRANSFORM the saving volume is slightly larger than in ADAPT.

A substantial part of the electricity demand is covered by electricity from solar energy within the sector built environment. In 2030 this is 29% in ADAPT and 30% in TRANSFORM and increases in 2050 to 65% in ADAPT and 68% in TRANSFORM. In the services sector, the electricity demand from data centres in 2030 is 13.1 PJ (3.6 TWh) in both scenarios and increases to 35.7 PJ (9.9 TWh) in 2050. However, these values are input parameters and not calculated by the model.

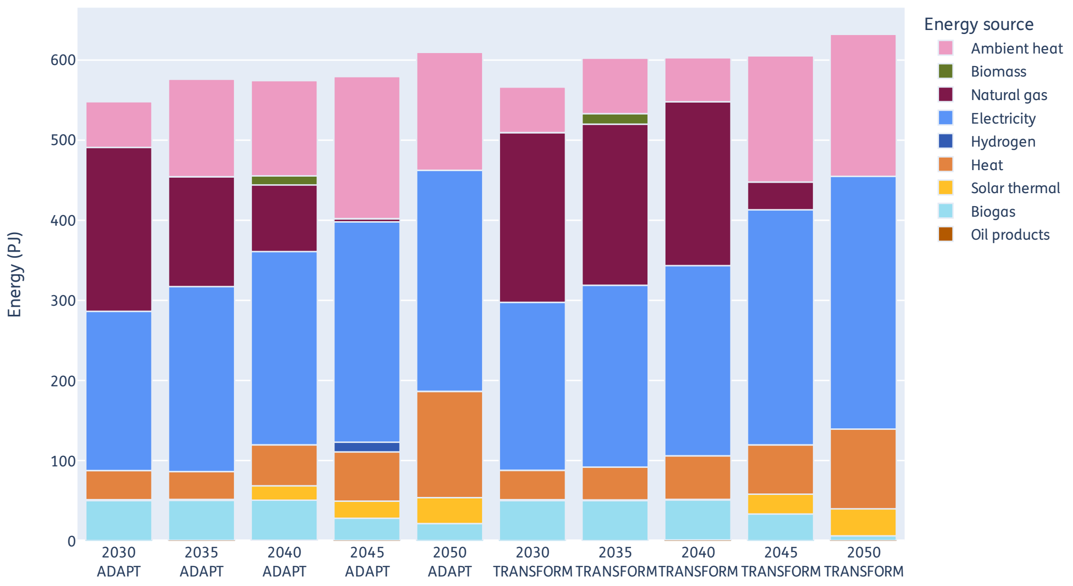


Figure 5.17: Energy consumption in the built environment in ADAPT and TRANSFORM

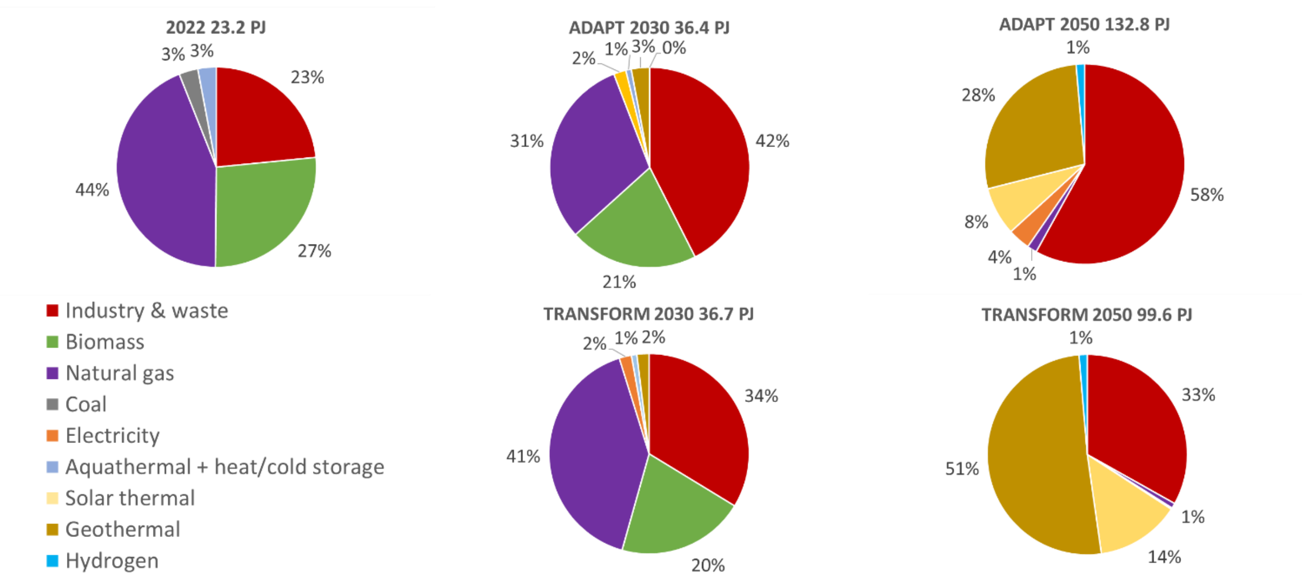


Figure 5.18: Energy supply mix district heating built environment in 2022 and in ADAPT and TRANSFORM for 2030 and 2050

5.3.5 Agriculture sector

Energy use in the agricultural sector mainly relates to the heat demand for horticulture greenhouses. In 2030, this heat will be largely generated from natural gas in both scenarios, often in CHPs that produce electricity, see Figure 5.19. This is supplemented with heat from geothermal sources and heat produced with biogas (often also with CHPs). After 2030, this sector will focus heavily on energy-saving measures in both scenarios (the effect of this measure disappears after 2035 due to the growth of the sector) and also the use of natural gas will disappear in this sector. An important reason for the latter is that after 2030 there will be no more reinvestments in CHPs when they have reached their technical lifetime. Heat supply is taken over by geothermal energy and biogas. In the ADAPT scenario, heat is also supplied by heating networks. Because the use of CHPs is greatly reduced, except for biogas, electricity demand will increase sharply after 2030. Due to the disappearance of natural gas-fired CHPs, their own electricity supply will also disappear. Figure 5.19, which only shows consumption, does not show electricity production by CHPs in 2030. This also applies to electricity production for solar PV, which will grow substantially after 2030. On balance, the agricultural sector in ADAPT will even produce 37% more electricity than it consumes in 2050. For TRANSFORM this is 44% more.

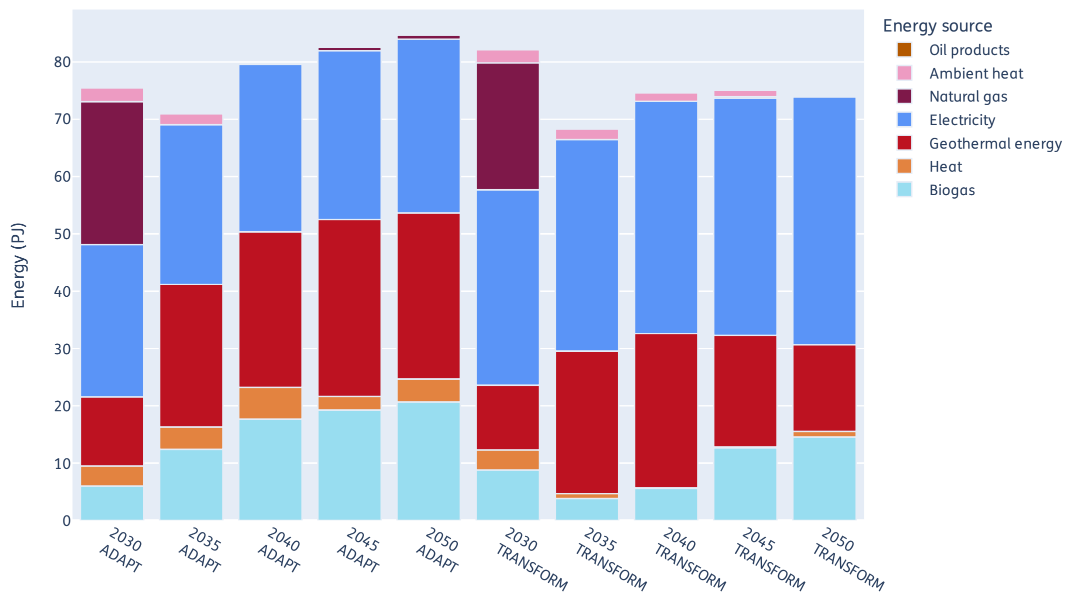


Figure 5.19: Energy consumption in the agricultural sector in ADAPT and TRANSFORM

5.4 Greenhouse gas emissions

5.4.1 Remaining GHG emissions

In 2030, in both scenarios the total GHG emissions is lower than the imposed target. For that year, there is also a target for final energy use of 1609 PJ (for industry, excl. refining, domestic transport, built environment, agriculture and aviation) and this causes 1.6 Mtonne CO_2eq lower GHG residual emissions in both ADAPT and TRANSFORM. After 2030, there is no additional target for final energy use and total GHG emissions decrease in both scenarios in accordance with the imposed targets (see Table 4.1).

Figure 5.20 shows this decrease of GHG emissions with a breakdown into CO_2 and non-CO_2 greenhouse gases. This figure shows the net CO_2 emissions, i.e. the CO_2 emissions that remain after deducting negative emissions, i.e. biogenic CO_2 or CO_2 from the air stored in empty gas fields under the North Sea. In addition to the greenhouse gases from the energy system, the GHG emissions from land use (LULUCF: land use, land use change and forestry) have also been taken into account. The figure shows that, in both scenarios, there is a substantial decrease in CO_2 emissions. But also non-CO_2 emissions decreases, in particular between 2030 and 2035. However, in ADAPT the decrease in non-CO_2 emissions is smaller than in TRANSFORM. The non-CO_2 emissions in ADAPT will not be fully reduced by 2050. GHG neutrality is achieved through carbon removal or negative emissions (storage of non-fossil CO_2) of 11.5 Mtonne. TRANSFORM shows a stronger decrease in non-CO_2 emissions, but also in this scenario non-CO_2 emissions remain in 2050. On the one hand, this stronger decrease is due to less methane emissions in the agriculture sector as a result of behavioural changes among consumers (scenario assumption). On the other hand, less use can be made of CO_2 storage in this scenario and therefore reduction options for non-CO_2 emissions are used more than in ADAPT. Also in TRANSFORM, non-CO_2 emissions cannot be completely reduced and greenhouse gas neutrality is achieved with negative emissions. In 2050 this amounts to 4.8 Mtonne.

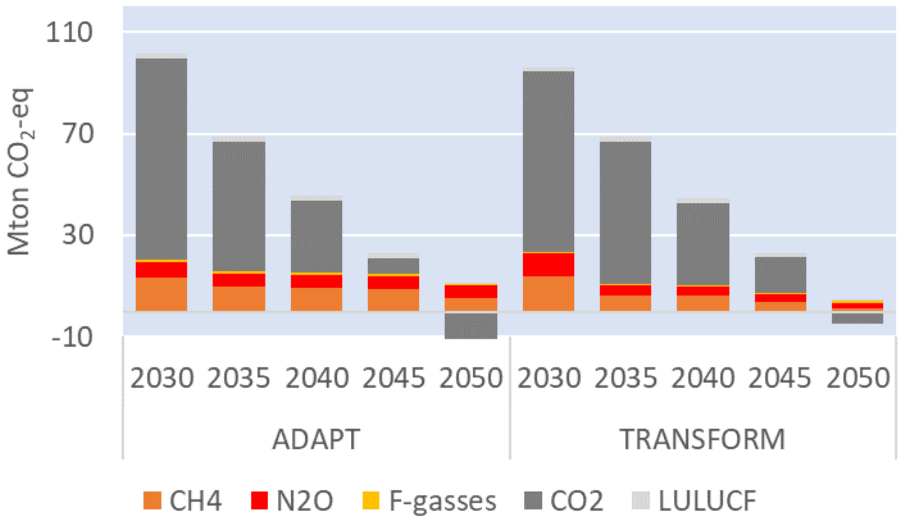


Figure 5.20 Remaining CO_2, non-CO_2 emissions in ADAPT and TRANSFORM. The graph shows emissions from domestic energy use (i.e. excluding international aviation and shipping)

While Figure 5.20 shows the net CO_2 emissions, Figure 5.21 provides insight into the total CO_2 emissions to the atmosphere and carbon removal through the storage of biogenic CO_2 (BECCS) and CO_2 from the air (DACCS) in empty gas fields. Compared to TRANSFORM, ADAPT has more CO_2 storage capacity available (40 Mton/y vs. 15 Mton/y). In 2050, 75% of this storage capacity is used in ADAPT for storing non-fossil carbon. In TRANSFORM this is about 90%, but in Monnes less than half of ADAPT. In fact, CCS is applied to most bioprocesses because CO_2 capture in these processes is more cost-effective compared to capturing fossil CO_2.

Because, in ADAPT in 2050, not sufficient negative emissions are achieved to compensate the remaining CO_2 and non-CO_2 emissions (a larger volume than in TRANSFORM), CO_2 is also removed from the air and stored (DACCS). No more biomass can be used (potential has been fully utilized) and capturing non-fossil carbon is more cost-effective than applying CCS to options that still use fossil fuels (or these options do not have a CCS application or other CO_2-free alternative). In TRANSFORM the use of DACCS is not required because negative emissions to compensate for residual CO_2 and non-CO_2 emissions (which are lower than in ADAPT) can be fully achieved with BECCS. Use of CO_2 storage is necessary in TRANSFORM scenario. This can be reduced from 15 to 12 Mtonne (at high costs), but the model analysis shows that below 12 Mtonne a climate-neutral target can no longer be met in combination with the demand for energy and products.

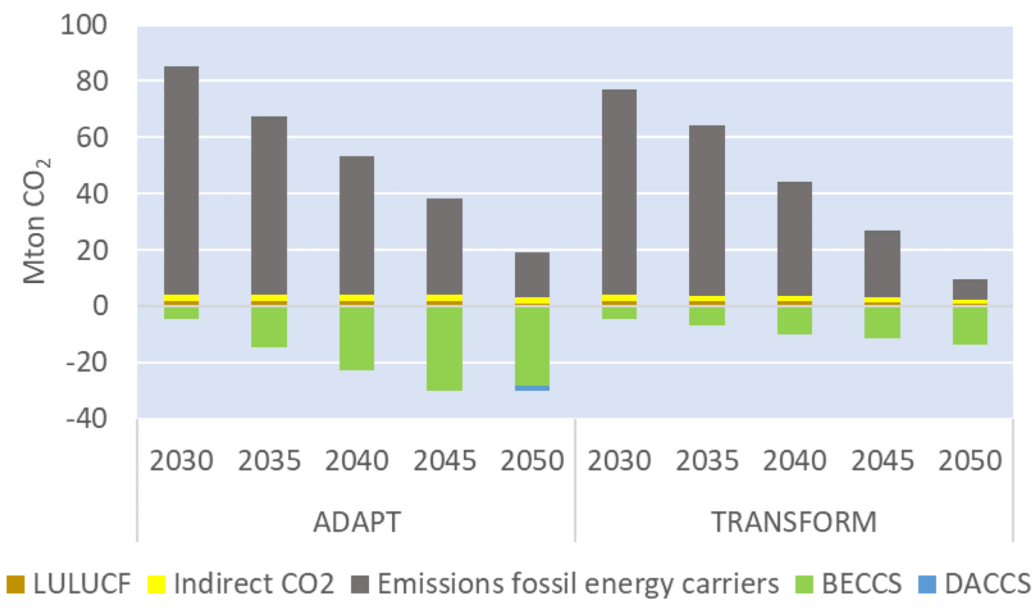


Figure 5.21: CO_2 emissions and carbon removal (negative emissions) in ADAPT and TRANSFORM

5.4.2 Carbon capture storage and use

CO_2 capture
If installations are equipped with CO_2 capture technology, carbon-containing fuels can continue to be used in the future. The captured carbon can be permanently stored in depleted gas fields (carbon capture & storage, CCS). This will help to reduce the CO_2 emissions. If the carbon comes from non-fossil fuels, such as biomass, this leads to an additional reduction in CO_2 emissions (also called negative emissions or carbon removal), because this CO_2 has already been captured from the atmosphere during the growth of the biomass and with CO_2 storage it is permanently removed from the carbon cycle. CO_2 capture applied to biomass processes is also referred to as BECCS (bio-energy carbon capture & storage). Negative emissions can also be achieved by removing CO_2 directly from the atmosphere and storing it: DACCS (direct air capture & storage). Instead of storing CO_2, the captured carbon can be used in the production of fuels, such as e-fuels, chemicals and plastics. When e-fuels are used, CO_2 is released back into the atmosphere. Only if non-fossil carbon is used in the production of e-fuels will this not lead to an increase in CO_2 emissions. If the carbon is fixed in chemicals and plastics, this can lead to long-term sequestration, depending on the duration of use. This carbon can be reused again, for example in plastic recycling, i.e. extending the sequestration. Instead of CO_2, the carbon can also be captured as CO (e.g. in the form of syngas) and used for the production of fuels and chemicals.

CO_2 capture is applied in both scenarios, but not all CO_2 is captured by a capture installation. Depending on the CO_2 flow, the capture percentage has a value between 90% and 99%. The remaining CO_2 still enters the atmosphere, see section 5.4.3.

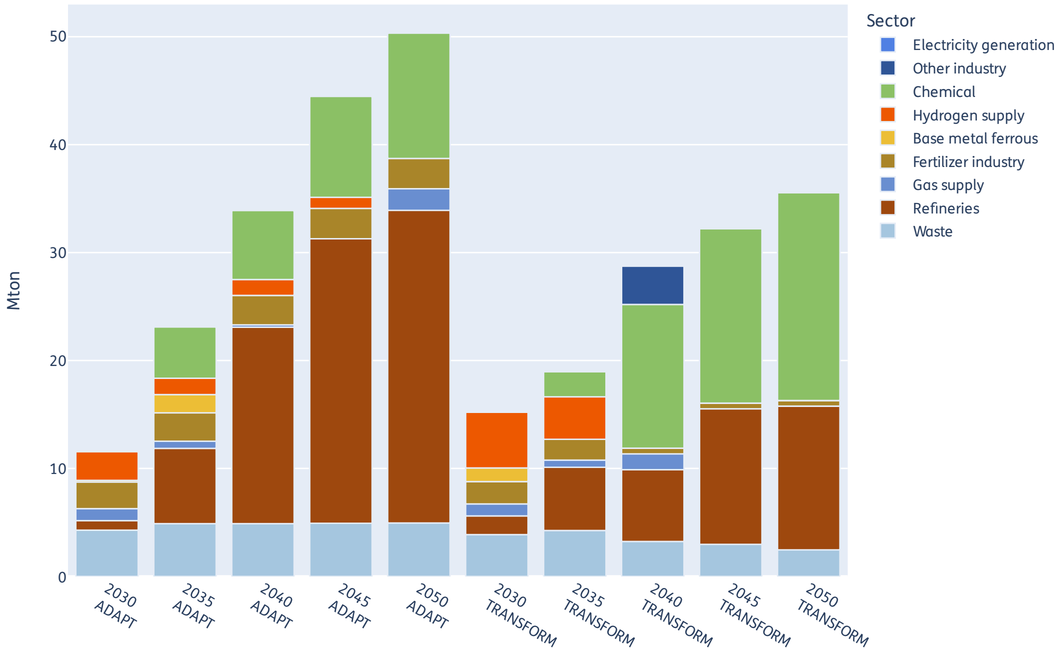


Figure 5.22 shows that CO_2 capture is applied in particular at refineries (in particular at biofuel production plants). In ADAPT this is more than in TRANSFORM, which has to do with a large CO_2 storage potential in ADAPT. CO_2 capture also takes place in both scenarios at waste incineration plants, in chemical processes and in fertiliser production. In fertiliser production, CO_2 capture in TRANSFORM decreases because in 2040 the switch is made to ammonia production from hydrogen. In both scenarios, CO_2 capture is also used in the production of blue hydrogen from natural gas, but this application disappears in ADAPT in 2050 and in TRANSFORM in 2040, see also Section 5.2.2.

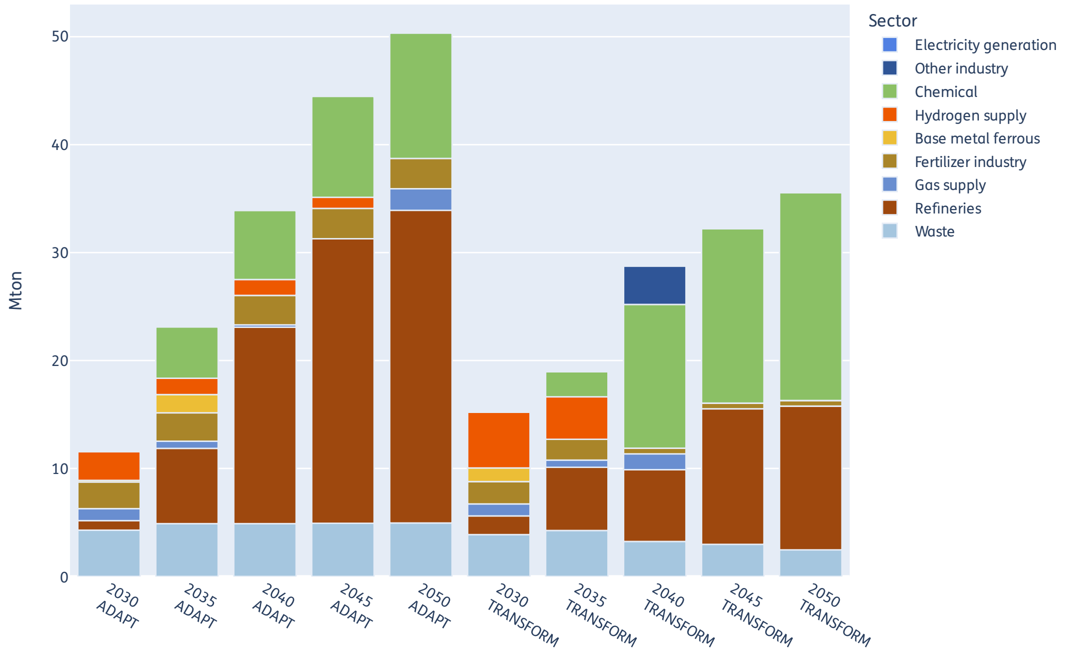


Figure 5.22: CO_2 capture in ADAPT and TRANSFORM scenarios

CO_2 storage and use

Both scenarios assume for carbon capture and storage (CCS) a storage potential in 2030 of 12.7 Mtonne. In ADAPT this gradually increases to 40 Mtonne in 2050, while in TRANSFORM the potential remains 12.7 until 2045 and then increases slightly to 15 Mtonne (see Table 4.3). From 2040 onwards, the potential for CO_2 storage in TRANSFORM will be fully utilized. In the period before that, about 80% of the potential is used. In ADAPT, the potential is fully utilized in 2030 and 2050. In the years in between this is 75 to 95%. The stored CO_2 concerns both CO_2 from fossil origin and from biomass (BECCS).

In both scenarios, part of the captured CO_2 is used (CCU), mainly as a feedstock for chemicals and plastics production or for the production of e-fuels in the refining sector, see Figure 5.23. In TRANSFORM these volumes are larger than in ADAPT, which can be explained by the higher ambitions with regard to use sustainable feedstocks and sustainable fuels. TRANSFORM uses more e-fuels in international aviation and shipping than ADAPT, see section 5.3.3.

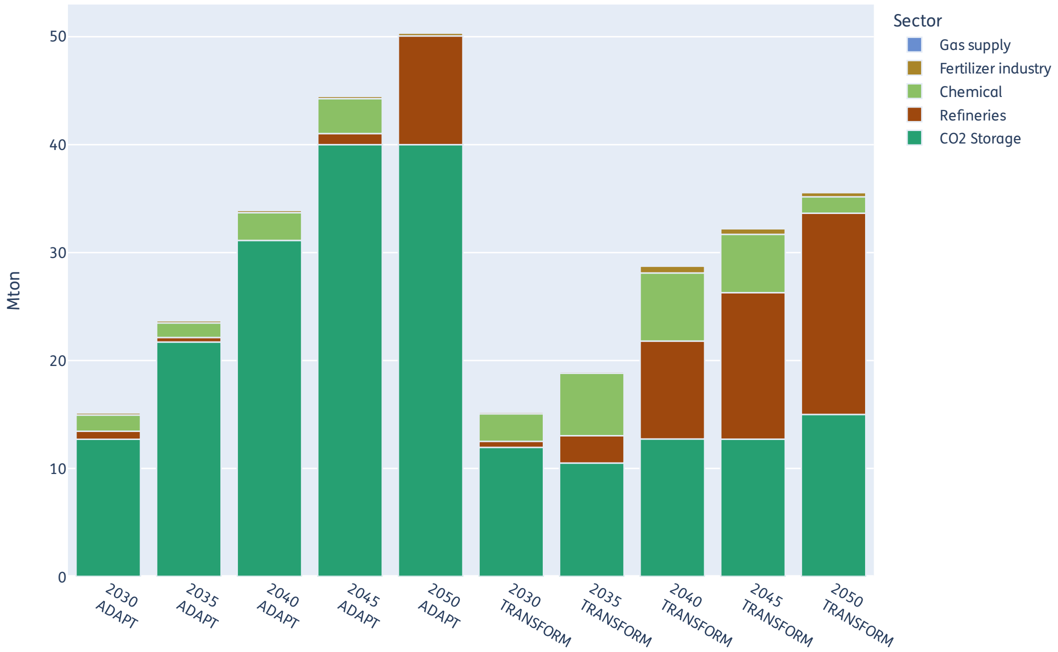


Figure 5.23: CO_2 storage and use in ADAPT and TRANSFORM scenarios (including CO capture is expressed as CO_2)

5.4.3 Carbon balance

Carbon balances have been constructed for both scenarios from the model results. These are shown in Figure 5.24 for 2030 and 2050 in the form of Sankey diagrams. The flows represent Mtonne carbon, but in reality they are either hydrocarbons or CO_2 (e.g. CCS, atmosphere[16]). A carbon balance illustrates changes in carbon use in the energy system, both changes in the total amount of carbon and the shift from fossil to non-fossil carbon use. The carbon balance also shows in which sectors carbon is used in the form of hydrocarbons and what the destination of the CO_2 is. The balances distinguish between fossil, biogenic and atmospheric carbon. When synthetic carbon is imported, the origin of the carbon is unknown, i.e. can be both fossil, biogenic or a mixture of both. Only in ADAPT in 2050 direct air capture is applied on a limited scale and an atmospheric carbon category appears in the Sankey graph, see for explanation Section 5.4.1.

In 2022 there was approximately 60 Mton carbon in the energy system (including feedstocks and bunker fuels), of which almost 90% was of fossil origin. In 2030, the total amount of carbon in ADAPT is 5% higher than in 2022, but in TRANSFORM 8% lower. In that year, in both scenarios, the majority of the carbon still comes from fossil sources (86% in ADAPT and 88% in TRANSFORM) and a small part is from biogenic origin (10% in ADAPT and 12% in TRANSFORM). In 2050, carbon use in ADAPT will be 14% higher than in 2022 and most of the carbon still comes from fossil sources (57%). The share of biogenic carbon has increased to 37%. Increased carbon use is due to an increase in energy demand (domestic and bunkers) and growth in production volume in industry. Due to assumed lower demand and decline in industrial production, carbon use in TRANSFORM will decrease by 33% in 2050

[16] To convert from carbon to CO_2, multiply by a factor of 3.75

compared to 2022. Moreover, most carbon comes from biogenic sources (61%) and only 25% from fossil sources.

In 2050, still a limited amount of oil is used in TRANSFORM for production of fossil fuels for export outside the EU and for the production of chemicals. Moreover, there is some room to emit fossil CO_2 (e.g. in industry, see Section 5.3.1, and domestic transport, see Section 5.3.2) because it is offset by negative emissions, i.e. biogenic CO_2 stored in depleted gas fields (BECSS). This is also the result of the zero GHG emission target for bunker fuels. This gives bunkers priority over domestic transport applications for biofuels. In ADAPT, the fossil carbon flows to export fuels, chemicals and the atmosphere is larger in 2050 than in TRANSFORM and fossil carbon is also used for the production of bunker fuels. This is the result of scenario assumptions about CO_2 storage potential (more than in TRANSFORM) and sustainability ambitions for chemicals and bunker fuels (less than in TRANSFORM). Note that the use of biogenic carbon in feedstocks does not result from a target in ADAPT, but is due to bio-naphtha as a by-product of biofuel production, especially biokerosene. Biokerosene consumption in aviation is larger in ADAPT than in TRANSFORM. Also in ADAPT, CO_2 emissions to the atmosphere (including remaining CO_2 emissions of capture installations) are compensated with storage of biogenic and some atmospheric CO_2, but the volume flow is larger than in TRANSFORM. In both scenarios, carbon in the form of CO_2 or CO is captured in industrial processes and used (CCU) for the production of synthetic fuels or chemicals. In the Sankey diagrams, CCU is shown on both the left (origin) and right side (destination). This carbon flow, which consists of biogenic and fossil carbon, is larger in TRANSFORM than in ADAPT. In ADAPT, 74% of the captured carbon (CCU and CCS) is of non-fossil origin and in TRANSFORM this is even 92%.

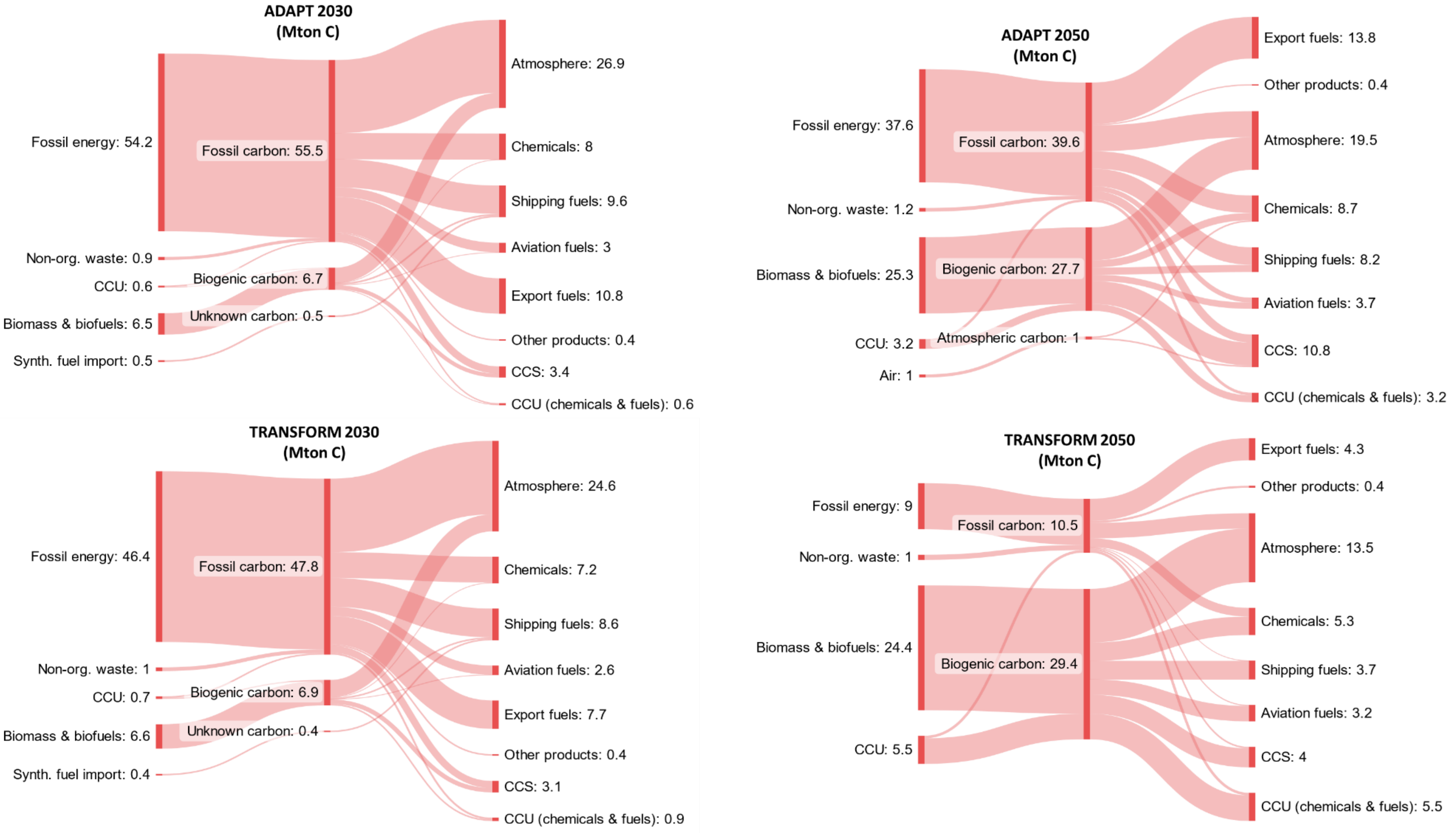


Figure 5.24: Carbon balances for ADAPT and TRANSFORM scenarios in 2030 and 2050

5.5 Energy and CO_2 infrastructure

The energy system calculated for the ADAPT and TRANSFORM scenarios also includes an infrastructure for transport of electricity, hydrogen, natural gas and CO_2. For this, the Netherlands is divided into 7 onshore and 7 offshore regions. Each onshore region has an energy demand and production (i.e. electricity, natural gas, hydrogen and heat); offshore regions only produce energy (i.e. electricity and hydrogen). Heat transport between regions is not possible. The transport infrastructure for electricity and hydrogen is roughly based on the topology of the current electricity and gas transport networks. The transport capacity between the regions is limited. In 2030, electricity transport between regions on land may not exceed 1.25 times the current electricity transport capacity. In 2040 this maximum is 2 and in 2050 2.5 the current transport capacity. Only in 2030 the maximum transport capacity is reached in two regions (Brabant and Zeeland) in the TRANSFORM scenario. After 2030, this maximum will not be reached in any of the scenarios. The electricity and hydrogen transport infrastructure is connected to the transport networks of neighbouring countries, taking into account existing connections and plans for their expansion.

Figure 5.25 shows a map with electricity transport flows in ADAPT 2050 and TRANSFORM 2050. In both scenarios, a significant transport of electricity produced offshore is transported to the onshore regions. Also the net import and export flows are shown. In 2050 in ADAPT and TRANSFORM most hydrogen is produced offshore. The map with hydrogen flows (Figure 5.26) shows the transport of hydrogen to the onshore regions and the net import and export flows. Finally, Figure 5.27 shows the transport of CO_2 in ADAPT and TRANSFORM in 2050. CO_2 is transported from land to storage locations at the North Sea. The amount of CO_2 that is stored in 2050 is shown in the figure. While in ADAPT CO_2 is captured and transported from 3 western regions, in TRANSFORM CO_2 is captured and transported from 5 regions but in a smaller volume. This has to do with the processes in which CO_2 capture takes place (see Section 5.4.2) and where they are geographically located.

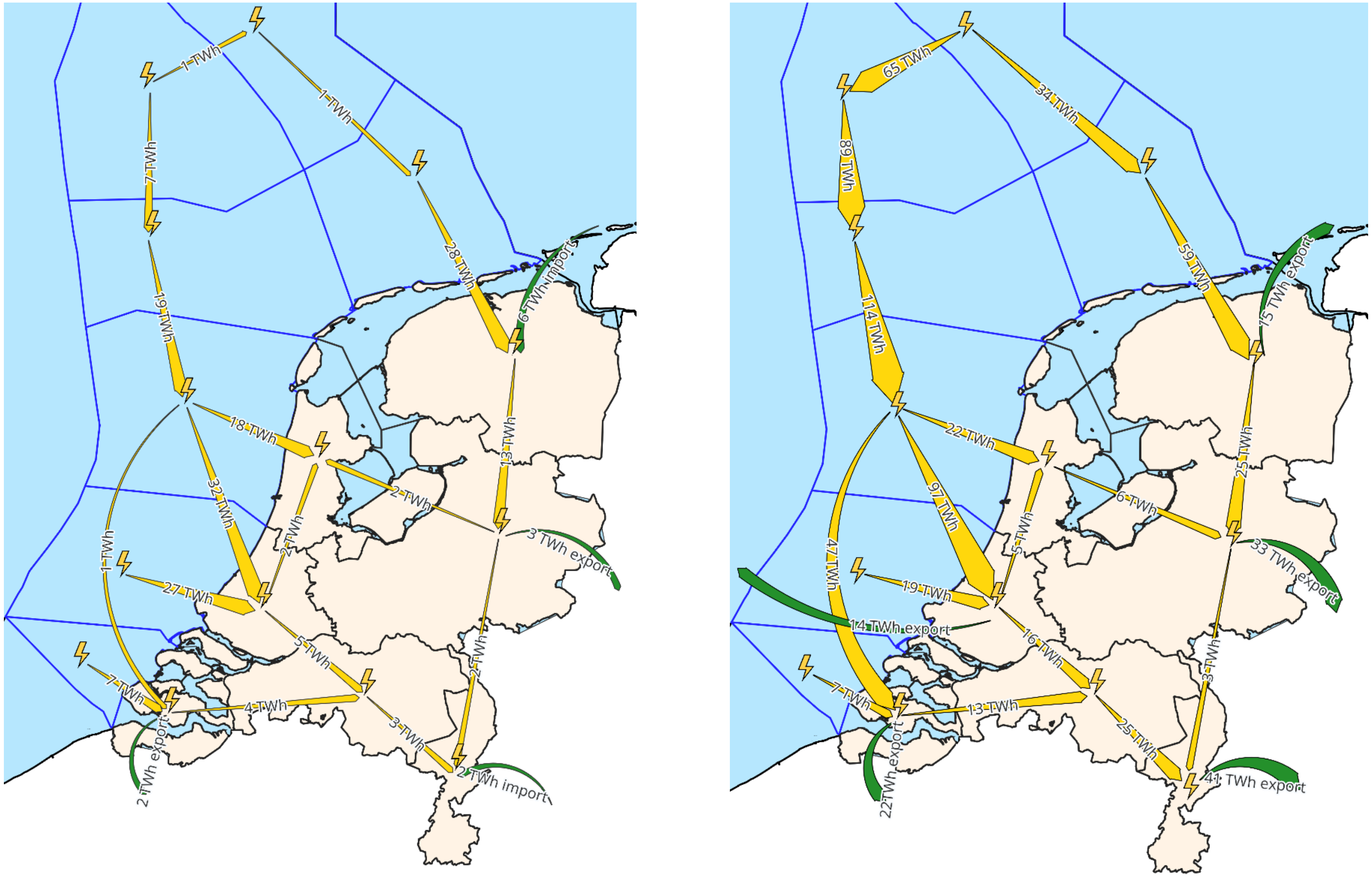


Figure 5.25 Net total electricity flows in TWh between regions in 2050 for ADAPT (left) and TRANSFORM (right)

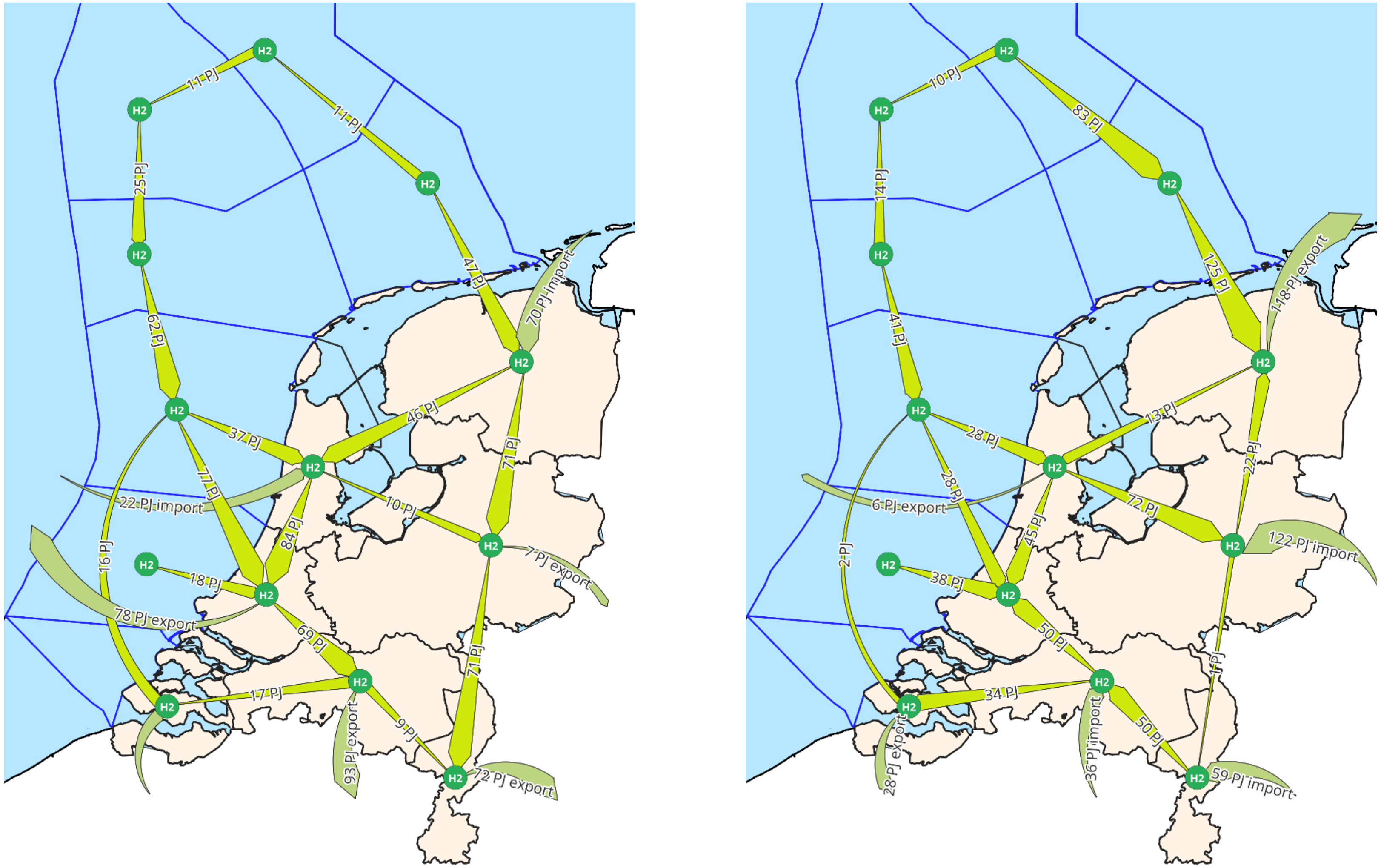


Figure 5.26 Net total hydrogen flows in PJ between regions in 2050 for ADAPT (left) and TRANSFORM (right)

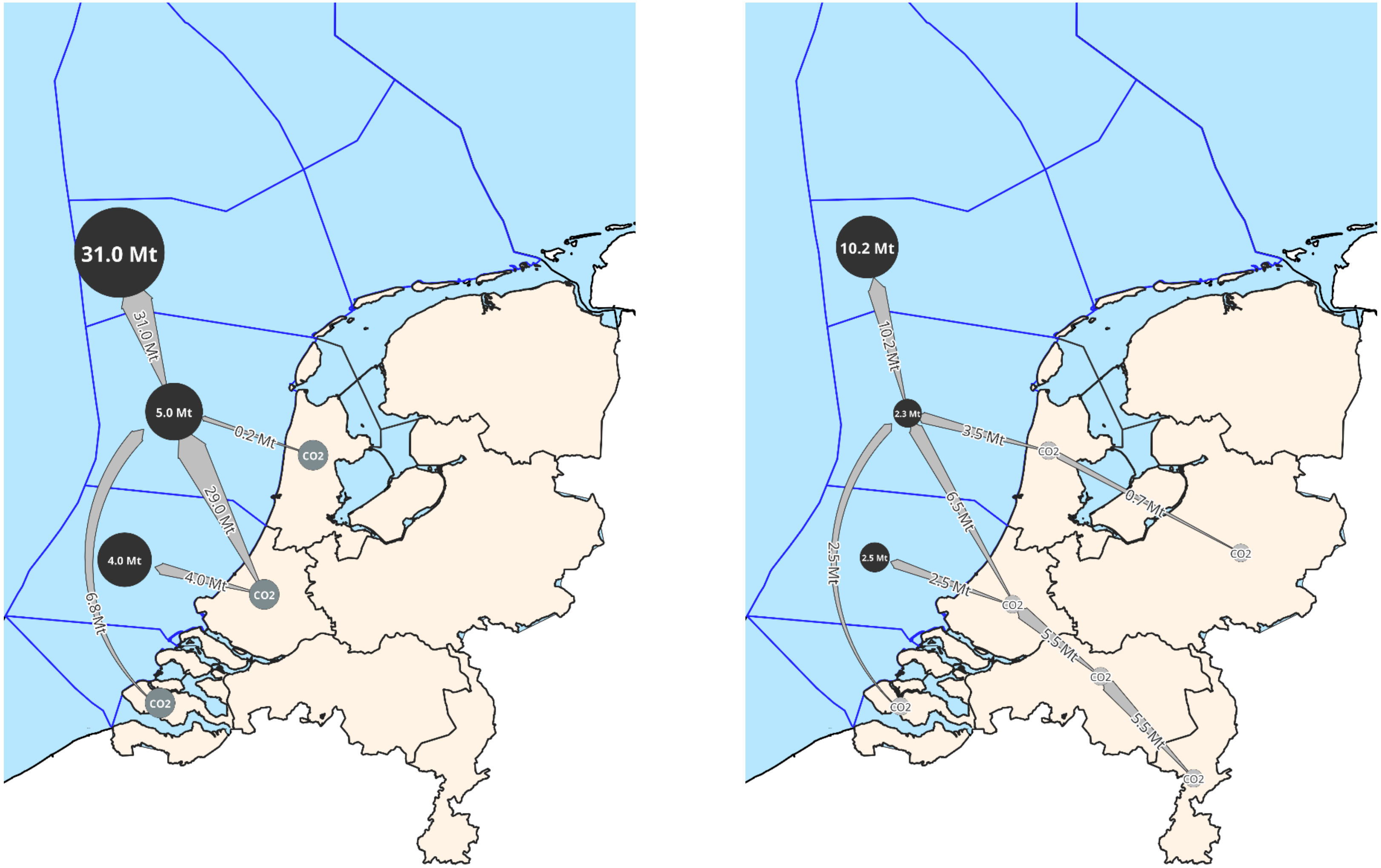


Figure 5.27 Total CO_2 flows between regions and CO_2 storage in offshore regions in Mtonne in 2050 for ADAPT (left) and TRANSFORM (right)

5.6 Investments and system costs

5.6.1 Investment costs

The OPERA model determines which investments need to be made for each year for which an energy system is calculated. In principle, this concerns all assets of the system (greenfield investments). By determining for each technology option what capacity expansion has taken place compared to the previous year and examining whether new options replace existing options, it can be determined what additional investments are required. The absolute value of investment costs are only meaningful within this analysis framework[17]. Therefore, Figure 5.28 shows not the absolute changes in investment costs but the cumulative relative change for ADAPT and TRANSFORM. The contribution of each sector to the change in investment costs is also shown in the graph.

The increase in investments required for the transition of the energy system in 2050 is approximately four times as high as the increase between 2030 and 2035, slightly lower for ADAPT and slightly higher for TRANSFORM. The strongest increase for both scenarios is in the period 2035-2040 and in TRANSFORM also in the period 2045-2050. Most investments are needed in energy production (including energy transport infrastructure), the built environment and the transport sector. Compared to the industry and energy sector, the built environment and transport involve investments that are smaller in size, but in very large numbers. In transport, replacements play a role due to a relatively shorter lifetime of the assets. Not all these investments can be attributed to the energy transition, since without an energy transition investments are also needed.

[17] For example, within the model framework, investments in domestic car fleet are fully included, while for homes only investments in indoor installations and insulation are considered. This leads to substantial differences in investment levels per sector, not all of which (e.g. complete passenger cars) can be attributed to the transition costs of the energy system.

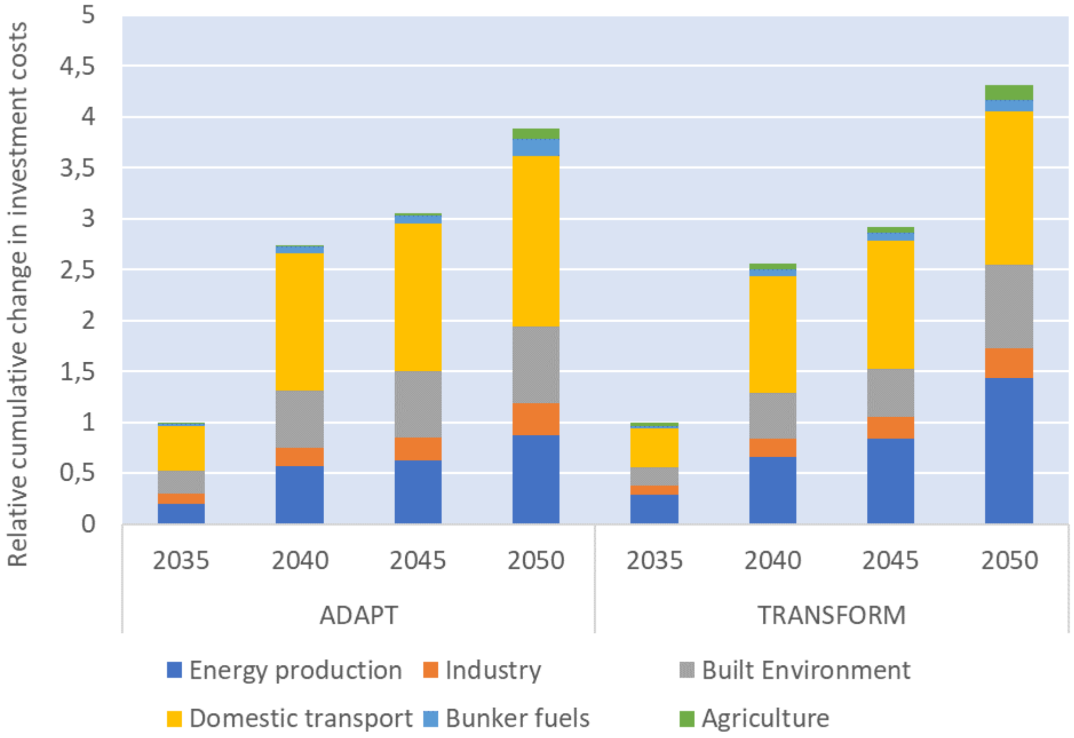


Figure 5.28: Cumulated relative change of total investment costs and contribution to change per sector for ADAPT and TRANSFORM (2035=100).

5.6.2 System costs

The OPERA model calculates an energy system with the lowest social costs. For this the annual total system costs are calculated. The total system costs are the sum of the annual capital costs[18], the annual operation and maintenance costs, energy transport costs and imported energy costs minus the revenues from exported energy. Which applies for the investment costs in the previous section also applies to the system costs: the absolute value of the system costs calculated by the model are only meaningful within this analysis framework. Therefore, the system costs of the different scenarios and years can best be compared relatively, as shown in Figure 5.29. For this graph, the total system costs for ADAPT in 2030 are used as reference. In subsequent years, annual total system costs for ADAPT increase and cumulate to slightly above 15% higher in 2050. The annual total system costs of TRANSFORM are lower than those of ADAPT in 2030. This is mainly due to lower energy demand and industrial production volumes as a result of behavioural changes assumed for this scenario. After an initial decline, system costs in TRANSFORM increase in 2040, then decrease, before increasing again in 2050, but remaining below the level of ADAPT. The change in system costs in TRANSFORM can be explained by the fact that companies that fall under the emissions trading system will no longer receive emission allowances from 2040 onwards. In the model analysis for TRANSFORM a zero GHG target for industry and the electricity sector has been applied (but not for ADAPT). As a result, in TRANSFORM an acceleration of industrial transformation takes place in 2040, with a knock-on effect on the energy supply.

[18] The annual capital costs is per technology determined from the investment costs, the economic life and the discount rate. Because optimization is based on social costs, a discount rate of 2.25% is used (Werkgroep Disconteringsvoet, 2020).

The increase in total system costs is the result of 1) rising energy demand and increased industrial production, 2) higher fossil fuel prices (see Table 4.4) and 3) investments in innovative technologies that are more expensive than conventional technologies (although cost reduction for innovative technologies is taken into account due to learning effects). The contribution of these explanatory factors differs per scenario. As already mentioned, the development of energy demand and industrial production levels in TRANSFORM are lower than in ADAPT. TRANSFORM also applies more innovative technologies at higher costs than in ADAPT. At the same time, more fossil fuels are used in ADAPT than in TRANSFORM. Therefore the ADAPT scenario is more sensitive to changes in fossil energy prices than TRANSFORM. If no greenhouse gas reduction is imposed, the share of fossil energy in the energy system will remain high and the system costs in 2050 will be higher than those of ADAPT and TRANSFORM. In such a scenario, greenhouse gas emissions do decrease because the share of renewable energy increases autonomously because wind and solar energy production becomes competitive with fossil energy production (Scheepers M. , et al., 2020).

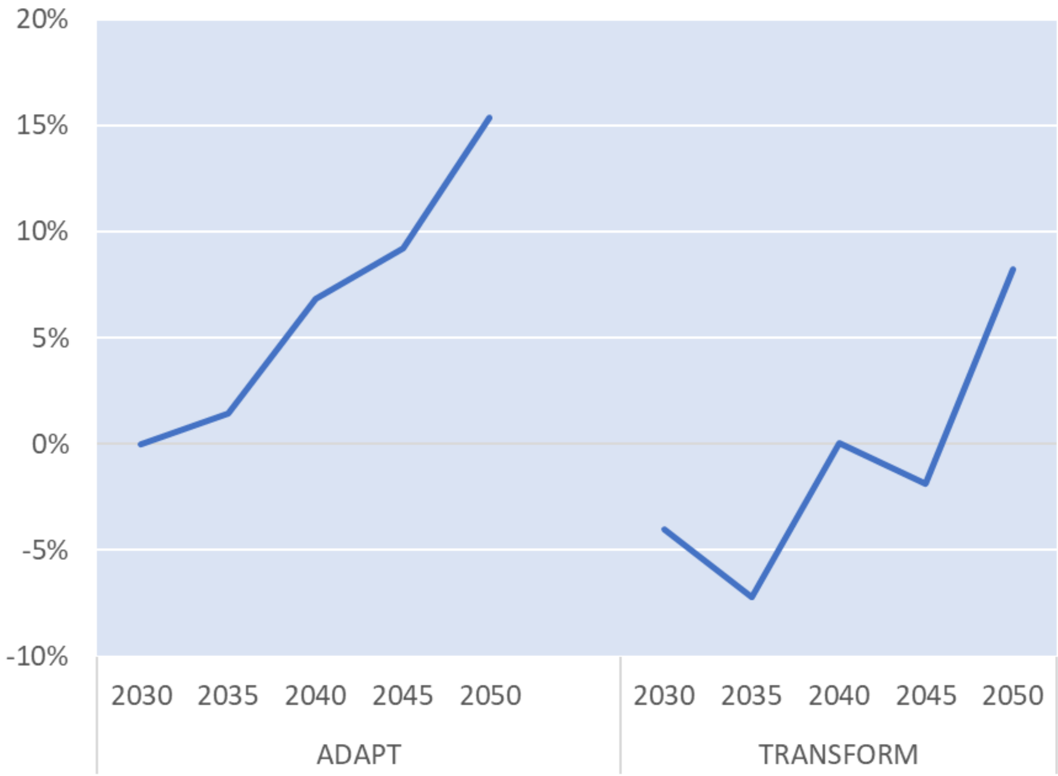


Figure 5.29: Relative change of annual total system costs for ADAPT and TRANSFORM compared to total system costs in ADAPT 2030

The breakdown of the annual system costs is illustrated in Figure 5.30 for the total system costs and the system costs for industry and energy production. In the total system costs, CAPEX dominates, followed by energy costs. For both scenarios, a clear shift from energy costs to CAPEX can be observed, with this shift being larger for TRANSFORM than ADAPT, due to a relative large amount of fossil fuels that continue to be used in ADAPT. The distribution of the cost categories differs per sector. In 2030, more than 80% of the system costs for industry will be determined by energy costs, which will decrease in 2050 to about 77% in ADAPT and 74% in TRANSFORM. The CAPEX costs increase from approximately 8% to 11% in ADAPT and 13% in TRANSFORM. The picture looks different for energy production. This sector has no net energy costs, but revenues shown as negative numbers. Compared to 2030, the

CAPEX in TRANSFORM will increase by a factor of 2.5 and in ADAPT by a factor 1.7. But the share of CAPEX in the system costs for energy production remains the same in both scenarios.

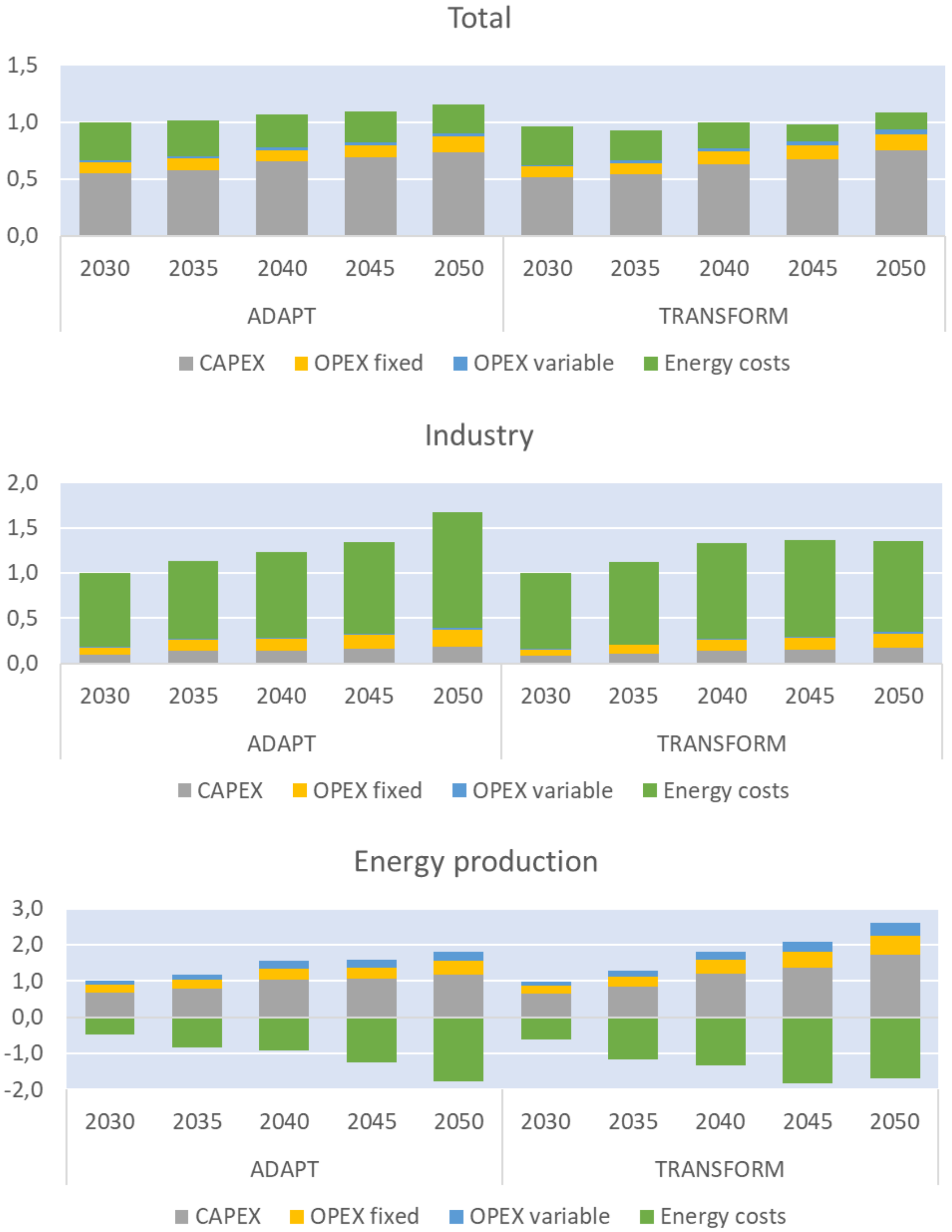


Figure 5.30: Increase of total system costs and system costs for sectors industry and energy production for ADAPT and TRANSFORM relative to system costs in ADAPT 2030 with a break down in cost categories (NB The energy production sector has no net energy costs but revenues. These are not shown)

5.7 What-if analyses

By changing assumptions for the scenarios, the effect on the scenario results has been investigated. The effect of changing energy and climate policy and market assumptions were examined through the following what-if analyses:

- Changing energy and climate policy assumptions:
  - Phasing out nuclear energy instead of building new nuclear power plants (for ADAPT and TRANSFORM).
  - Applying a target for final energy consumption of 1609 PJ, not only for 2030, but also to later years (for ADAPT and TRANSFORM).
  - GHG neutral in 2045 instead of 2050 (for ADAPT and TRANSFORM).
  - Less strict target circular carbon (only for TRANSFORM, since a strict target only applies for this scenario).
  - A lower CO_2 storage capacity (for TRANSFORM)
- Changing market assumptions:
  - A maximum for the electrolysis capacity on the assumption that the optimal capacity cannot be achieved in time (only for TRANSFORM because this scenario shows the highest electrolyser capacity).
  - A restriction in electricity trade with foreign countries because the optimal interconnection capacity cannot be realized on time (only for TRANSFORM because this scenario shows the highest electricity exports).
  - A doubling of the import price for biomass (for ADAPT and TRANSFORM).
  - The demand for bunker fuels for shipping reduced by 50% (for ADAPT and TRANSFORM).

Because the energy system is calculated with a cost optimization model, changing assumptions not only has consequences for the sector to which the change primarily relates, but also has impact on other sectors. The optimization model calculates a new energy system with the lowest system costs and makes new choices for all energy and non-energy use in all sectors, which can change the volume of energy production and demand as well as the energy mix in all sectors. The discussion of results of the what-if cases below focuses on the most important changes, comparing the results of the what-if cases with the ADAPT and TRANSFORM base scenarios.

The results of the what-if case without new nuclear power plants are reported in text box 2 in Section 5.2.1, the results of the what-if case with a maximum electrolyser capacity can be found in Section 5.2.2. and results for applying a lower CO_2 storage capacity in TRANSFORM in Section 5.4.1.

Final energy consumption target for all years

In the years after 2030, in which no target for final energy consumption has been used for the base scenarios, final energy use is slightly above the Energy Efficiency Directive (EED) target of 1609 PJ for 2030, see Figure 5.31. Final energy consumption is up to 4% higher except for TRANSFORM in 2040. In that year, final energy consumption is 8% higher than in 2030 in that scenario, only to decline again in subsequent years. The increase in TRANSFORM between 2035 and 2040 can be attributed to developments in the chemical industry. The chemical industry produces synthetic and bio-methanol that is used as shipping fuel. Energy use and energy losses to produce chemicals fall under the final energy consumption. Between 2040 and 2045 there is a substantial decline in final energy use. This is the result of two changes: the production of synthetic and bio-methanol for shipping is decreasing, but the largest decrease is caused by a sharp increase in the use of ambient heat by heat pumps in buildings. According to the EED definitions, ambient heat does not count as a final demand. Because, according to the EED, the refinery sector also falls outside the final energy consumption as it preliminary produces fuels, it could be argued that this should also apply to the chemicals that are used as fuel. If this were corrected, the final energy consumption in TRANSFORM would decrease.

Applying the final energy consumption target for all years in the what-if case hardly changes the results of the scenario, because the reduction in final energy consumption in the what-if case is relatively small compared to the base scenarios. Only a small shift can be observed from the production of chemicals to fuel production by refineries.

Also an (indicative) target for primary energy consumption for 2030 applies (1935 PJ), but has not been used as target in the base scenarios. Primary energy consumption is the sum of final energy consumption plus the energy consumption for producing energy carriers, such as liquid and gaseous fuels, electricity and heat. Figure 5.31 shows that primary energy consumption in ADAPT and TRANSFORM is above the indicative target and increasing. This is caused by higher energy consumption (e.g. through the use of CO_2 capture at refineries) and energy losses (e.g. production of hydrogen and synthetic and biofuels) in the energy supply sector. Because this is an indicative target, no what-if case has been analysed in which the energy system has to meet a target for primary energy consumption.

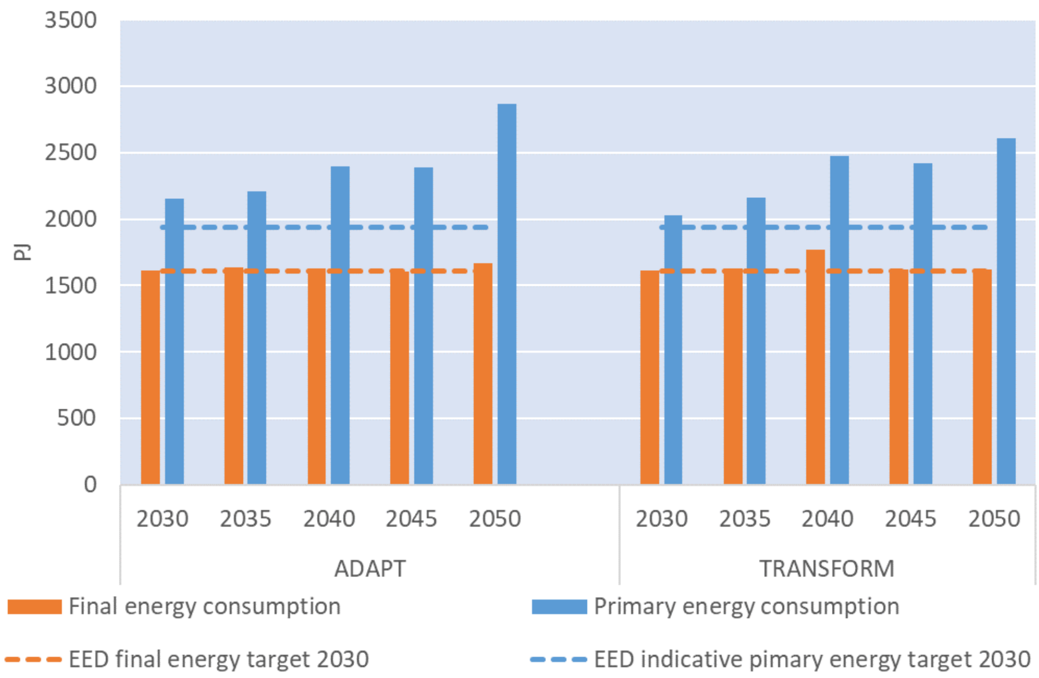


Figure 5.31: Final and primary energy consumption according to definition Energy Efficiency Directive (EED)

GHG neutral in 2045
The what-if case in which the energy system must achieve greenhouse gas neutrality by 2045 shows for both scenarios that demand cannot be met under the condition of net zero greenhouse gas emissions. The model has insufficient options available or options have too limited capacity to calculate an energy system that meets the objectives.

Restriction in electricity export

If the interconnection capacity for electricity import and export with neighbouring countries is limited, this will lead to a reduction in net electricity exports in TRANSFORM. In the what-if case, the export is 50% lower than in the base case. This has no consequences for electricity production, which remains virtually the same in volume and mix. The non-exported electricity is used for more domestic hydrogen production. This increases by 45% in 2050 and at the same time the net import of hydrogen decreases by 30%. On balance, there is more hydrogen available for exports (+36%) and the production of methanol (+75%) ammonia as a shipping fuel (+11%). Import and export of electricity also contribute to balancing the electricity system. With smaller interconnection capacity, the contribution of these flexibility options decreases. However, a larger electrolyser capacity (27 GW in the what-if case compared to 21 GW in the base case) provides more flexibility.

Higher biomass import prices

To investigate the sensitivity of the scenario results to the import price of biomass, this price was doubled in a what-if case. For 2050 there is no effect on the total use of biomass. However, shifts are visible in the use of biomass in the various sectors. For example, the use of biofuels is decreasing. In ADAPT, biofuel use for domestic transport is 45% lower than in the base scenario and fossil oil products return to the energy mix. In TRANSFORM, the use of biofuels in aviation decreases by 12% and in international shipping by 10% compared to the base scenario in favour of the use of e-fuels. In ADAPT, the use of biomass as a feedstock increases by 19%, while in TRANSFORM no change is visible. In addition, the energetic use of biomass in industry increases by about 6% for both ADAPT and TRANSFORM. It can be concluded that biofuels use is most sensitive to the price of biomass. The biomass that is not used for biofuels production is used in industry for energetic and non-energetic applications, despite the higher costs.

Change in the maritime bunkering volume

Maritime bunkering in the Netherlands is relatively large, when compared with other countries in Europe. However, there are uncertainties regarding whether this large bunkering activity will continue in the Netherlands or potentially shift to other regions globally, where the supply of renewable fuels is expected to be more cost-competitive. Moreover, the newly introduced regulation, FuelEU Maritime, sets a target for reducing GHG intensity, but applies only to ships with a gross tonnage above 5000 and to energy voyages between EU ports, as well as to 50% of energy used on voyages, where the arrival or departure ports are outside the EU. Consequently, this regulation does not cover all maritime bunkering. In light of these uncertainties, a what-if analysis has been carried out in which the demand for bunker fuels for international shipping has been halved for the ADAPT and TRANSFORM scenarios.

In TRANSFORM, reducing the bunkering demand by half leads to a substantial increase in the use of renewable fuels, including biofuels and e-fuels, in domestic transport by approximately 70%. This relates to the less demand for the maritime bunkering. Reducing bunkering demand has little effect on the aviation sector. Biofuel supply increases slightly and e-fuels reduces.

Reducing maritime bunkering demand by 50% in ADAPT, results in a significant shift from HFO to LNG in 2050. Thus larger use of LNG combined with mainly biofuels appear as the low cost supply option to achieve a 50% GHG emission reduction. In this case, the demand for synthetic ammonia appears very limited. In TRANSFORM, this demand reduction results in 90% reduction in ammonia, followed by bio-methanol and synthetic diesel. At the same time, use of synthetic methanol appears higher in this what if, when compared with the base scenario.

Lower circular carbon target
The TRANSFORM scenario introduces a goal for 2050: to achieve an 80% circular carbon target for the production of large volume organic chemicals. This target means that by 2050, 80% of the olefins and aromatics production should be from circular feedstocks like biomass, waste, and renewable synthetic feedstock, with carbon originating from biogenic sources. Presently, there are no formal requirements for olefins and aromatics production to meet this target.[19] In this what-if case, we examine the impacts of this circular carbon target by reducing the target to 25%. In this what if case, the fossil fuel consumption in domestic transport disappears in 2050. This is due to the decreased demand for renewable feedstock to produce olefins and aromatics, and consequently, a higher utilisation of biofuels and e-fuels in domestic transport. This shows the significance of future competition between the transport sector and the chemical industry, especially if the chemical sector is also mandated to produce circular and renewable building blocks.

The aviation sector follows a comparable trend. Availability of biomass plays a significant role for this sector. When sufficiently available, the model choses biokerosene above e-kerosine as a low cost option, with the additional benefit of producing negative emissions via CO_2 storage. In the maritime shipping sector, the larger availability of biomass and renewable hydrogen as a consequence of less demand for these resources from the chemical industry, will result in 2050 in a higher biofuels supply compared with the TRANSFORM base scenario. Consequently, the demand for synthetic ammonia is reduced.

Impact on system costs
For the what-if cases, the cost optimization model OPERA has been used to calculate an energy system with the lowest social costs. The relative change in the total system costs for 2050 is shown in Figure 5.32 for the different what-if cases compared to the base scenarios[20]. With a more restrictive boundary condition, the total system costs increase. This applies to the what-if cases with a limitation of the electrolyser capacity, no new nuclear power stations, a final energy efficiency target for all years and a lower CO_2 storage capacity. Also if the price of imported biomass doubles, the total system costs increase. When the boundary conditions are alleviated, system costs decrease. This is shown by the what-if cases with a lower demand for marine bunker fuels and a lower target for circular carbon. The total system costs for the what-if case with a final energy efficiency target for all years deviate from this for TRANSFORM 2050. Despite an additional restriction, the system costs are slightly lower (-3%) than those of the base scenario. This can be explained by the fact that the energy system has been adjusted in the previous period with higher costs (the total system costs for 2040 are 1% higher than in the base scenario), which results in lower total system costs in the what-if case in 2050 compared to the base scenario.

The extent to which the preconditions have been adjusted has an effect on the change in system costs. This is the largest when the biomass import price is doubled (+ 8.8% for ADAPT 2050) and the demand volume of marine fuels is halved (-9.7% for TRANSFORM 2050). If the change of total system costs is small, such as with a restriction of the electrolyser capacity (+0.2% for TRANSFORM 2050), this means that the energy system with this restriction is a near-optimal solution. The restriction on new nuclear power stations also leads to a limited increase in the total system costs (in 2050 +1.2% for ADAPT and +2.5% for TRANSFORM),

[19] The EU legislative gaol is to achieve 50% recycling of plastic packaging by 2025. In the Netherlands, there are plans to introduce a national obligation for plastic producers to promote the use of recycled or biobased plastic. The intention is to increase this obligation to 25%-30% plastic recyclate or biobased plastic by 2030.
[20] Changes in system costs for the what-if Limited electricity export are not shown, because effects on import/export prices that also influence system costs have not been determined.

which means that a system without new nuclear power stations can also be seen as near-optimal energy system.

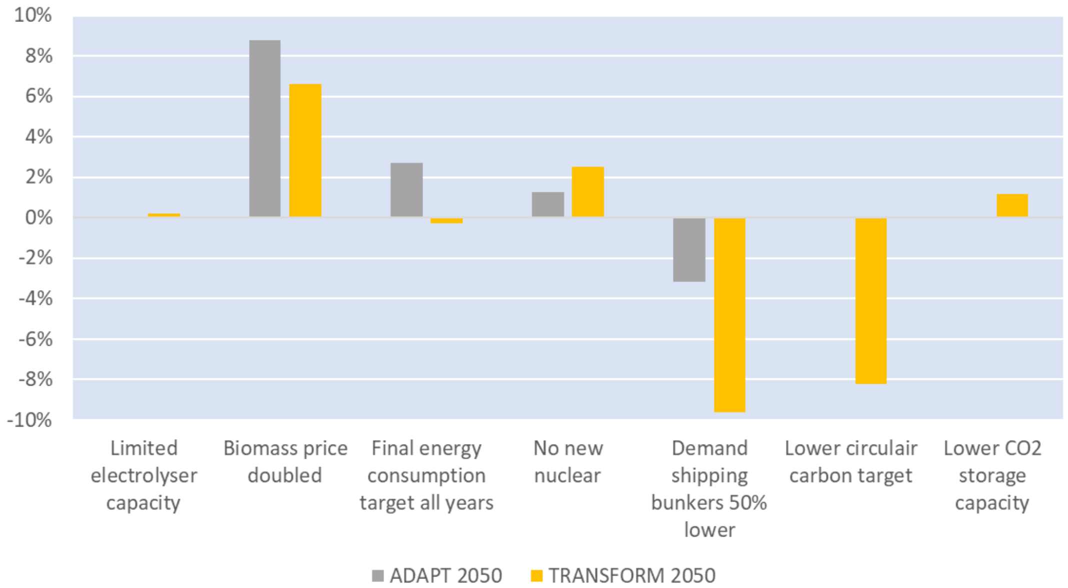


Figure 5.32: Changes in total system costs in 2050 for the what-if cases compared to the base scenarios ADAPT and TRANSFORM

5.8 Comparison with other scenario studies

5.8.1 Previous TNO scenario studies

In 2020 and 2022, TNO also published results of scenario studies for the Dutch energy system for the period 2030-2050 (Scheepers M. , et al., 2020) (Scheepers M. , et al., 2022). These scenario studies were carried out for the same scenarios, i.e. ADAPT and TRANSFORM. The differences between this new scenario study and the previous scenario studies are related to the parameterization of the scenarios. These are based on new insights and market and policy developments. Improvements have also been made to the OPERA model. The adjustments relate to:

- Expectations regarding energy and mobility demand and development of industrial production.
- Expected developments in fossil fuel prices.
- Greenhouse gas reduction targets and other policy targets.
- Including new technologies and updating of techno-economic data.
- Improvements to the OPERA model.

Table 5.2 compares this study with those of previous scenario studies for a number of selected results in 2050. It is important to realize that the 2020 study still assumed a 95% GHG reduction target. From 2022, GHG neutrality is assumed by 2050. In contrast with this study and the 2022 study, there were no sustainability targets for feedstocks and bunker fuels in the 2020 study. This explains why electricity and hydrogen production in the 2020 study is lower than in subsequent studies. Fossil fuel use is also higher in the 2020 study. In the current study, electricity and hydrogen production in TRANSFORM is slightly lower than in the 2022 study, while for ADAPT it is higher. One explanation is that hydrogen import and export plays a role in the current study, while this was not the case in the 2022 study.

Table 5.2: Comparison of selected results from previous scenario studies for the Netherlands with ADAPT and TRANSFORM

Values for 2050	Unit	TNO 2020		TNO 2022		TNO (This study)	
		ADAPT	TRANSFORM	ADAPT	TRANSFORM	ADAPT	TRANSFORM
Electricity production	TWh	352	490	315	621	373	570
o.w. offshore wind	TWh	215	320	192	386	192	343
o.w. onshore wind	TWh	30	46	33	54	37	54
o.w. solar PV	TWh	77	78	51	120	101	122
o.w. nuclear energy	TWh	0	0	0	43	34	41
Electricity import	TWh	23	41	53	8	28	17
Electricity export	TWh	80	85	32	85	26	141
Hydrogen	PJ	122	158	257	738	416	561
Biomass	PJ	891	891	945	854	890	859
Geothermal energy	PJ	120	288	58	88	114	117
Fossil fuels	PJ	1651	537	1415	125	1335	248
CO_2 storage	Mtonne	42	0	50	15	40	15

5.8.2 Other long term scenario studies for the Netherlands

Scenario studies for the Dutch energy system have recently been published by the Dutch grid operators – Integrale Systeemverkenning 2030-2050 (Afman, et al., 2023) – and the Environmental Assessment Agency – Transitieverkenning Klimaatneutraal (TVKN) 2050 (Daniels & Strengers, 2024). Table 5.3 compares scenario results of this study with the two other scenario studies for some selected outcomes. The results differ because different storylines are used and therefore the scenario assumptions are different. In the TVKN 2050, study the availability of energy sources and feedstocks on the one hand and policy objectives on the other are varied between the scenarios[21]. The TVKN 2050 results also indicate a range for the selected results that is determined by varying scenario assumptions within a certain bandwidth. In the II3050 scenarios, assumptions about the development of the industry, technology use, availability of energy and feedstock sources and imports are varied[22].

There are also differences in how the scenario results are calculated. A simulation model is used in the II3050 study. In addition to assumptions about energy demand, assumptions are also made (i.e. exogenous) for the energy demand and supply mix. TNO and PBL use both the OPERA cost optimization model to calculate the scenarios, where the energy demand and supply mix are determined endogenously by the model. Furthermore, TNO has determined the volume of import and export of electricity and hydrogen from and to neighbouring countries with a market model. PBL has also done this, but only for electricity.

Although there are differences in the assumptions and the way in which the scenarios are calculated, it is still interesting to see the range of the results of the different studies. Table 5.3 shows that TRANSFORM assumes a higher electricity production than II3050 and TVKN 2050 scenarios (only 2% higher than II3050-National Leadership and 17% higher than TVKN 2050-Pragmatic, limited). ADAPT is at the lower end of the bandwidth and the electricity production is comparable to two of the II3050 scenarios (European Integration and International Trade). In all scenarios, except ADAPT, more electricity is exported than imported. The most electricity is exported in TRANSFORM, 74% more than the II3050 European Integration scenario, the scenario with the highest exports of all other scenarios. The domestic electricity demand of ADAPT and TRANSFORM (results from production plus

[21] TVKN 2050:
- Specific targets, less limited: Relative wide availability of energy carriers and feedstocks, no additional targets for energy use, no target for phasing out fossils.
- Pragmatic, limited: Limited availability of energy carriers and feedstocks, no additional targets for energy use, no target for phasing out fossils.
- Pragmatic, less limited: Relative wide availability of energy carriers and feedstocks, ceiling on primary energy consumption, phasing out fossils.

[22] II3050 :
- National leadership: Limited industry reductions, new industry synthetic molecules based on recycled carbon and direct air capture, strong electrification, substantial renewable generation, limited nuclear, substantial heat networks.
- Decentralized initiatives: Strong reduction energy-intensive industry, strong electrification and hydrogen for industry, substantial renewable generation, energy hubs.
- European integration: No reduction in industry, new industry synthetic molecules based on CCU and bio-feedstocks, green gas (also from import) in addition to electrification and hydrogen, CCS and blue hydrogen, hydrogen in the built environment, nuclear in base load.
- International trade: Strong reduction energy intensive industry, relocation of industry abroad, substantial hydrogen in addition to biomass, CCS, direct air capture and electrification, substantial hydrogen imports, built environment uses hydrogen.

import minus export) is within the range of II3050 and TKVN 2050, but clearly lower for industry variants.

In all scenarios, most electricity is produced from wind and solar. If the total electricity production is relatively high, more electricity is produced with offshore wind, as in TRANSFORM and the TVKN 2050 scenarios. Nuclear energy is used in two II3050 scenarios (National Leadership and European Integration) and two TVKN 2050 scenarios (Pragmatic, limited and Selective, less limited). Most nuclear electricity is produced in II3050 European Integration scenario, followed by ADAPT and TRANSFORM. The nuclear electricity production in the other II3050 and TVKN 2050 scenarios with nuclear energy is well below this volume.

All II3050 scenarios and one TVKN 2050 scenario (Specific targets, less limited) assume a higher hydrogen consumption (including exports) compared to ADAPT and TRANSFORM (II3050-International Trade almost twice higher than TRANSFORM). The range for hydrogen consumption in TVKN 2050 is larger than that of ADAPT and TRANSFORM. In two of the II3050 scenarios (European Integration and International Trade), the import and export of hydrogen is higher than in ADAPT and TRANSFORM. Hydrogen import in TVKN 2050 is comparable to ADAPT and TRANSFORM, but TVKN 2050 does not assume hydrogen export.

The energy production of geothermal energy in ADAPT and TRANSFORM is larger than that of the II3050 and TVKN 2050 scenario studies. TVKN 2050 shows a much larger biomass use than ADAPT and TRANSFORM (up to 50% more). This is the result of difference in assumptions on biomass import. The assumed biomass use in the II3050 European Integration scenario is comparable to ADAPT and TRANSFORM, but considerably lower in the other II3050 scenarios.

With the exception of the TVKN 2050 Specific Objectives, less limited scenario, a significant amount of fossil oil will still be used in 2050 in all other scenarios, in particular in the II3050 scenarios and in ADAPT. In these scenarios, a (large) part of the fossil oil is exported as oil products. The TVKN 2050 scenarios assume no export of oil products. The CO_2 storage volume (for fossil and biogenic CO_2) in TVKN 2050 (20-40 Mtonne) is comparable to that in ADAPT and TRANSFORM (15-40 Mtonne). A comparable CO_2 storage volume is also assumed in II3050 European integration and International trade, but in these scenarios CO_2 is not only stored from the Dutch energy system, but also from abroad. In the two other II3050 scenarios, no or very limited CO_2 storage is assumed.

Because of assumed reductions in industrial activities, the II3050 scenarios Decentralized initiatives and International Trade have characteristics that are more comparable with the TRANSFORM industry variants of this study. Electricity production in the TRANSFORM industry variants is lower compared to the TRANSFORM base scenario, mainly due to less electricity production from offshore wind, solar PV and nuclear. However, electricity production is in these variants still higher than in the II3050 scenarios Decentralized initiatives and International Trade. Also biomass use is lower in the industry variants compared to TRANSFORM base scenario, but higher than the two II3050 scenarios. Although, hydrogen use increases in the industry variants, partly due to higher imports, the values are lower than those of II3050 International Trade.

Table 5.3: Comparison of selected results from other long-term scenario studies for the Netherlands with ADAPT, TRANSFORM and TRANSFORM industry variants

Values for 2050	Unit	II3050 (2023)				TVKN 2050 (PBL, 2024)				TNO (This study)		
		Decentral Initiatives	National Leader-ship	European Inte-gration	Inter-national Trade	Specific targets, less limited	Pragmatic, limited	Pragmatic, less limited	Total range*	ADAPT	TRANSFORM	TRANSFORM Industry variants
Electricity production	TWh	421	557	388	371	453	487	468	391-519	373	570	505-518
o.w. offshore wind	TWh	214	343	181	219	312	323	318	243-326	192	343	314-338
o.w. onshore wind	TWh	48	64	32	43	31	38	34	25-40	37	54	54
o.w. solar PV	TWh	143	135	110	110	105	95	89	89-123	101	122	72-81
o.w. nuclear energy	TWh	0	21	55	0	0	24	22	0-29	34	41	24-30
Electricity import	TWh	54	42	61	61	6	6	6	5-8	28	17	10-17
Electricity export	TWh	60	69	89	81	40	39	38	27-41	26	141	141-162
Domestic electr. demand	TWh	415	530	360	351	419	454	436	355-500	375	446	275-320
Hydrogen supply	PJ	573	808	819	1092	671	467	511	324-806	416	561	654-730
o.w. import	PJ	182	202	407	803	286	0	184	0-308	141	236	161-409
o.w. export	PJ	214	243	403	427	0	0	0	0-0	280	156	130-239
Biomass	PJ	308	228	922	307	1053	1288	831	678-1289	890	859	752-809
Geothermal energy	PJ	22	50	31	24	20	58	79	3-197	114	117	59-117
Fossil fuels	PJ	785	848	1921	1551	1	313	310	1-638	1335	248	126-248
o.w. export	PJ	725	725	1606	1430	0	0	0	0-0	702	216	125-261
CO_2 storage	Mtonne	3	0	35**	19**	20	40	30	20-50	40	15	15

* Excluding variants with high capacities for wind or nuclear

** Including 16 and 10 Mtonne CO_2 coming from other countries for European integration and International trade respectively

6 Results scenario variants for industry

In this chapter, the results of the industry variants are presented and discussed. First, Section 6.1 shows the results per industry sector. Section 6.2 then discusses the effects that changes in the industry variants have on the future Dutch energy system. Results of the industry variants are compared with the TRANSFORM scenario.

6.1.1 Refineries

The Dutch refineries currently supply fossil fuels and feedstocks not only to the domestic market but also to Europe and beyond. In TRANSFORM, oil refining is projected to decrease by 2050, with a majority of the products being exported. Fuel demand of the transport sector will shift towards renewable fuels and to meet this demand, renewable refineries will have to be established. While the refinery commonly refers to industrial facilities where crude oil is processed and refined to produce various products for the transport sector and the petrochemical industry, renewable refineries refer to processes that produce bio-and synthetic-fuels and feedstock. Among the various value chains, production of methanol, regardless of bio or synthetic, and synthetic ammonia production are categorized as chemicals and not included under the refineries. Nevertheless, they are also used as fuel for the transport sector, particularly, maritime shipping.

Figure 6.1 shows the TRANSFORM scenario results for refineries. As set within the scenario framework, traditional oil refineries are steadily decreasing while renewable refineries are being established to meet the evolving demand. By 2050, the oil refinery output is reduced by 75%, compared to 2030. While currently 75% of the fossil fuel produced in refineries are used to meet the demand for domestic transport and the bunkering in the Netherlands, this reduces to 15% in 2050. Hence, in future approximately 85% of the fossil refinery fuel output is exported.

The renewable refineries consist of Hydroprocessed Ester and Fatty Acids (HEFA), where used cooking oil (UCO) and animal fat (AF) can be further proceeded to range of products, and bio and synthetic Fischer Trospsch (FT) synthesis. The process are optimized to increase kerosene production. Diesel, one of the by-products, is supplied mostly to the maritime bunkering and substitutes heavy fuel oil (HFO). The other important by-product is renewable naphtha, which is further utilized in the chemical industry.

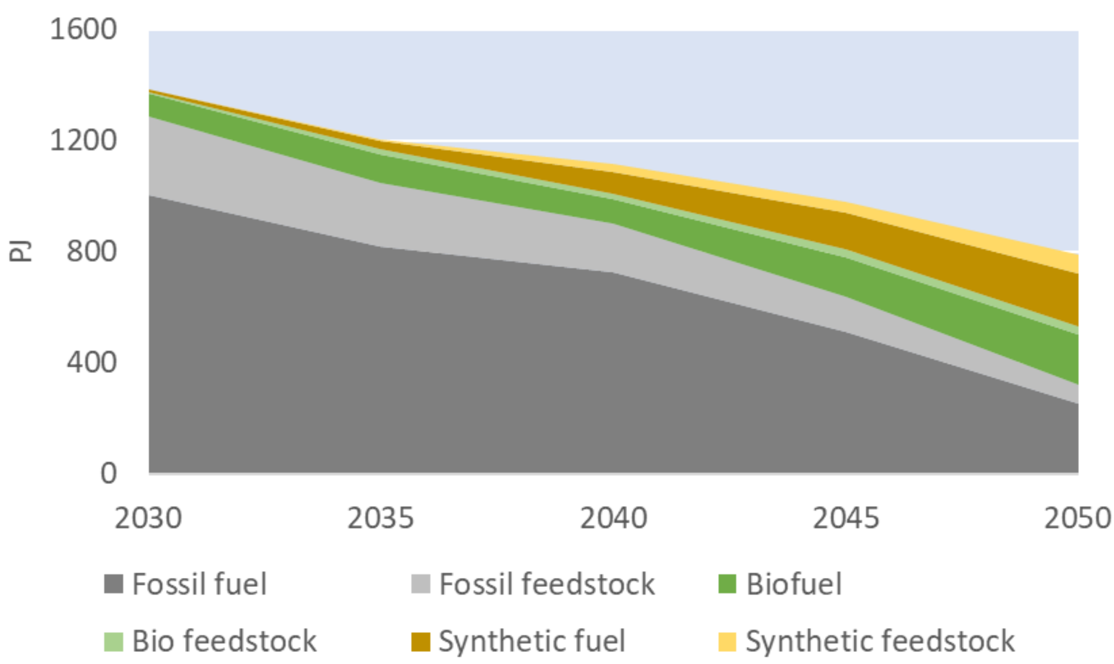


Figure 6.1: Production of fuels and feedstocks according to TRANSFORM

Figure 6.2 presents the three industry variants in comparison to the TRANSFORM base scenario. In order to facilitate ueenderstanding the main differences of the industry variants are recapped in Table 6.1. Further details can be found in Table 4.7 in Section 4.2.

Table 6.1: Assumptions for refineries in industry variants

	Competitive & Import	Less Competitive	Less Competitive & Import
Renewable refineries	• Only intermediates are imported, e.g. hydrogen and biomass pyrolysis oil. • H_2 import price 2.5 €$_{2015}$/kg in 2030 and 1.8 €$_{2015}$/kg in 2050 • Bio-pyrolysis oil price 8 €$_{2015}$/GJ	• Half of the renewable fuel demand in transport is imported. • No import of intermediates.	• Half of the renewable fuel demand in transport is imported. • This variant also includes import, e.g. hydrogen and biomass pyrolysis oil. • H_2 import price 2.5 €$_{2015}$/kg in 2030 and 1.8 €$_{2015}$/kg in 2050 • Bio-pyrolysis oil price 8 €$_{2015}$/GJ
Traditional oil refining	• Oil refineries stay the same as TRANSFORM.	• Oil refineries production is halved due to competition, in comparison to TRANSFORM.	• Oil refineries production is halved due to competition, in comparison to TRANSFORM.

Competitive & Import variant
Due to import of biomass pyrolysis oil and hydrogen, the production capacity for the synthetic value chain reduces. Consequently, the overall output of the synthetic FT refinery decreases by more than

45%, compared to TRANSFORM. This relates to the relatively high production costs of e-FT compared to bio-based value chains, leading to more production of biofuels, and also synthetic methanol. Thus, in this scenario imported biomass pyrolysis oil is upgraded to biofuels and imported hydrogen is upgraded to methanol for the shipping sector. Since the methanol production and use are categorised as chemicals, it is not included in the refinery figure. These align with the cost-optimisation within the OPERA model. Consequently, the potential for importing renewable fuels sightly changes the production portfolio of renewable refineries

Less Competitive variant
As a result of more international competition, in this variant the capacity of oil refineries is reduced by 50% compared to TRANSFORM. In addition, both biorefineries and synthetic refineries seemingly play a lesser role than TRANSFORM, compensated by imports. In 2050, biorefineries appear approximately 30% less in this variant than TRANSFORM, and synthetic refineries 40% less. This relates to the relatively high production costs of e-FT compared to bio-based value chains, leading to a preference of importing synthetic fuels. This aspect aligns with the cost-optimisation within the OPERA model.

Less Competitive & Import variant
The Less Competitive & Import variant follows the same logic as Less Competitive, with the addition of allowing biomass pyrolysis oil. Renewable refineries decrease in this scenario when compared with the TRANSFORM results, synthetic refineries experiencing the largest effect (47% less than TRANSFORM), followed by biorefineries (18% less). Biomass pyrolysis oil based value chains corresponds to around 20% of the total fuel production in 2050 in this variant.

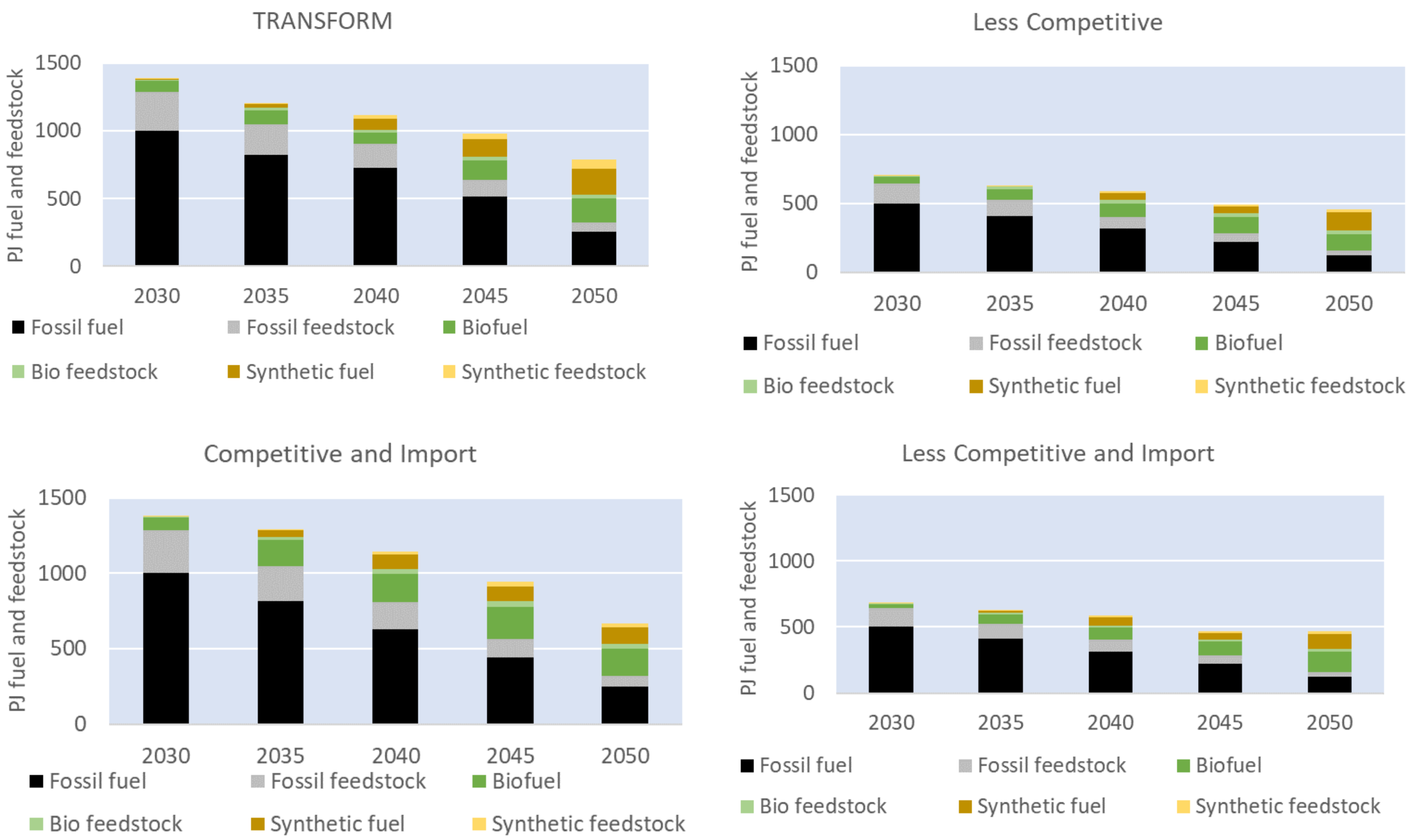


Figure 6.2: Fuels and feedstock production according to TRANSFORM and the industry variants

6.1.2 High value chemical production

In TRANSFORM, a target for non-virgin fossil carbon content is set for 2050 (80%). In the sector, there is a significant shift of feedstock use from fossil towards biobased, followed by synthetic feedstock (see Figure 6.3). One of the reasons for such result is the considerable shrink of fossil refineries (85% in 2050) and growth of renewable refineries, see Section 6.1.1. The considerable shrink from the fossil refinery sector in TRANSFORM affects directly the aromatics production. With lower production of reformates/aromatics by fossil refineries, alternative ways of production are selected by the model, the bio route appears as the preferred option. It is important to highlight that no imports of renewable chemicals are allowed in TRANSFORM and few standalone aromatics production routes are present in the model. Also, the production of e/bio-kerosene increases the availability of e/bio-naphtha to steam crackers because the latter is a by-product of renewable kerosene.

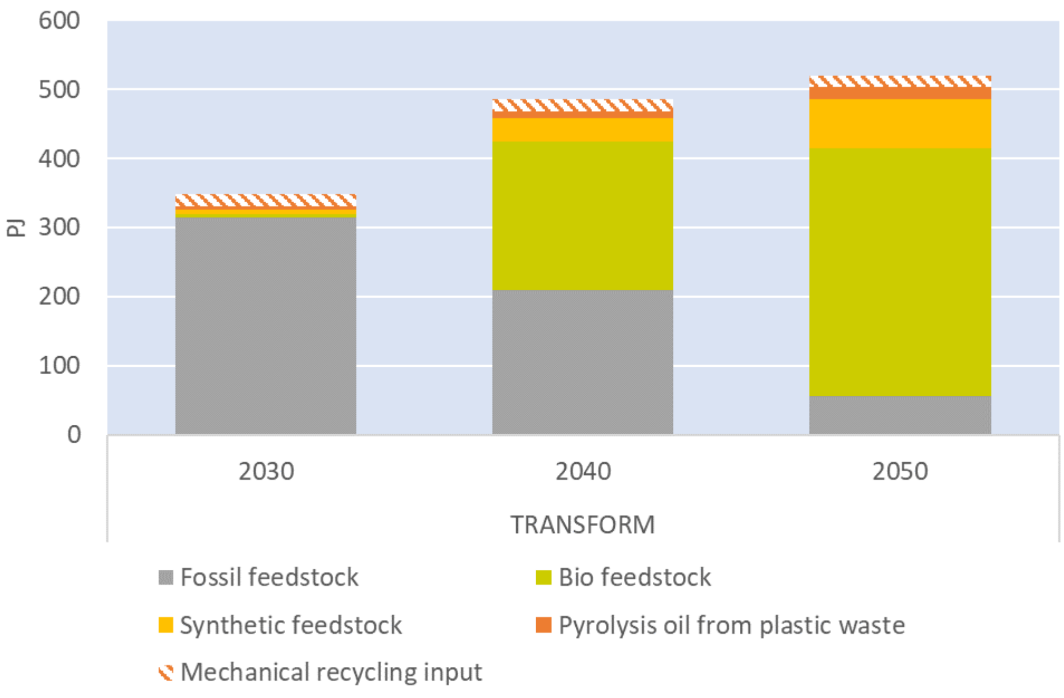


Figure 6.3: Feedstock use for the production of high value chemicals for TRANSFORM[23]

Technology selection
Regarding the production of olefins, electrification of conventional steam crackers shows as one of the most relevant technologies in 2050 in TRANSFORM, followed by bioethanol dehydration. However, electric crackers use a significant share of fossil naphtha (around 43%). Methanol to olefins has smaller presence mainly due to limited availability of renewable methanol to be used in the chemical sector. A similar situation occur for mechanical recycling: the limited availability of plastic waste for recycling (domestic plastic waste only) hinders its contribution to the sector. For aromatics production, biomass to aromatics becomes the most relevant production route. The significant shrink in 2050 of fossil refineries decreases the production of reformates (conventional feedstock for

[23] Mechanical recycling is not a production route of high value chemicals, it substitutes the demand for virgin plastics, therefore, the demand for HVCs. This technology appears in the results for comparison purposes only.

aromatics production) and aromatics. For this reason, the standalone bio-based aromatics production route becomes responsible for meeting the 2050's volumes demand.

Feedstock selection
For the overall high value chemicals production, biobased materials are the most relevant feedstocks in 2050. This is mainly due to the standalone production of aromatics via biomass gasification. Synthetic feedstocks also become more prominent in 2050 because of higher availability of e-naphtha as by-product from synthetic fuels production from renewable refineries. When looking closely to steam crackers, both bio and e-based naphtha are similarly relevant. Circular feedstocks are limited to domestic availability only, therefore, its share in 2050 is restricted.

TRANSFORM and industry variants
Table 6.2 summarizes the main characteristics of the industry variants.

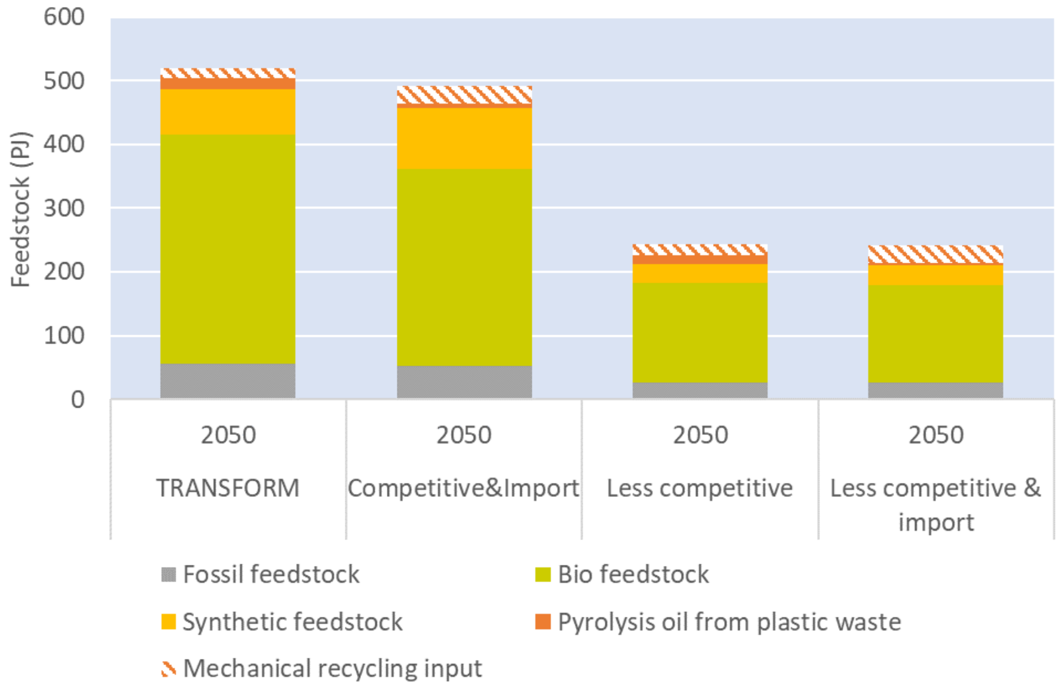


Figure 6.4 shows the feedstock consumption for the industry variants in comparison to TRANSFORM in 2050. Figure 6.5 compares the technology selection for olefins production between TRANSFORM and the industry variants. A similar comparison is made for aromatics production in Figure 6.6.

Table 6.2: Assumptions for high value chemical production in industry variants

	Competitive & Import	Less Competitive	Less Competitive & Import
High value chemaicals production	• Same production level as in TRANSFORM.	• Half of the production level of HVCs as in TRANSFORM.	• Half of the production level of HVCs as in TRANSFORM.

	Competitive & Import	Less Competitive	Less Competitive & Import
Imports	• Import of intermediates and plastic waste allowed (10% of EU plastic waste)*.	• No imports allowed..	• Import of intermediates and plastic waste allowed (10% of EU plastic waste)*.
Recycling efficiency	• Same as in TRANSFORM.	• Mechanical recycling efficiency (90% in comparison to 80%) due to mono plastic waste policy push considered. • Both gasification of plastic waste and pyrolysis of plastic waste efficiencies are kept the same as in TRANSFORM.	• Mechanical recycling efficiency (90% in comparison to 80%) due to mono plastic waste policy push considered. • Both gasification of plastic waste and pyrolysis of plastic waste efficiencies are kept the same as in TRANSFORM.

Based on (Stegmann, Daioglou, Londo, & Junginger, 2022), one of the projections for plastic waste generation in the EU is around 25 Mtonnes in 2050. More information about the assumptions on plastic waste availability can be found in Appendix D.

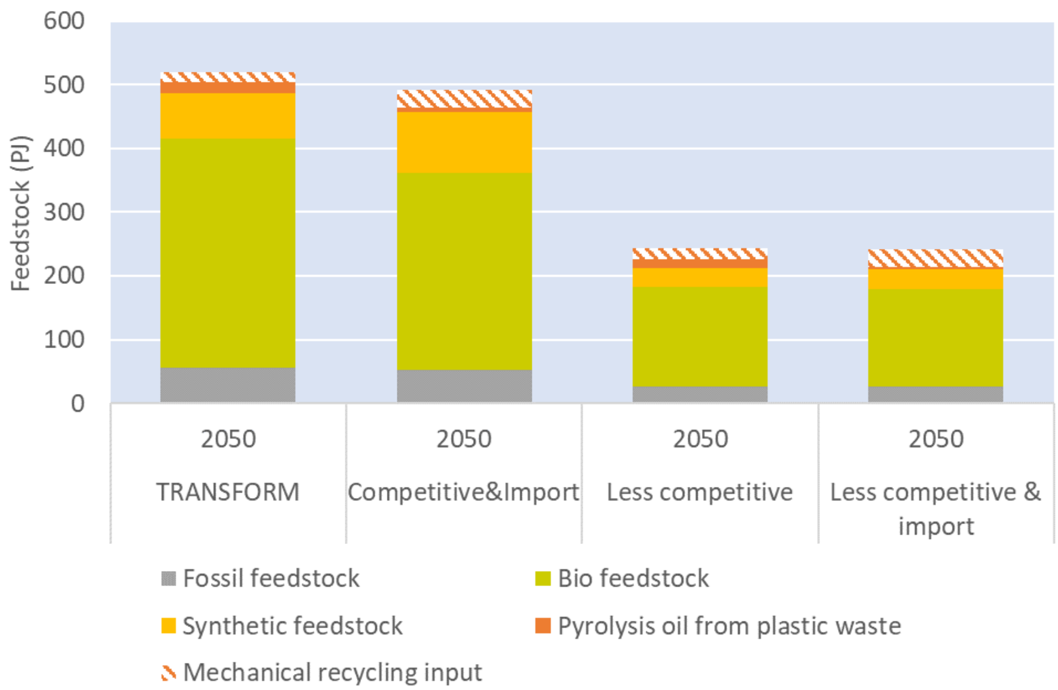


Figure 6.4: Feedstock consumption for high value chemicals production in the industry variants and TRANSFORM in 2050

The Less Competitive variant allows more use of fossil feedstock in the conventional steam crackers (around 89% in 2050) than in TRANSFORM (0% in 2050). This effect relates to much lower availability of bio and synthetic naphtha from renewable refineries, when compared to

TRANSFORM. For the variants Less Competitive & Import, the feedstock use for HVCs production presents lower share of synthetic naphtha and higher presence of mechanical recycling. Result mainly connected to the higher availability of plastic waste for recycling and with the lower availability of bio and synthetic naphtha from renewable refineries in the Less Competitive & Import variant. For the variant Competitive & Import, more synthetic naphtha is available due to higher activity of renewable refineries and there is more plastic waste for recycling. In all variants, biobased feedstock is still the most relevant feedstock for the sector, mainly due to standalone aromatics production.

Regarding technology selection for olefins production, bioethanol dehydration is not selected anymore in the industry variants. In the Less Competitive variants, a higher share of conventional cracking with fossil naphtha is allowed due to the reduction of activity, which resulted in less GHG emissions (making it easier to reach the emissions targets). Electric cracking shows up as the second relevant technology for the variants, however, the feedstock mix, except for the Less Competitive variant, still presents significant share of fossil naphtha. For aromatics production, the industry variants are very similar to TRANSFORM in terms of technology selection.

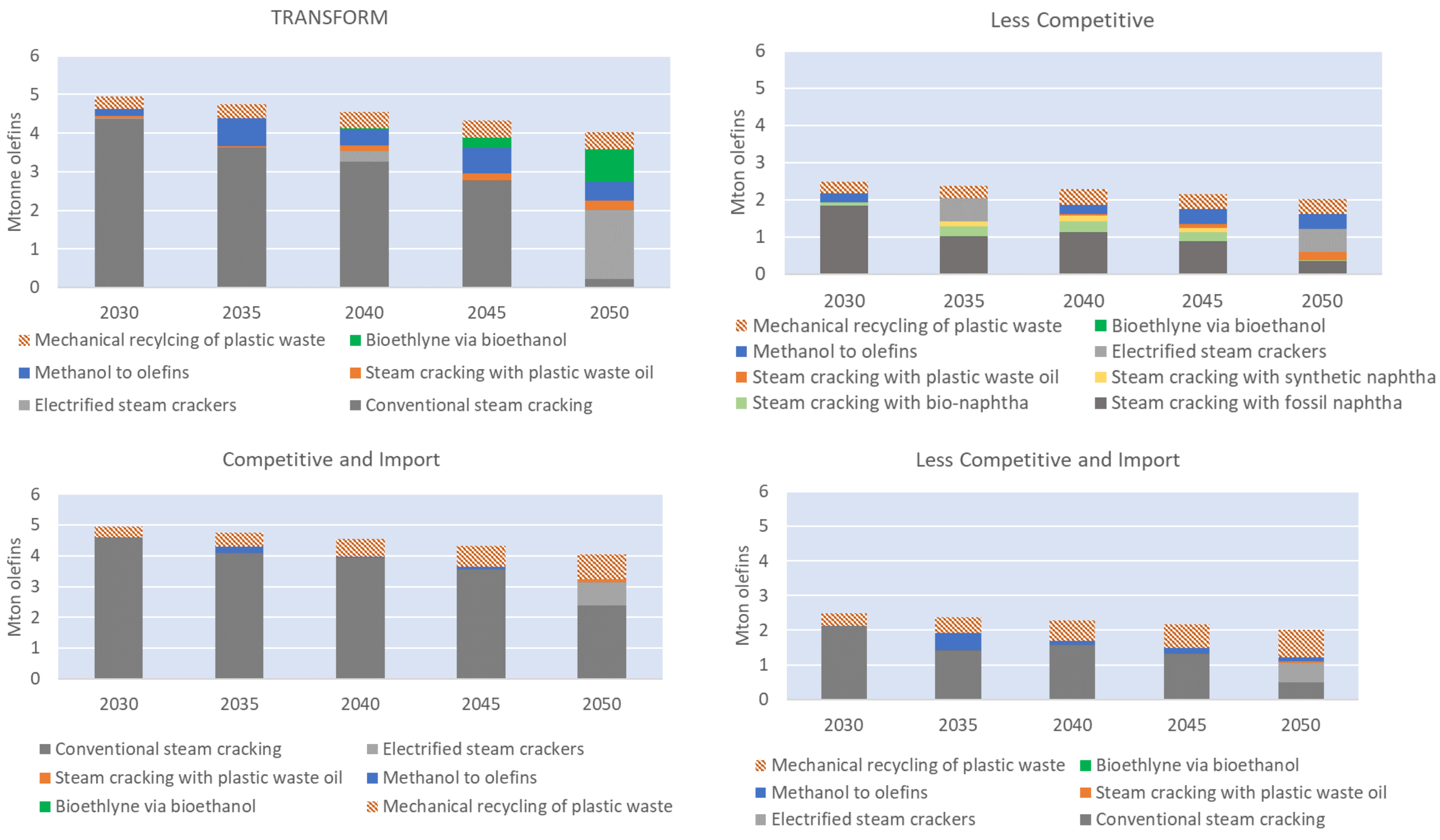


Figure 6.5: Olefin production according to TRANSFORM and the industry variants

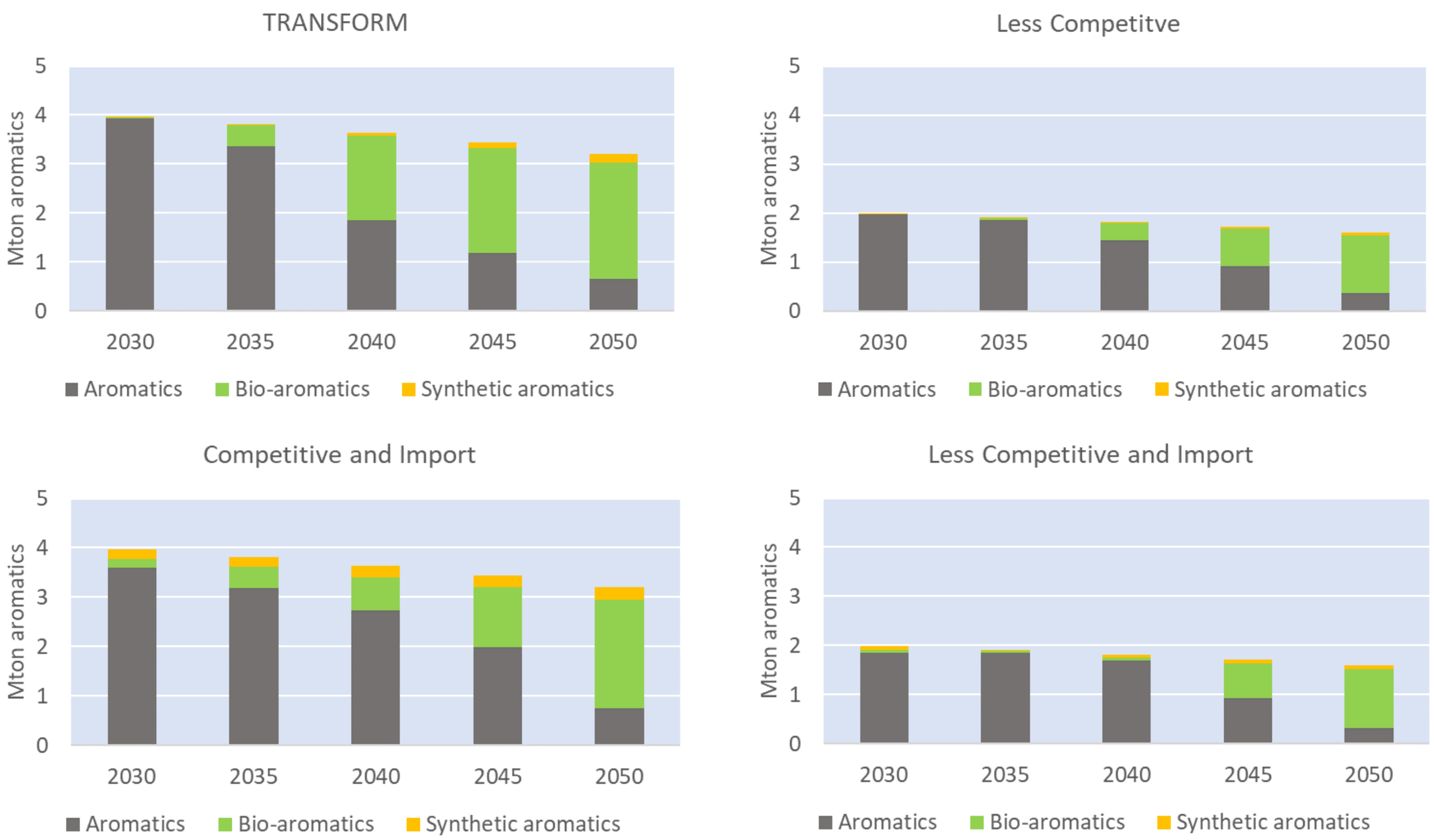


Figure 6.6: Aromatics production according to TRANSFORM and the industry variants

6.1.3 Steel production

Figure 6.7 shows the technologies used and volumes produced for steel production in TRANSFORM and the three industry variants. TRANSFORM follows the planned transition for steel production through a partial switch from coal-based to direct reduced iron steel production (DRI) with natural gas in 2030. In 2040, natural gas will be replaced by (green) hydrogen and in 2045, all steel production will switch to DRI with hydrogen. This gradual transition is possible because steel production takes place in two blast furnaces: one blast furnace will be converted to DRI in 2030 and the second will follow in 2040.

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In the Less Competitive variant, the production volume drops by 50% (scenario assumption). In this scenario variant, the second blast furnace will be decommissioned in 2030. In the industry variants with import, pig iron production takes place elsewhere and iron is imported in the form of hot bricket iron (HBI). Smelting imported HBI requires more energy than iron production from DRI at the same location as steel production. Moreover, steel production based on HBI has consequences for the different steel qualities produced. In the Competitive and Import scenario variant, HBI imports will take place from 2040 onwards instead of converting the second blast furnace. In the Less Competitive and Import scenario variant, the blast furnace converted to DRI on natural gas will be decommissioned in 2040 and all steel production will take place on the basis of HBI.

The technology and volume changes have consequences for the use of fossil fuels and green hydrogen. In the Competitive & import and Less Competitive variants, coal and natural gas will continue to be used until 2035, but in the Less Competitive variant with a smaller volume. In the Less Competitive & Import variant, no hydrogen demand arises in steel production.

Figure 6.7: Steel production in TRANSFORM and three industry variants (DRI: direct reduced iron; EAF: electric arc furnace; HBI: hot briquetted iron)

6.1.4 Fertiliser production

For fertiliser production, ammonia is the most important semi-finished product and the most energy-intensive to produce. The analysis of the scenarios and industry variants therefore mainly focuses on ammonia production. The production of ammonium nitrate and urea from ammonia is not shown here. In the modelling the energy consumption for producing these products are part of the fertiliser production process. To reduce CO_2 emissions, TRANSFORM will use CCS in ammonia production from natural gas in 2030 and 2040 (see Figure 6.8). Furthermore, it is assumed that 15% of the ammonia is imported (as ammonia produced from green hydrogen). In this scenario, a partial switch is made in 2040 to ammonia production based on external produced hydrogen supplied via a hydrogen transport pipeline. This is more cost-effective than hydrogen production with electrolysers at the fertiliser production site, mainly because of the difference between electricity and hydrogen transport costs. In the two less competitive variants, international competition leads to the closure of one of the two fertiliser production sites. In the Less Competitive variant, ammonia production in the remaining fertiliser plant will gradually switch to ammonia production based on externally supplied hydrogen in the period 2040-2045. In this variant, CCS will be applied in up to 2035. That is a result of the optimization. In reality, this intermediate step may be skipped. In the Less Competitive and Import variant, ammonia production will end in 2040 and fertiliser production will take place entirely on the basis of imported ammonia. In the Competitive and Import variant, both fertiliser production plants remain in operation. The ammonia production at one of the plants is converted to externally supplied hydrogen and the ammonia production plant is decommissioned at the other location to be replaced by imported ammonia.

Compared to the TRANSFORM scenario, the demand for hydrogen for ammonia production changes in the industry variants. In the Competitive & Import variant, hydrogen demand is lower compared to TRANSFORM due to an increase in the import of ammonia. Although the ammonia production in Less Competitive is lower, the hydrogen is almost the same as in TRANSFORM. In the Less Competitive & Import variant, there is no demand for hydrogen because ammonia is imported.

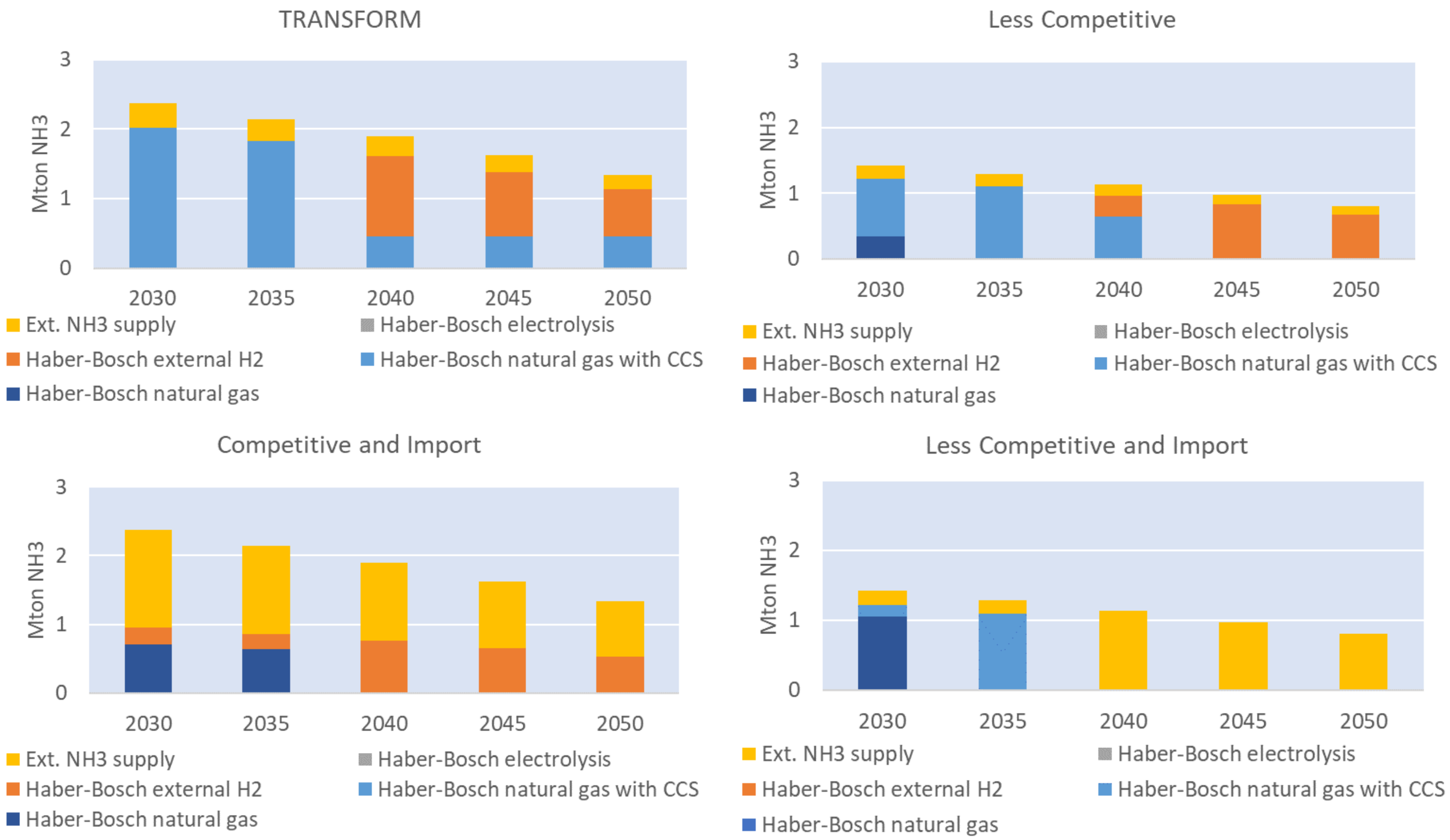

Figure 6.8: Ammonia production in TRANSFORM and industry variants

6.2 Results total energy system

6.2.1 Energy supply and demand

In the industry variants, the total primary energy supply decreases compared to TRANSFORM, see Figure 6.9. In 2050, the primary energy supply in the Competitive & Import variant will be 4% lower than in TRANSFORM. In the Less Competitive and Less Competitive & Import variant this is 13% and 15% lower respectively. The decrease for energy supply from renewable sources is less, between 3% and 13%. A lower domestic energy supply is compensated with energy imports. In TRANSFORM, approximately 74% of the primary energy supply will be imported in 2030 and largely consists of fossil fuels. By 2050, energy imports will have fallen to 31%, mainly, biomass, electricity and hydrogen. The import share is larger in the industry variants: 34% in the Less Competitive variant, 37% in the Competitive & Import variant and 38% in Less Competitive & Import variant.

Due to the import assumptions, the primary feedstock supply in the industry variants Less Competitive and Less Competitive & Import is lower than in TRANSFORM: 44% and 51% lower respectively in 2050. Compared to TRANSFORM, the primary feedstock supply for Competitive & Import is 8% higher. The assumptions made for the industry variants have an effect on energy consumption: primary energy consumption for domestic energy in the industry variants is 6% to 13% lower than TRANSFORM in 2050. This also applies to the final energy consumption. In the Competitive & Import variant, more methanol will be used as shipping fuel in 2050. If the definition from the Energy Efficiency Directive (EED) is used and corrected is made for this methanol use, the final consumption remains below the EED target of 2030. In the two other sector variants, the final energy consumption is lower than in TRANSFORM and approximately 2% below the EED target for 2030.

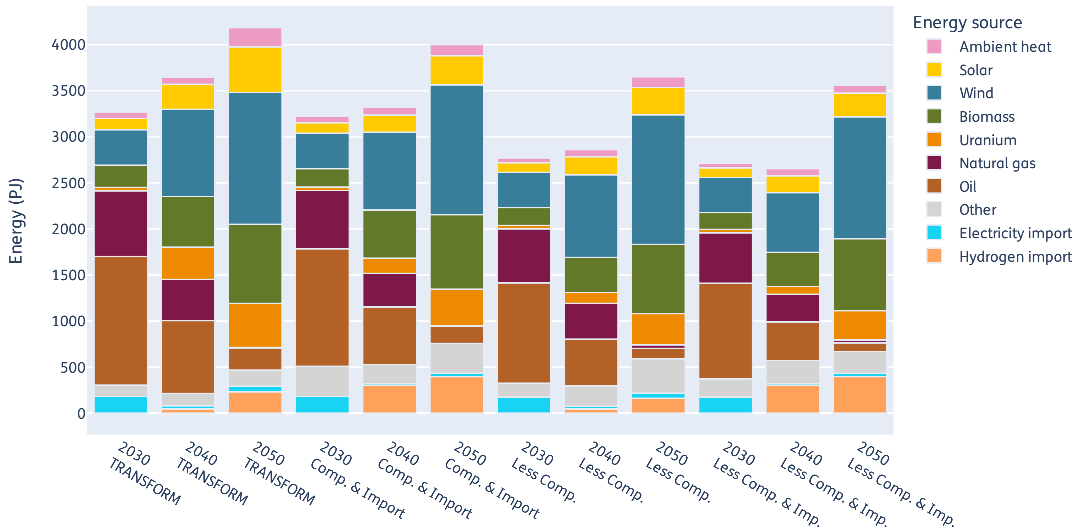

Figure 6.9: Total primary energy supply, including feedstocks and bunkers, for TRANSFORM and industry variants

6.2.2 Carbon balance

Carbon balances have been created for the industrial variants in the form of Sankey diagrams. These are shown in Figure 6.10 for 2050 compared to TRANSFORM. The total amount of carbon in the system in Competitive & Import is almost equal to that in TRANSFORM. But in Less Competitive and Less Competitive & Import, the total carbon in the system decreases by 14% and 9% respectively. This is mainly caused by a decrease in the amount of fossil carbon by approximately 40% in both variants and corresponds to the primary fossil energy use (see Figure 6.9). While TRANSORM and industry variants are climate neutral in 2050, fossil carbon is still used. As already indicated in Section 5.4.3, this is possible through 1) export of fossil fuels outside the EU, 2) use of fossil carbon in the production of chemicals, 3) storing fossil CO_2 in the available CCS storage capacity and 4) compensating fossil CO_2 emissions with negative emissions.

The Less Competitive and Less Competitive & Import variants use less biogenic carbon than in TRANSFORM and the Competitive & Import variant. Lower use of fossil and biogenic carbon in these variants can be entirely attributed to the assumptions regarding lower chemical production and fuel production in refineries. The amount of stored carbon (CCS) in the industry variants is the same as in TRANSFORM. Slightly more biogenic CO_2 is stored and less fossil CO_2, which can be explained by a decrease in fossil carbon in the system. The use of captured carbon is lower in Less Competitive and Less Competitive & import than in TRANSFORM, due to lower production levels in refineries and chemical plants.

Importing semi-finished products in the two import variants has only a modest effect on the carbon balance: the non-organic waste flow increases slightly due to the import of plastic waste and the synthetic fuel import also increases compared to TRANSFORM and the Less Competitive variant. The import of biofuels and bio-naphtha is not distinguished separately (fall under biomass).

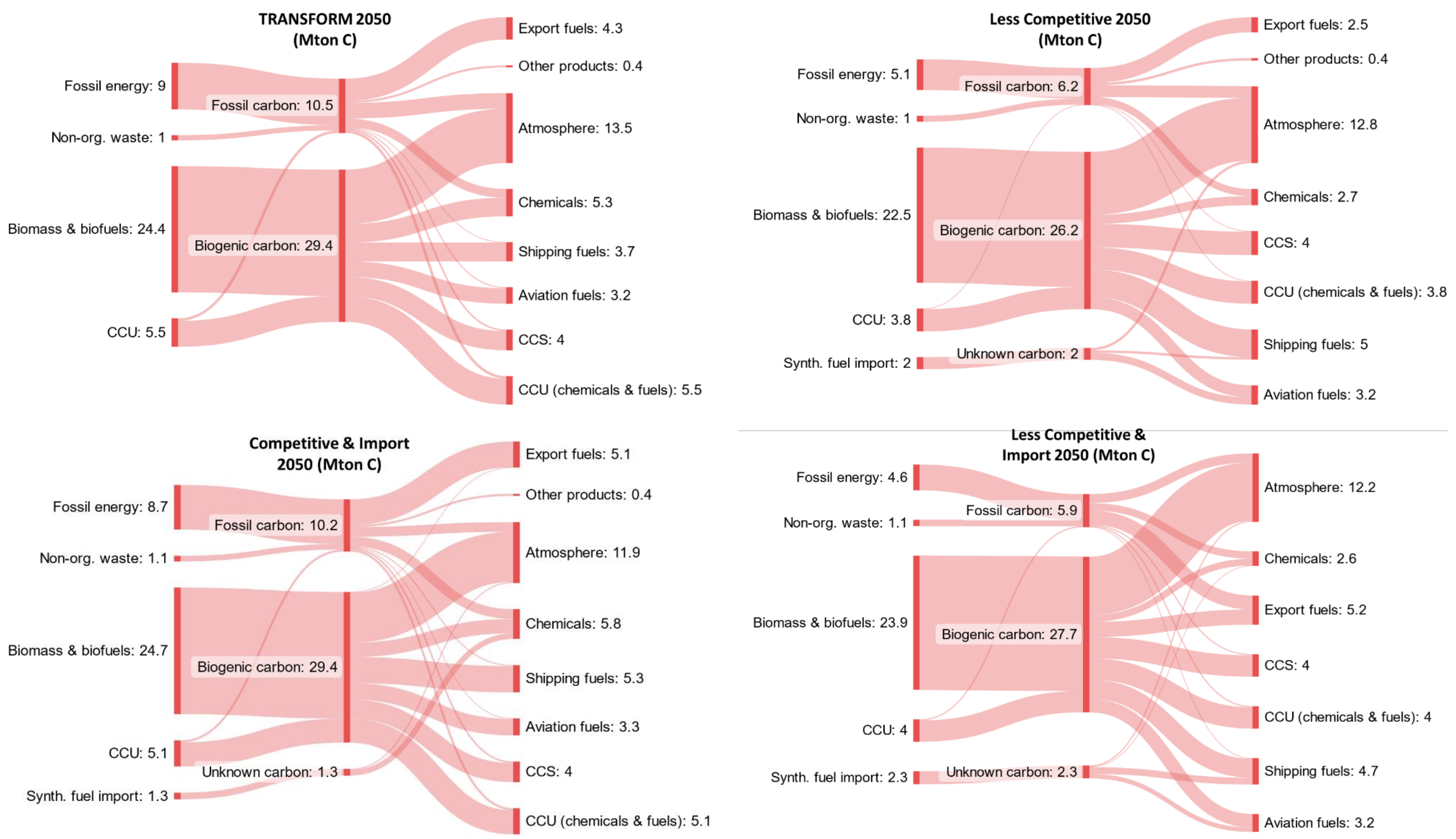

Figure 6.10: Carbon balances for TRANSFORM and industry variants in 2050

6.2.3 Electricity

Figure 6.11 shows that electricity consumption in the industry variants is lower than in TRANSFORM. This is mainly due to changes in electricity consumption in the industrial sector. In 2050, the total consumption in the Competitive & Import variant hardly differs from that in TRANSFORM. However, in the two other industry variants, electricity consumption is considerably lower due to the assumed lower industrial production level in the four energy-intensive industries. The increase in electricity demand between 2035 and 2045 is also different in the industry variants than in TRANSFORM. The growth of hydrogen production with electrolysers is lagging behind, but in 2050 the electricity demand for hydrogen production will also increase substantially in the industry variants. In the Less Competitive variant this is even higher than in TRANSFORM, see Section 6.2.4 for a further explanation.

The total electricity production shows a similar trend as electricity consumption, see Figure 6.12. The increase in electricity demand will be met by expanding the production capacity for wind, solar and nuclear energy, supplemented by imports. However, the electricity production growth in the industry variants is smaller than in TRANSFORM: in 2050, electricity production from wind and solar energy will be 4% lower in Competitive & Import, 5% lower in Less Competitive and 13% lower in Less Competitive & Import. Electricity production from nuclear energy shows a similar trend.

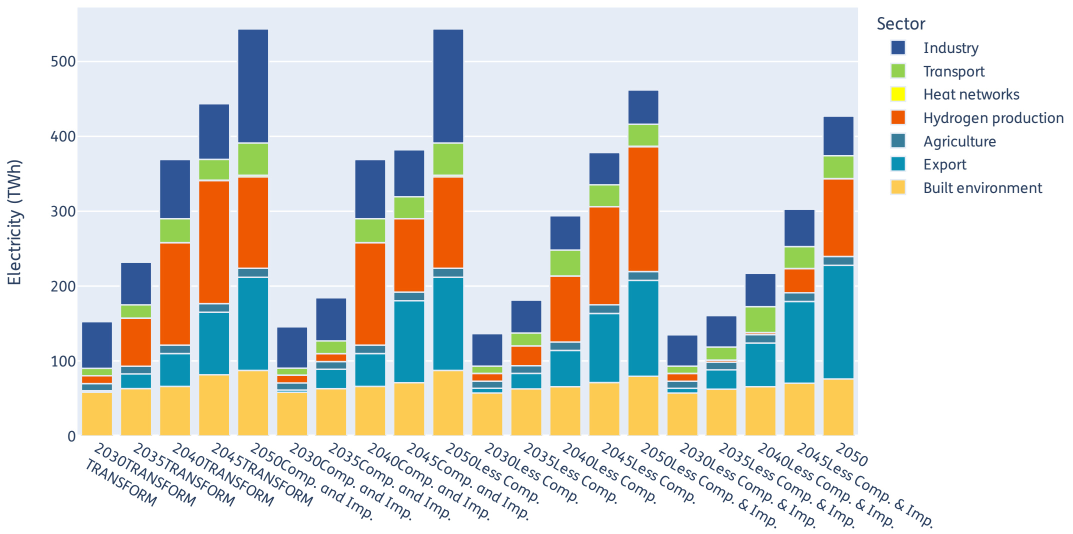

Figure 6.11: Electricity consumption according to TRANSFORM and the industry variants

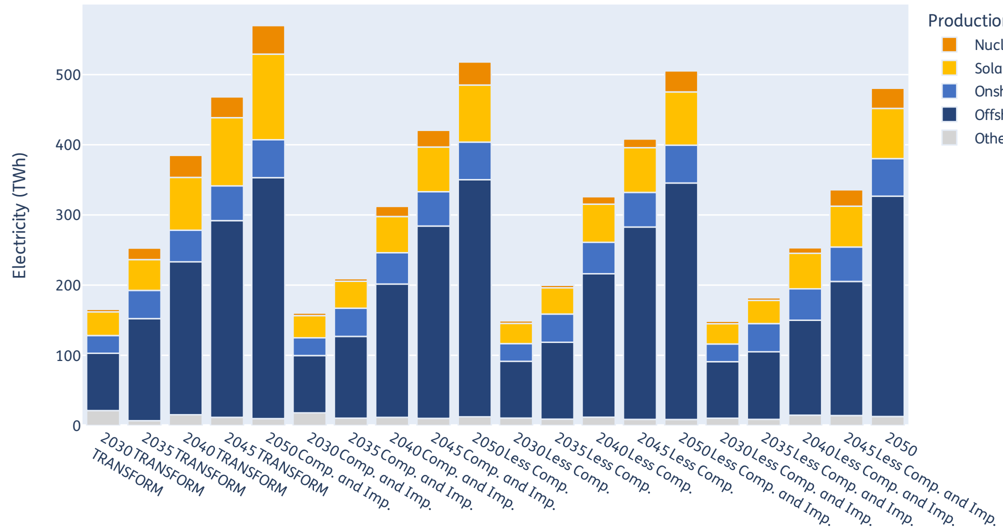

Figure 6.12: Electricity supply according to TRANSFORM and industry variants

6.2.4 Hydrogen

In the Competitive & Import variant, the import price for hydrogen becomes competitive with domestic production, resulting in an increase of total hydrogen consumption (see Figure 6.13) and more hydrogen imports (see Figure 6.14). This higher consumption takes place in the production of power-to-liquids and methanol, in the built environment and in electricity production. While in TRANSFORM hydrogen is mainly used for district heating in the built environment, in the Competitive & Import variant hydrogen is also distributed in residential areas. The hydrogen demand for steel and fertiliser production becomes lower, because the products in these industries are partly produced from imported semi-finished products in this scenario variant. Figure 6.14 shows that the strong increase in domestic hydrogen production with electrolysers in TRANSFORM in 2040 will take place later in the Competitive & Import variant. In 2050, domestic hydrogen production in the variant hardly differs from the base scenario.

In the Less Competitive variant, production in the four basic industries is considerably lower than in the base scenario. This leads to lower hydrogen consumption in these industrial sectors, but due to a shift to other energy consumption sectors (e.g. built environment) overall, hydrogen consumption is comparable to the base scenario. In the Less Competitive & Import variant, hydrogen consumption is higher than in TRANSFORM. The increase in hydrogen demand for several consumption sectors in this industry variant is similar to that in Competitive & Import, with an even higher hydrogen supply to distribution grids in residential areas.

In the Less Competitive variant, domestic hydrogen production with electrolysers is larger than in TRANSFORM. A larger hydrogen production is possible because in this scenario variant more electricity is available for hydrogen production than in TRANSFORM and competition with imports from abroad is limited. In the Less Competitive & Import variant, domestic hydrogen production in 2050 is about 25% lower than in TRANSFORM. The net hydrogen import in this variant is comparable to Competitive & Import.

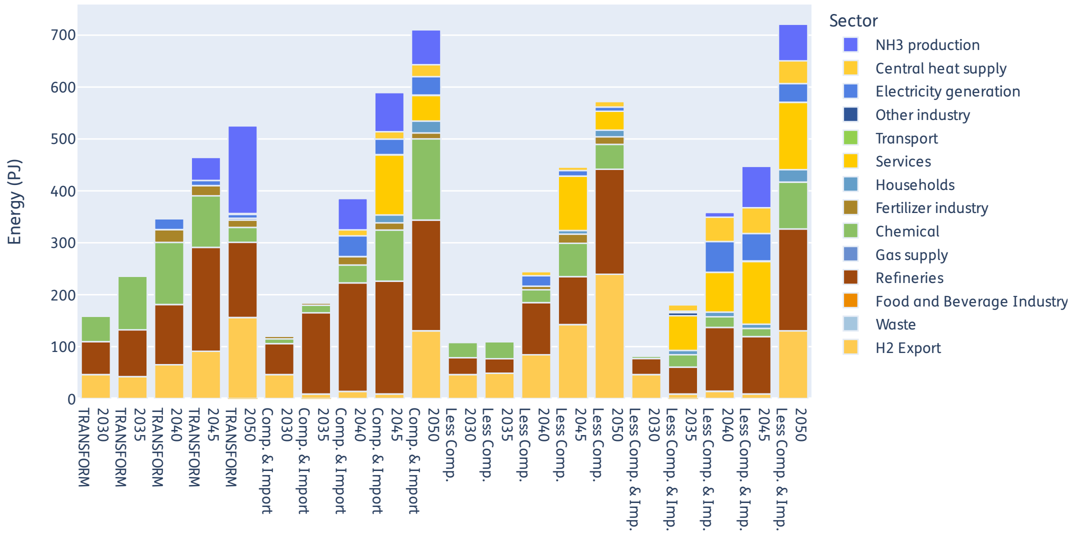

Figure 6.13: Hydrogen demand according to TRANSFORM and industry variants (P2L: power to liquid)

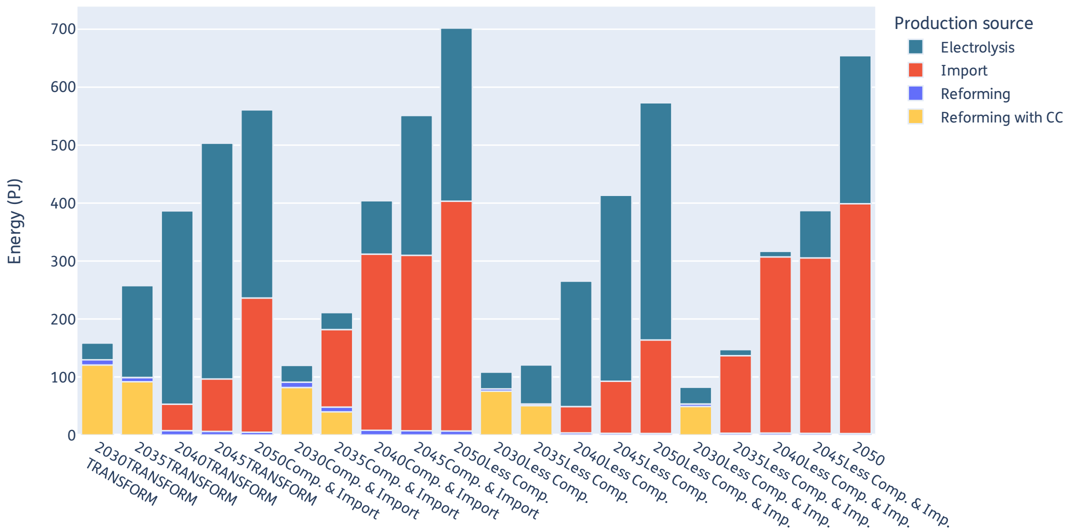

Figure 6.14: Hydrogen supply according to TRANSFORM and industry variants

6.2.5 Biomass

Figure 6.15 shows the origin and destination of biomass for TRANSFORM and the industry variants in 2050 in the form of Sankey diagrams. The use of biomass (including imported biofuels and bio-naphtha) is 4% to 13% lower in the industry variants compared to TRANSFORM. Biomass mainly plays a role in two of the four industrial sectors considered: refineries and high-value chemicals production. The energetic use of biomass in fertiliser and steel production is limited. In the Less Competitive and Competitive & Import variants, the decrease in biomass imports is partly compensated by an increase in biofuel and bio-naphtha imports. In the less competitive variants, the scenario assumptions lead to lower biomass use in the industrial sector compared to TRANSFORM, especially for the biomass used as feedstock (i.e. approximately 50 to 60% lower). In the Competitive & Import variant, biomass use increases, because in addition to primary biomass, bio-feedstocks can now also be imported. In all industry variants, energetic use decreases because of lower energy demand. Since less biomass is needed as feedstock in the less competitive variants, more biomass becomes available for energetic applications in other sectors, such as the built environment (biomass use in the form of green gas 6 times higher than in TRANSFORM) or biofuels for domestic transport (6 to 8 times higher). In the Less Competitive & Import variant, the wide availability of biomass even leads to the export of biofuels. In the Competitive & Import variant, the primary biomass is supplemented with imports of biofuels, resulting also in a higher use of green gas in the built environment compared to TRANSFORM (factor 6 higher) and biofuels in domestic transport by a factor (factor 5 higher).

Because the Less Competitive variants requires less biomass for the use as a bio-feedstock for the production of chemicals, the cap on imported biomass can be reduced. In such a what-if case, the energetic use of biomass in industry decreases, but the import of biofuels increases.

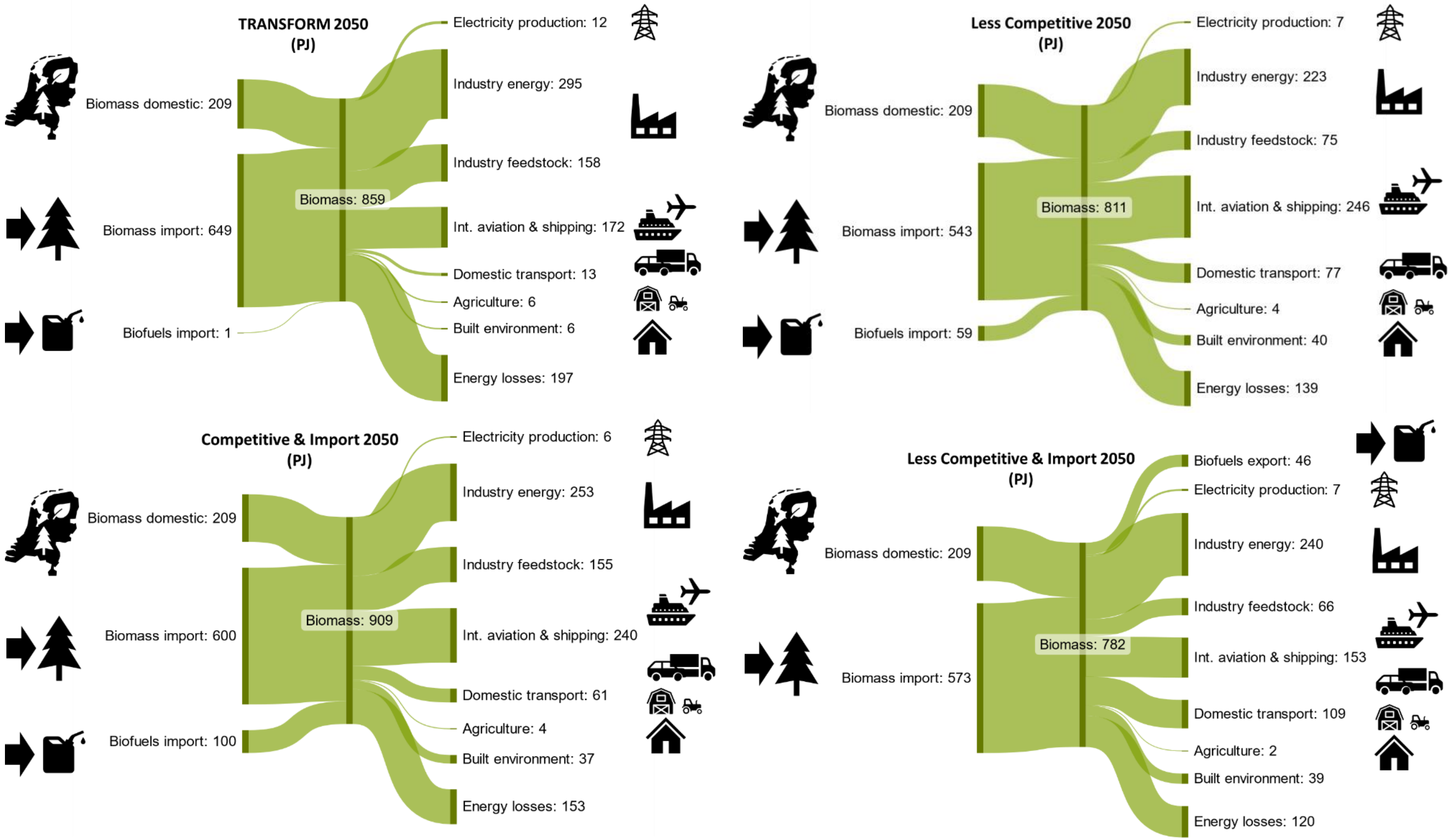

Figure 6.15: Origin and destination of biomass according to TRANSFORM and industry variants in 2050

6.2.6 Investment and system costs

Investment costs
Section 5.6.1 discussed the cumulative relative change in investment costs for TRANSFORM. Figure 6.16 shows these changes for the industry variants. In the industry variants, the investment costs are lower and increase in the period 2040-2045 less sharply than in TRANSFORM. Relative large changes are taking place in the industry sector. But this sector has a relatively smaller contribution to the cumulative change in investments of the total energy system. A reduction in industrial production and/or more imports has, however, an effect on the energy production sector. The increase in investments is in that sector in the industry variants lower than TRANSFORM. A difference in investment costs in the built environment can also be observed. This is related to the use of hydrogen for heating buildings in the industrial variants, which results in lower costs in the built environment than in TRANSFORM.

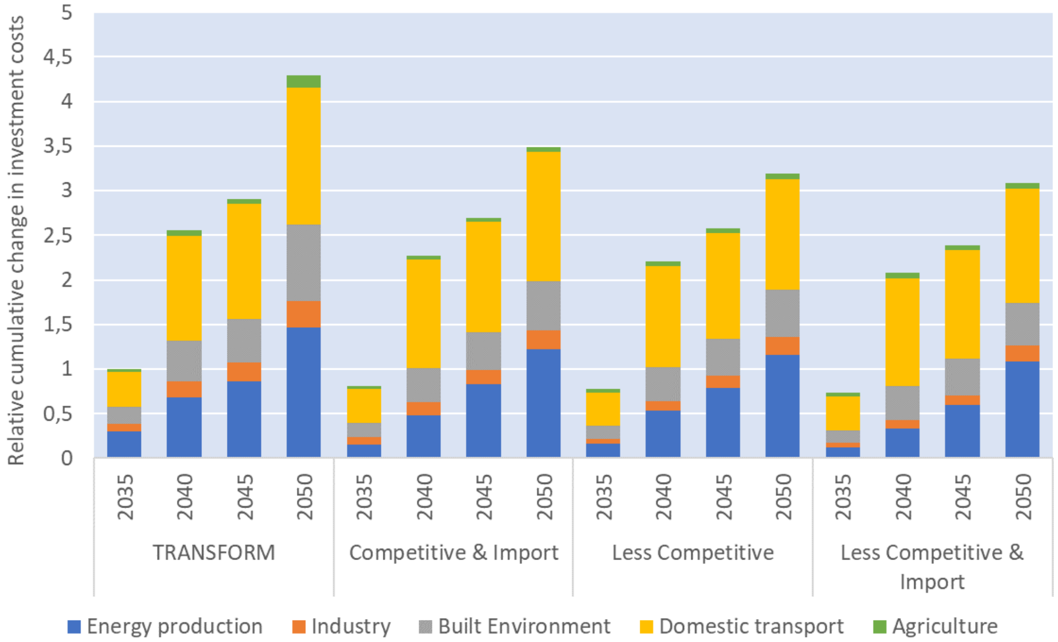

Figure 6.16: Cumulated relative change of total investment costs and contribution to change per sector for TRANSFORM and industry variants (TRANSFORM 2035=1)

System costs
The total system costs for the industry variants are compared with TRANSFORM in Figure 6.17. The development of the total system costs in the industry variants follows a similar course as in TRANSFORM (NB values for TRANSFORM differs from Figure 5.29 because a different reference has been chosen), but the levels are lower. This is especially the case in the Less Competitive and Less Competitive & Import variants. As the figure shows, this is the result of lower system costs in the industry. This applies to 2030 (which is compared with TRANSFORM 2030) but continues thereafter. The costs for bunker fuels actually increase in these variants. The increase in system costs in 2040 in Competitive & Import and Less Competitive & Import appears to be the result of a strong increase in hydrogen imports, see also Figure 6.14.

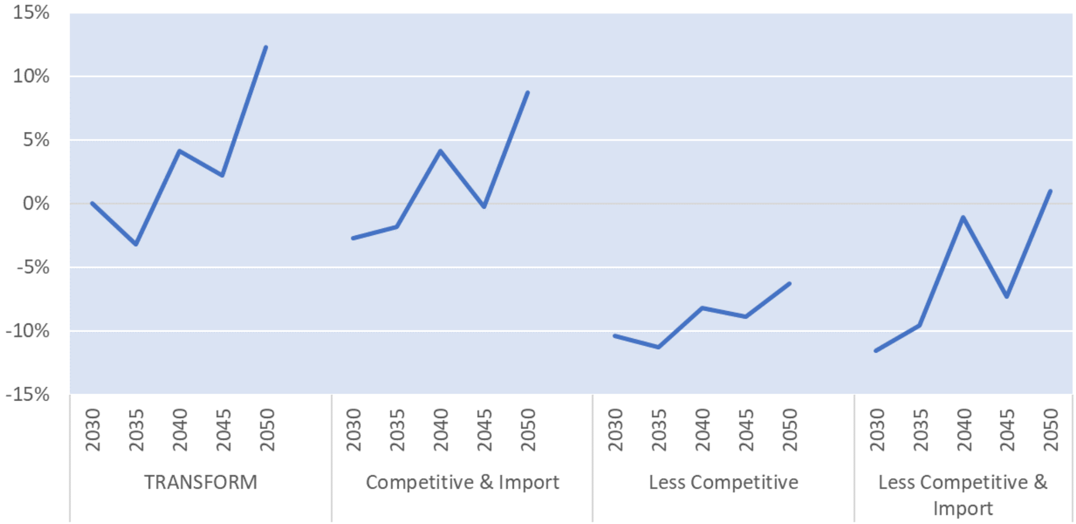

Figure 6.17: Relative change of annual total system costs for TRANSFORM and industry variants (TRANSFORM 2030 is the reference).

7 Key observations and conclusions

7.1 Key observations

Analysis of the ADAPT and TRANSFORM scenarios results and the results for the industry variants provides the following insights:

- *Energy supply and consumption*
  - Electrification of energy consumption and a shift from fossil to renewable electricity production results in a reduction in energy conversion losses in electricity production, mobility (e.g. electric vehicles) and heating appliances (e.g. heat pumps). But this reduction is offset by an increase in energy consumption and an increase in energy conversion losses in new energy applications (such as bioprocesses and hydrogen production). As a result, the total primary energy supply in TRANSFORM and ADAPT, which in 2030 is approximately equal to the current primary energy supply, will increase after 2030 in both scenarios.
  - TRANSFORM shows a lower growth in total primary energy supply after 2030 than ADAPT. This is related to the assumed different consumer behaviour, which leads to a lower demand for energy, mobility and industrial products in TRANSFORM. The smaller increase mainly occurs in non-energy use (feedstocks) and bunker fuels. When only domestic energy consumption is considered, the total primary energy supply in TRANSFORM in 2050 is slightly higher than in ADAPT.
  - For 2030, ADAPT and TRANSFORM meet the target for final energy consumption of 1609 PJ according to the Energy Efficiency Directive (EED). In both scenarios, final energy consumption will increase by a maximum of 10% after 2030 (for the years after 2030, no target for final energy consumption has been imposed). Most energy saving options have relatively low costs and in order to meet the greenhouse gas target, the use of these options in a cost-optimal energy system leads to a limited increase in final energy consumption. It should be noted that the production of chemicals that are also used as fuel (such as ammonia and methanol) is included. If this energy use is not counted as final consumption, as is the case with fuel production in refineries, this results in a lower final energy consumption.
  - The primary energy consumption in ADAPT and TRANSFORM, which in addition to the final energy consumption also includes the losses for energy conversion and energy distribution, is above the (indicative) EED target of 1935 PJ in 2030. Primary energy consumption will increase further after 2030 in both scenarios. This is caused by higher energy consumption (e.g. through the use of CO_2 capture at (bio)refineries) and increasing energy losses in the energy supply sector (e.g. hydrogen production, synthetic and biofuels production and electricity production from nuclear energy).
  - The energy transition causes a substantial shift in the primary supply mix. In both scenarios, the fossil energy supply is largely replaced by sustainable energy supply (wind, sun and biomass). Due to differences in the scenario assumptions, this shift is larger in TRANSFORM than in ADAPT. The share of nuclear energy also increases in both scenarios.

- *Electricity*
  - Due to the electrification of energy consumption in all end-user sectors and the use of electricity for hydrogen production, electricity consumption in ADAPT in 2050 is 2.7 times higher than in 2022. In TRANSFORM, electricity consumption increases by a factor of 3.2. In 2050, 29% of the electricity is used for hydrogen production in both scenarios (see below).
  - The scenarios envisage a tripling of Dutch electricity production (TWh) in 2050 compared to 2022 for ADAPT and an almost fivefold increase in TRANSFORM. The production capacity (GW) is growing by a factor of 3.4 to 4.5, respectively.
  - In both scenarios, the share of fossil fuels in electricity production (about 51% in 2022) decreases rapidly to less than 3% in 2035. In 2050, only a small amount of natural gas (less than 0.1%) and hydrogen (0.2%) is used for electricity production. Electricity production shifts to wind and solar energy, of which offshore wind accounts for the largest share. By 2050 the share of wind and solar will have increased to 85% in ADAPT and 91% in TRANSFORM.
  - In both scenarios, the Borssele nuclear power plant remain in operation until 2043. Electricity production from nuclear energy gradually increases from 2035 by expanding the number of nuclear power stations, which in 2050, depending on the scenario, will result in a capacity of 4.8 to 5.2 GW and a share for nuclear electricity between 7% and 9%. In addition to two new large nuclear power plants (3 GW), nuclear energy capacity will be expanded in the scenarios with small modular reactors (SMRs). The SMRs are located near industrial clusters and, in addition to electricity production, also supply steam to industrial processes. Scenario results for nuclear energy generation are the result of cost optimization taking into account the boundary condition of a maximum capacity.
  - Scenario results of ADAPT and TRANSFORM and the industry variants give a clear indication that the optimal size of the nuclear production capacity is related to the electricity demand. If the electricity demand is lower, as with ADAPT and the industry variants compared to TRANSFORM, then the need for electricity production capacity is smaller. This has more effect on the nuclear capacity than the capacity for sustainable electricity production. If no new nuclear power stations are built, the total installed capacity will decrease in 2050 because both scenarios have used the maximum potential of wind and solar energy. As a consequence the electricity production is lower than in the base scenarios. Lower availability of electricity leads to less hydrogen production.
  - The total annual system costs in scenarios without new nuclear power plants are higher than in ADAPT and TRANSFORM. In order to meet the base load demand, in such a scenario with a relatively larger share of wind and solar energy, more flexibility options must be used with marginally higher costs, such as energy storage.
  - The scenario modelling shows that it is cost-optimal to install a relatively large amount of intermittent power and to use a significant part of it for hydrogen production with electrolysers. The electrolysers usually run at partial load and hydrogen is stored in empty salt caverns on land. When limiting the capacity of the electrolysers by 25% in TRANSFORM, hydrogen production is only limited to a reduction of 2% as full load hours increase from 4200 to 5000. Overall this offers less flexibility to the system increasing curtailment and need for more energy storage in batteries. In addition to the flexible operation of hydrogen production, demand response, energy storage in batteries and import and export of electricity with neighbouring countries contribute to balancing the electricity system.
  - During the year, electricity is imported from and exported to neighbouring countries. Compared to domestic production, net exports vary, depending on the year

considered, in ADAPT between 1% and 15% and in TRANSFORM 1% and 22%. Only ADAPT shows in 2050 a net import volume compared to 1% of domestic production. If the interconnection capacity for electricity import and export with neighbouring countries is limited, this will lead to a reduction in net electricity exports. An analysis of the TRANSFORM scenario with this restriction shows that this will have no consequences for electricity production, which remains virtually the same in terms of volume and mix. The non-exported electricity is used for more domestic hydrogen production.

- *Hydrogen*
  - Hydrogen use, currently estimated at 180 PJ per year and produced almost entirely from fossil fuels, will increase in future and will be produced from renewable sources. Future hydrogen demand is partly substitution for hydrogen produced from natural gas, such as in fertiliser production and oil refineries, but also new hydrogen demand, such as for production of iron (i.e. direct reduced iron), chemicals production and the production of sustainable fuels (i.e. e-fuels). Some of the hydrogen used in chemical processes will be produced in the same production plants. Hydrogen will increasingly be supplied externally via pipelines. According to the ADAPT and TRANSFORM scenarios, the demand for this merchant hydrogen will amount to around 150 PJ in 2030. This demand will grow in ADAPT to above 400 PJ (with a net export of 138 PJ) and in TRANSFORM to well above 500 PJ in 2050 (with a net import of 75 PJ).
  - The demand for merchant hydrogen is met by the production of green hydrogen with electrolysers from renewable electricity and blue hydrogen produced from natural gas in combination with CCS. In both ADAPT and TRANSFORM, blue hydrogen will be produced up to 2035, but after that all hydrogen is produced as green hydrogen with electrolysers. If green hydrogen becomes the most cost effective way to produce CO_2-free hydrogen, it is questionable whether producers will invest in blue hydrogen for such a short period.
  - In the scenarios hydrogen is both imported and exported. In ADAPT there is still a net import in 2030, but this will change to a net export from 2035 onwards. Hydrogen export is an alternative to hydrogen storage in periods of oversupply from variable wind and solar electricity production. This is therefore essentially an extension of the flexibility options for balancing the electricity system, where cost optimization determines the extent to which the options are used. In TRANSFORM there is already a net export in 2030. By 2050, net exports will have increased from 75 PJ to more than 130 PJ, depending on the scenario.
  - Electrolysers will have a total size of 2 GW by 2030. This capacity will grow to 15 GW in ADAPT and 21 GW in TRANSFORM in 2050. A large number of these electrolysers will be installed on offshore platforms near offshore wind farms and produce hydrogen at times when there is a surplus of wind energy. The hydrogen is then transported to land and stored in underground salt caverns. From there, hydrogen is transported to industrial customers via pipelines. If sufficient electrolyser capacity cannot be realized in time, the consequences for hydrogen production will remain limited because a lower capacity can be compensated by a higher capacity factor.

- *Carbon*
  - Despite the growth of renewable energy production, the energy system, including bunker fuels and feedstocks, will still run on fossil fuels for a long time. Today, the fossil share is about 85%. In 2030 this will have fallen to 69% and 66%, respectively in ADAPT and TRANSFORM and in 2050 to 30% and 6%. The relatively high remaining share in 2050 in ADAPT has to do with lower sustainability ambitions with regard to bunker fuels and feedstocks and the possibility of storing a significant volume of CO_2

in depleted offshore gas fields. In TRANSFORM, the sustainability ambitions are higher and less CO_2 can be stored. Despite these higher ambitions, this scenario will not become completely fossil-free. In 2050, a small amount of oil will still be used in refineries for exporting oil products in both scenarios.

- Today, biomass is mainly used for energetic applications, approximately 200 PJ annually. In 2030, the use of biomass in both scenarios will grow to around 240 PJ and in 2050 the biomass use in ADAPT will be 603 PJ and TRANSFORM 662 PJ. This is met by the maximum available domestic supply and supply through imports, 890 PJ and 859 PJ respectively. Large part of the biomass is used to meet the carbon demand for the production of sustainable fuels (biofuels and e-fuels) and, in TRANSFORM, the production of chemicals and plastics. In 2050, biomass will also be used to cover the heat demand in industry, the built environment and the agricultural sector, both by direct firing and in the form of green gas and biogas. In both scenarios this is approximately 45% of the total biomass use.
- Biofuel consumption appears to be sensitive to the biomass price. If the import price for biomass becomes higher the demand for biofuels decreases. Instead of a reduction of total biomass use, biomass that is not used for biofuel production shifts to other energetic (e.g. heating applications) and non-energetic applications in industry.
- Although no explicit sustainability target for feedstock use applies for ADAPT, biomass is used as bio-feedstock in this scenario. This is due to the demand for biofuels, in particular biokerosene in aviation (demand is higher in ADAPT than in TRANSFORM). In the production of biokerosene, bio-naphtha is a by-product that is used as a sustainable feedstock in the production of chemicals and plastics. As a result, by 2050 in ADAPT, 40% of the carbon in chemicals and plastics will be of biogenic origin.
- Fossil fuels are gradually disappearing in domestic transport, especially in favour of battery-electric vehicles, both in passenger and freight transport. In 2030, fossil fuels will be partially replaced by biofuels as a result of RED III targets. After 2030, no specific target for renewable fuels have been applied. Significant electrification of road transport will eliminate the need for biofuels by 2040. However, biofuel demand remains for sectors that are very difficult to electrify (i.e. inland shipping). No hydrogen is used, but synthetic diesel is used in limited quantities in 2050.
- Despite TRANSFORM's sustainability ambitions, a small amount of fossil fuels will still be used in domestic transport in 2050, mainly for heavy duty vehicles (HDV). This is caused by the zero GHG target for international air and shipping, which results in biofuels being prioritized for bunker fuels and not enough biofuels being available for domestic transport. It is more cost-effective to offset the associated fossil CO_2 emissions with negative emissions than to completely reduce the fossil fuels consumption in the domestic transport sector.
- Sustainable fuels are needed to make international aviation and shipping more sustainable. In aviation, the importance of e-kerosene is higher in TRANSFORM than in ADAPT, mainly due to the limited available biomass sources and competitive demand from other sectors, especially the chemical industry. In shipping, ammonia appears to be the preferred choice, followed by renewable methanol. Because greenhouse gas emissions in ADAPT only need to be reduced by 50% by 2050, fossil fuels will remain part of the fuel mix. If the demand for shipping fuel decreases significantly, TRANSFORM will shift some biofuels to domestic transport and the demand for ammonia decreases. In ADAPT, a significant drop in demand for shipping fuels results in a different fuel mix with more LNG being used.
- In 2050, TRANSFORM will still use fossil oil in the petrochemical sector, mainly in the form of residual gases, a by-product of the production of fossil fuels for export and chemicals and plastics (it is assumed that 80% of the carbon used in chemicals and

plastics should come from circular carbon, therefore 20% can come from of fossil carbon). The fossil CO_2 emissions released are offset by negative emissions, i.e. storage of biogenic CO_2. This is apparently more cost-effective than capturing and storing the fossil CO_2.

  - If in TRANSFORM a lower target for circular feedstock is used, the demand for renewable feedstock reduces and as a result, more biofuels can be produced. Hence in 2050, fossil fuels will disappear from the fuel mix in domestic transport. This shows the significance of future competition between the transport sector and the chemical industry.
  - CO_2 capture is mainly applied in oil and biorefineries, waste incineration, hydrogen production, chemical and fertiliser production plants. In fertiliser production, CO_2 capture in TRANSFORM decreases due to the switch to ammonia production from hydrogen. In both scenarios, hydrogen production from natural gas will disappear, in ADAPT in 2050 and in TRANSFORM in 2040. The total carbon capture will grow from 15 Mtonne in 2030 to 51 Mtonne in ADAPT and in TRANSFORM to 35 Mtonne in 2050. In ADAPT, three quarters of the captured carbon (CCU and CCS) is of non-fossil origin and in TRANSFORM this is more than 90%.
  - In 2050, the full available CO_2 storage capacity is used in both scenarios. In ADAPT this is 40 Mtonne and in TRANSFORM 15 Mtonne. Because negative emissions in TRANSFORM are necessary to compensate for difficult to reduce GHG emissions, this scenario is not possible without CO_2 storage. However, this capacity can be reduced from 15 to 12 Mtonne (at high costs), but the model analysis shows that below 12 Mtonne a climate-neutral target can no longer be met in combination with the demand for energy and products.
  - In ADAPT in 2050, negative emissions are needed to compensate for remaining GHG emissions and CO_2 is removed from the air and stored (DACCS) given that the potential of BECCS has been fully utilized and applying CCS to other alternatives that still use fossil fuels is no longer cost-effective. In TRANSFORM, the use of DACCS is not required because the need for negative emissions are lower than in ADAPT and can be fully achieved with BECCS.
  - About 30% of fossil and non-fossil carbon will be used for bunker fuels and as feedstock for chemicals and plastics production in 2050. This ratio is the same for both scenarios, but in ADAPT the volume is larger than TRANSFORM. The remaining 70% of the carbon is reused (CCU), stored (CCS), exported or emitted to the atmosphere.

- *Heat*
  - In 2030, fossil fuels will still play an important role in meeting industrial heat demand. This remains the case in ADAPT after 2030, but in TRANSFORM this decreases significantly. The heat demand is taken over by biomass and biomass derived fuels, electrification (electro boilers and industrial heat pumps), geothermal energy and, from 2040, by small modular nuclear reactors (SMRs) operated as CHP units. In contrast to a decrease in heat demand due to energy efficiency measures, there is also an increase in heat demand due to new applications (e.g. CO_2 capture, bio-processes).
  - Today, the heat demand in the built environment is still largely covered by natural gas. In both scenarios, natural gas boilers will have partially been replaced by (hybrid) heat pumps by 2030. The further electrification of heat demand will continue after 2030. Initially, the heat demand will also be met with green gas, but the share of green gas will decrease from 2045 because biomass is re-directed to be used as bio-feedstock in industry and for the production of biofuels. The use of hydrogen in the built environment is very limited and only takes place in ADAPT. In 2030, heat

networks will provide approximately 6% of the heat demand of the built environment. In 2050, this share will grow to 16% in TRANSFORM and 22% in ADAPT. In addition to residual heat from industry and waste incineration, geothermal energy is an important sustainable heat source for district heating (depending on the scenario a share of 28% to 51%).
  - In the agricultural sector, the heat demand is largely determined by horticulture greenhouses. Until 2030, large part of the heat demand will still be met with natural gas boilers and combined heat and power units (CHP). After 2030, CHP units will no longer be applied (except for biogas) and natural gas will disappear from the energy mix in both scenarios. This is taken over by biogas, geothermal energy and electrification of the heat demand. Heat networks also play a modest role in ADAPT.

- *Costs*
  - The energy transition requires large investments that will increase over the years. The scenarios show that investments will increase by approximately a factor of 4 between 2035 and 2050, slightly less for ADAPT, slightly more for TRANSFORM.
  - The annual total system costs for ADAPT are approximately 15% higher in 2050 than in 2030. The increase in costs is due to 1) an increasing demand for energy, mobility and products 2) rising fossil energy prices (in this scenario continues to use a significant amount fossil fuels) and 3) higher investment costs of innovative technology.
  - The total system costs for TRANSFORM will be lower than those of ADAPT in 2050. This is mainly due to lower demand for energy, mobility and products as a result of behavioural change by consumers. Compared to 2030, system costs in TRANSFORM increase due to the application of innovative technology, but expenditure on fossil fuels decreases substantially compared to ADAPT.
  - The CAPEX of the energy production sector in ADAPT is approximately 75% higher in 2050 than in 2030. In TRANSFORM, the CAPEX increases by a factor of 2.5 during this period. This has to do with the difference in electricity and hydrogen production between both scenarios.
  - More than 80% of the system costs for the industry sector in 2030 will be determined by energy costs. This will drop to around 75% in 2050. The system costs for industry in 2050 for ADAPT will be almost 70% higher than in 2030. This is mainly due to an increase in energy costs. In TRANSFORM, the increase in CAPEX is larger than in ADAPT, but energy costs increase less sharply, meaning that the increase in system costs in 2050 compared to 2030 is limited to about 35%, half of the case in ADAPT.

- *Industry variants*
  - The possibility to import semi-finished products and/or lower industrial production as a result of international competition limits increase of total primary energy supply (including bunker fuels and feedstock) in the industry variants compared to TRANSFORM. Imports (hydrogen, ammonia, biofuels, etc.) are larger than in TRANSFORM, resulting in a higher amount of imported energy than in TRANSFORM. The use of feedstocks becomes smaller, most strongly in the two variants with strong international competition. In these variants also the final energy consumption in variants is lower than in TRANSFORM and below the EED target for 2030.
  - Electricity consumption in the industry variants is lower than in TRANSFORM. This is mainly due to changes in electricity consumption in the industrial sector. The lower demand for electricity also leads to lower electricity production. However, this effect is less significant for electricity from wind and solar than for nuclear electricity production.

- In industry variants that assume the import of semi-finished products, the price of imported hydrogen is set more attractive compared to domestic production. The lower price for hydrogen leads to an increase in hydrogen use and an increase of hydrogen imports. For example, the decreased hydrogen demand for steel and fertiliser production is shifting to other industrial sectors, but also to sectors outside industry, such as the built environment (hydrogen as a heating fuel). On balance, in these industry variants more hydrogen is consumed than in TRANSFORM.
- In some industry variants the domestic hydrogen production increases. As a result of lower production or imports, the energy-intensive industry needs less electricity. Therefore, more electricity becomes available for green hydrogen production. An increase in hydrogen supply leads to more hydrogen use outside the industrial sector.
- For the four industrial sectors examined in the industry variants, the use of biomass mainly takes place in refineries and the production of high-quality chemicals. If the production volume of these industries in the Netherlands decreases as a result of stronger international competition, biomass use will decrease by almost 50%, but there will also be a shift from feedstock to energetic use in industry and in other sectors, such as the built environment (e.g. green gas) and transport sector (e.g. biofuels). If the assumption on the availability of biomass imports is changed to a lower import volume, energy consumption in industry will decrease, but imports of biofuels for domestic transport and bunkers will increase.
- The total carbon use (fossil + biogenic) is lower in all three industry variants compared to TRANSFORM and especially in the two variants with more international competition and lower Dutch production. Lower use of fossil and biogenic carbon in these variants can be entirely attributed to the assumptions regarding lower chemical production and fuel production in refineries. Importing semi-finished products in the two import variants has only a modest effect on the carbon balance.
- The amount of stored carbon (CCS) in the three industry variants is the same as in TRANSFORM. This also applies to the storage of biogenic carbon, i.e. negative emissions. Due to the lower production level of refineries and chemical plants, less carbon is captured in the two variants with strong international competition compared to TRANSFORM.

7.2 Conclusions

Based on this scenario study, the following main conclusions can be drawn:

- *Energy-intensive industry and fuels for international transport determine future energy demand of the Dutch energy system*
  The future development of energy-intensive industry (refineries, high value chemicals, steel industry and fertiliser industry) and the demand for fuels produced in the Netherlands for international aviation and shipping determine the development of a climate-neutral energy system for the Netherlands. If the production volume of energy-intensive industry remains virtually the same, in the future 40 to 50% of Dutch energy demand will come from industry (energetic and non-energy consumption), about the same as today. However, if this industry experiences more competition, resulting in reduced production in the Netherlands and/or the energetically intensive part of the production chain is moved abroad (with the import of semi-finished products), then this study shows that the share may drop to just above 30%. The energy volume of fuels supplied from the Netherlands for international aviation and shipping (600 PJ) is approximately comparable to the heat and electricity demand of all buildings in the Netherlands. This could remain the case in the future, but it is also possible that this will be almost halved if seagoing vessels also get their fuel from foreign ports.

- *Electrification and demand for green hydrogen will result in significant growth in electricity demand*
  Due to electrification of the energy demand for heat and mobility, the demand for electricity is increasing significantly. Compared to current electricity consumption, domestic electricity demand will therefore grow by a factor of approximately 2.5. Because electricity will also be used for the production of green hydrogen in the future, this will result in a further increase in electricity demand. The domestic electricity demand will then increase by approximately a factor of 3. More than 90% of the hydrogen is intended for industry (including for sustainable production of steel and fertilizer) and the production of synthetic fuels (including for aviation). If energy-intensive industry shrinks and/or the energy-intensive part of the production process is moved abroad, electricity demand will grow by a factor of more than 2 to 2.5 instead of a factor of 3. If that development takes place, the demand for hydrogen will not have to decrease. It may then become attractive for the built environment to use hydrogen as a heating fuel (up to about 14%), especially if the import price for hydrogen is competitive with the costs of domestic hydrogen production. Hydrogen production can also contribute cost-effectively to absorbing excess wind and solar power for which there is no demand. Electricity exports also contribute to keeping the electricity system in balance. The size of that contribution does depend on the capacity expansion of the electricity networks.

- *Nuclear energy can supplement renewable electricity production from salar and wind*
  Wind and solar energy are the main energy sources from which electricity will be produced in the future. In 2030, the share of wind and solar will be between 73% and 85% and in 2050 this could grow to 90%. Compared to 2022, total production capacity in 2050 will grow by a factor of 3 to 4, stronger than electricity demand because wind turbines and solar panels cannot produce electricity all hours of the year. Nuclear energy can also become part of the electricity production mix (with a share of 7% to 9% in 2050) if the plans for two new nuclear power stations (3 GW) are realized and small modular reactors with heat supply to industry (SMRs) are also applied (in total 2 GW). A future sustainable energy system without nuclear power is also possible, but the social costs for the energy system will then be higher because more costs will have to be incurred for flexibility options to meet baseload demand with wind and solar power alone. With a shrinking industry and/or import of semi-finished products from abroad, electricity production in the Netherlands does not have to grow as strongly. Because the base load demand is smaller, the production of electricity from nuclear power plants grows relatively less compared to that from wind and solar power.

- *Carbon continues to play an important role in a climate-neutral energy system*
  Depending on the scenario, the total amount of carbon (as hydrocarbons) in the energy system will remain almost the same or up to 40% lower than it is now. In a greenhouse gas-neutral energy system, carbon remains necessary for the production of fuels (including aviation and shipping fuels) and the production of chemicals and plastics. The energy transition makes it necessary to replace fossil carbon by sustainable carbon, such as biomass and recycled plastics. But a significant reduction requires additional policy. With a shrinking industry, the amount of carbon drops by almost 50%. Nevertheless, fossil carbon can remain present in the system and GHG-reduction target can be achieved. For instance, refineries will still export fossil fuels and some fossil carbon will be used in the production of chemicals. Fossil carbon is also stored as CO_2 in depleted gas fields under the North Sea and fossil CO_2 emissions are compensated with negative emissions (captured and stored non-fossil CO_2). Completely eliminating the use of fossil

fuels can lead to high system costs. In addition, it is cost-effective to capture and store CO_2 when converting biomass into fuels and chemicals. Biogenic carbon capture and storage can compensate for CO_2 emissions released by fossil applications that are difficult to make sustainable. Carbon removal or negative emissions is also needed to compensate for difficult-to-reduce non-CO_2 greenhouse gas emissions, such as methane emissions from agriculture.

- *Primary energy consumption increases due to application of sustainable technologies*
  In 2030, the energy system can meet the target for final energy consumption from the Energy Efficiency Directive (EED) of 1609 PJ, but achieving the (indicative) target for total primary energy consumption of 1935 PJ is difficult. After 2030, without an explicit efficiency target, final energy consumption will be, depending on the scenario, 4% to 10% above the target for 2030. Many efficiency measures are also used to achieve the greenhouse gas emissions reduction target. In addition, lifestyle changes can also contribute to both emission reduction and lower energy consumption. Primary energy consumption will continue to increase and will be well above the indicative target of 2030. This is due to the introduction of (new) technologies for energy conversion that lead to additional energy losses (e.g. electrolysers for hydrogen production, nuclear power plants, processes that convert biomass into fuels) and new energy demand (e.g. CO_2 capture). A shrinking industry and/or relocation of energy-intensive part of the production chain abroad results in lower final and primary energy consumption.

- *Major investments are required, but system costs do not need to increase significantly*
  Achieving the energy transition requires significant investments that will increase in the coming decades. The increase in investments is dampened by technology learning, i.e. a decrease in costs as a result of innovation and implementation of new technologies. The annual social costs for the entire energy system will increase, especially if fossil fuels continue to be used and consumers do not change their lifestyle. If this does happen and the use of fossil fuels decreases, the increase of annual costs of the energy system will be significantly less. The annual system costs are shifting from energy purchasing costs to capital costs, especially if the energy system is made more sustainable. However, the annual system costs for industry continue to consist largely of energy purchasing costs, although these may decline somewhat relatively. In a scenario with far-reaching sustainability, the system costs for the industry will be much lower than in a scenario with less far-reaching sustainability and where a substantial amount of fossil fuels continues to be used.

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Appendix A
OPERA model modifications

Overview of modifications to the OPERA model compared to the TNO scenario study published in 2022 (Scheepers M. , et al., 2022). Changes in targets, potentials, etc. are not included, since they are part of the scenario description, see Section 3.1.

General
- The Climate and Energy Outlook 2022 (KEV 2022) (Klimaat en Energieverkenning, 2022) has been used as background scenario. This means that demand projections, lower limits of renewable energy technologies and conversion data of several conventional technologies are brought in line with the KEV 2022.
- A CO_2 pipeline network has been added for transport of CO_2 to underground storage in depleted offshore gas fields. CO_2 storage has been assigned to offshore regions, each with an own storage potential.

Built environment
- In the services sector, data centres are included as a specific activity (expressed in gross floor area).

Agriculture
- Update of energy savings options.

Mobility and bunkers
- Investment cost of hydrogen trucks have been increased.
- Ships using ammonia have been included.
- Methane slip has been added for LNG ships.
- Busses and inland freight navigation have been included as specific transport activities.

Industry
- Production of high-quality chemicals is expressed in Mtonne of olefins and Mtonne of aromatics instead of only in Mtonne of ethylene
- Integration of mechanical plastic recycling.
- Data for the production of olefins have been updated.
- Biofuel production data has been updated.
- Import of hot briquetted iron and further processing to make steel has been added.
- Import of ammonia is included.
- Update of energy savings options.

Energy

- A coupling has been made with the I-ELGAS model. Therefore, next to trade of electricity with neighbouring countries, also trade of hydrogen is included.
- The OPERA model has some freedom to deviate from the electricity and hydrogen import-export profiles from I-ELGAS. The deviation room has been set at +-10% per time-step. The model uses hourly trade prices for electricity and hydrogen to decide on this.
- Small modular nuclear reactor (SMR) has been included. An SMR can produce electricity and heat (steam).

Appendix B
Industrial sectors, current situation and production alternatives

B.1 Refineries and fuel production

Current situation
There are 6 refineries in the Netherlands with the crude oil name plate capacity of around 67 Mt per year (2861 PJ) (PoR, 2017) (Olivera & Schure, 2020). Five of these refineries are located in the Rotterdam/Europort region and one of them in Zeeland and they contribute to around 5.7% of the European total primary capacity (Concawe, 2023). The capacity of Dutch refineries accounts for approximately 10% of the European production.

The refineries total production was in the range of 55-62 Mt per year between 2010-2020. Around 57-67% was related to transport fuels (gasoline, kerosene, diesel and HFO), 11-13% related to other fuels (LPG and heating oil), and 13-19% naphtha and aromatics. Among the products, naphtha and aromatics and kerosene production have followed an increasing trend. Gasoline and fuel oil production have been decreasing.

There is an overall trend, where refineries in Europe have been shut down and/or are in the process of transition to low carbon fuels production. Currently, 5 refineries are in operation. Gunvor refinery in Europoort closed its crude processing units in 2019 and 2020. It currently has plans to construct a biofuel refinery with the total production capacity of 7000 kt/a., the facilities are planned to be constructed on the previously decommissioned lubricant oil plant. Gunvor also has plans to partner with Dow to purify pyrolysis oil, derived from plastic waste and use existing unit at its refinery site in Rotterdam. Moreover, they signed an agreement with Air products for a green ammonia terminal. Shell has announced its aim to reduce the production of traditional fuels by 55% by 2030 and provide more low-carbon fuels such as biofuels for road transport and aviation, and hydrogen. In line with this strategy Shell has announced a final investment decision to build 820 kt/year biofuel facility at the Pernis Refinery. For comparison, Shell refinery nameplate capacity is 21,000 kt/year. In addition, Shell took the final investment decision to build a 200 MW electrolyser to produce hydrogen. The renewable electricity will come from the North Sea. Part of the grey hydrogen in the refinery will be replaced by green hydrogen.

The targets and the requirements introduced in various energy and transport related policies and legislative documents will affect the demand for fossil fuels and the need for alternative/renewable fuels within the time frame up to 2050. Thus, they will have a great impact on the future of conventional refineries. While a large part of the current refinery product portfolio relates to transport fuels the future demand for the petrochemical industry will also influence the sector. Around one fourth of the refinery output relates to feedstocks for the petrochemical industry, mainly naphtha and LPG, but also integrated aromatics production in refineries. Any demand change in the chemical industry (for instance increased circularity resulting in less demand and/or increased demand for renewable intermediates) will affect the demand for feedstocks from refineries.

Overcapacity in northwest Europe and the completion already has resulted in closing of refineries. Over the last decade, around 13% of refining capacity in Europe closed (Ricardo, 2022). How far the Dutch refineries will continue to produce fossil fuels and shift to producing low carbon/renewable fuels will relate to resilience of the Dutch refineries in the coming decades.

Process alternatives
The relevant alternatives relate to shift from fossil fuels to renewable resources. In the short-to-medium term co-processing renewable/biogenetic intermediates (i.e. biomass pyrolysis oil) can be a feasible option, high demand for renewable fuels will require a shift to renewable refineries. Thus, the alternatives will be bio-based and renewable electricity based refineries. The value chains included are as follows:

- Fossil refinery + CCS
- Biorefineries using lignocellulosic feedstocks (biomass gasification + FT synthesis/methanol/DME production; biomass-to-ethanol, alcohol-to-jet; biomass pyrolysis followed by upgrading)
- Biorefineries using UCO&AF (UCOME, HVO and HEFA production)
- Biogas refineries using digestible feedstock, producing bioLNG
- Bio-intermediate co-processing in conventional refineries
- P-t-X (methanol, drop-in fuels, H_2, ammonia) using both point source and DAC
- Conventional biofuel production

B.2 Organic chemicals industry

Current situation
There are six operating steam crackers with an ethylene nameplate capacity of over 4 Mt/year (Petrochemicals Europe, 2020a). Ethylene is one of the main products from steam crackers; however, other relevant chemicals, such as propylene, butadiene, benzene, hydrogen, and acetylene, compose the total product portfolio of these sites. Together with ethylene, they are usually called high value chemicals (HVC). For ethylene and propylene the Dutch production and conversion are much larger than the import and export trade flows. Only little ethylene and propylene is imported by comparison, yet there is a significant export to EU countries. The Netherlands is a net exporter of ethylene, propylene, and butadiene. These monomers are mainly exported to neighbouring EU countries, using pipelines. As such, the Dutch chemical industry is highly clustered and integrated, resulting in cost-efficient exchange of materials and energy both at domestic level and within the Antwerp-Rotterdam-Rhine-Ruhr Area (ARRRA) cluster. Figure b.1 illustrates this cluster integration.

For this sector to reduce GHG emissions there is a need for decarbonising the energy demand and for shifting its feedstock use from fossil resources to sustainable and renewable resources, product innovations and circular economy. National statistics for the Netherlands for the past 10 years indicate that naphtha represents approximately 70% of the fossil feedstock for the petrochemical industry in the country and LPG accounts around 20%.

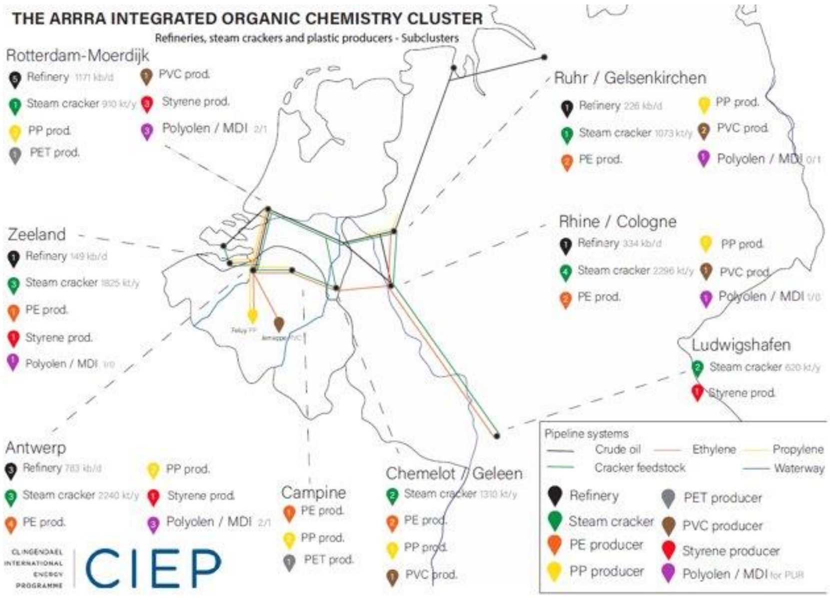

Figure B.1: Production of high-quality chemicals is expressed in Mtonne of olefins and Mtonne of aromatics instead of only in Mtonne of ethylene presentation of ARRRA organic chemical industry cluster (Meijering & van Leeuwen, 2021)

Process alternatives
The following GHG emissions mitigation options for the steam crackers can be considered:
- Electrification of steam crackers
- CCS add to steam crackers
- Ethanol-to-ethylene
- Methanol-to-olefins
- Methanol-to-aromatics
- Pyrolysis oil-to-aromatics
- Co-processing of biooil
- Pyrolysis oil (plastics) co-processing
- Bio/renewable naphtha co-processing

B.3 Steel industry

Current situation
The world's largest markets (Asia/EU/North America) are largely self-sufficient (net export ≤ 10%). The world demand for iron and steel will grow by 30% until 2050. European demand has been stabilizing since 2000 at approx. 140-150 Mtonne/a and supplies are : 37% construction, 16% automotive, 15% engineering, 14% metal ware, 12% pipes, 6% other products[24]. Towards 2050 energy transition requires steel (infrastructure & industrial machines, such as wind turbines) - annually 10% NL steel capacity. Some large turbine builders aim for 10% green steel in 2030. However, material substitution can be an important development for the demand for steel. For example, alumina or recycled/bioplastics used for cars. The projection of EU steel demand conducted by Krishnan (2017) predicts that demand will decline from 161 Mt in 2016 to 130 Mt in 2050 (see MIDDEN-report).
*TATA Steel Netherlands (TSN) produces for Europe (6.6 Mtonne, 4,3% of EU production). TSN uses only 15-20% scrap intake due to product quality high-purity steel. Part of the steel

[24] European steel in figures, Eurofer, 2022

production of TSN is construction steel; construction and engineering steel (33%) and quality high-purity steel for packaging (16%) and automotive applications (32%) are made in a certain ratio. At TSN raw iron is produced from ore via coal fired blast furnace and steel is produced from pig iron and scrap via a gas-fired oxy-steel factory. Because of its location TSN can easily import raw materials and coal by ship. Furthermore, TSN has a pellet mill and can process cheaper ores than its competitors.

In the ARRRA area (Antwerp-Rotterdam-Rhine-Ruhr-Area) there are other steel factories: ArcelorMittal in Gent, Belgium and ThyssenKrupp in Duisburg, Germany (both blast furnace + oxygen furnace). In Belgium and Germany there are also several steel mills outside the ARRRA area: 4 other blast furnace + oxygen furnace in Germany, 16 other arc furnace plants in Germany and 3 other arc furnace plants in Belgium.

Due to the availability of CO_2-free electricity, TSN will be competitive in the future with German and other domestic steel mills, but less competitive with countries such as Sweden (and possibly Spain). The competitive position is potentially disadvantageous compared to countries such as Australia and Brazil, with a lot of renewable energy and iron ore[25].

Process alternatives

- Deployment on direct reduction iron (DRI) process in combination with electric arc furnace (EAF) for steel production. DRI first on natural gas (optional with CCUS) and later on hydrogen. This fits in with the EU trend in which 15% of the demand for DRI-EAF is planned for 2030. An EAF initiative is underway in Groningen region with 1/6 of the capacity of TSN.
- Application of a more efficient technique (Hisarna) with CCS.
- Full electrification of the iron production process (ULCOWIN or ULCOLYSIS). These techniques are currently on TRL 2 – 4.
- Purchasing pig iron and applying only (EAF) for steel production.
- Increase of scrap use to 30% for TSN production mix; this requires R&D efforts.

B.4 Fertiliser industry

Current situation

The world market for fertilisers is roughly divided into US, EU and Asia, with supply and demand roughly in balance (margin trading). Global demand will increase by about 30% towards 2050.

The Dutch production of nitrogen compounds mainly takes place for fertiliser consumption in the agriculture sector of Western Europe, but also exports take place to the US, Canada and Brazil (over 95% is exported). Prospects for demand in Europe are stable, but since this year the Netherlands has been aiming to reduce use in agriculture via the Nitrate Directive Action Programme. Due to the long-term transition to circular and precision agriculture, less fertiliser will be needed. Nitrogen fertiliser can be partly circular through recovery from waste water and manure fermentation.

Fertiliser plants produce two products: urea (containing carbon) and ammonium nitrate (without carbon).

In the Netherlands there are currently two fertiliser plants: OCI in Limburg (Chemelot) and Yara in Sluiskil, Zeeland. The location of OCI can become problematic regarding logistics of electricity, CO_2 and H_2. On the other hand the OCI side is much more integrated in the

[25] Analyse voor Programma Verduurzaming Industrie - Analyse als input voor routekaart verduurzaming industrie, Guidehouse, 2023

Chemelot site: NH_3 is not only used for fertiliser products, but also as input for other chemicals. The Yara site has a good vicinity to the sea, so convenient for export. However, the site is isolated and not integrated in an industrial site.
Urea is (also) used as AdBlue. Since diesel demand will shrink, AdBlue demand will shrink.
In Belgium and Germany there are other fertiliser plants, within the ARRRA area, but also outside this area.

Process alternatives
The following process changes can be considered:
- Production of ammonia with green hydrogen up to 35% to 50% in 2030 (RED III obligation)
- Import of ammonia for ammonium nitrate production (up to half of the hydrogen demand for ammonia in 2030).
- Urea production with CCS.
- Shift from (fertiliser) intensive agriculture to regenerative or circular agriculture (demand-driven).
- Shift from urea to ammonium nitrate. An important difference, however, is that urea as a fertiliser works for days/weeks, where ammonium nitrate is absorbed quickly. Ammonium nitrate leaches out faster, urea partly volatilizes and acidifies the soil.

Appendix C
Biomass import potential to the Netherlands

Biomass can be imported from other countries within the EU and from outside of the European Union (EU).

Import from EU
Various studies have analysed the biomass potential across Europe, providing a wide range of estimates (Panoutsou & Maniatis, 2021) (Strengers & Elzenga, 2020) (Faaij, 2018). A recent study has updated the supply potentials and costs of biomass, with a specific focus on advanced biofuel production. This assessment encompasses biomass types listed in the Renewable Energy Directive (REDII), Annex IX, commissioned by the European Commission (EC, 2024). While building upon existing research like S2Biom, this study employs new and refined baseline data, methodologies, and scenario assumptions. The assessment provides a technical potential for each biomass type, further categorized into three mobilization scenarios: Low, Medium, and High (European Commission, 2023).

- Technical potential refers to the maximum biomass availability given current technological capabilities (including harvesting techniques, infrastructure, and accessibility) and minimal sustainability considerations. This excludes dedicated food crops but includes their residues in the technical potential, considering spatial constraints due to other land uses and ecological reserves.
- In the Low bioenergy scenario, biomass utilization in the energy sector is not a primary focus, but resource-efficient biomass use is encouraged. This scenario prioritizes sustainable practices and imposes strict sustainability criteria, limiting the extraction of forest and agricultural residues and the cultivation of biofuel-specific crops. Material conversion of biomass for other purposes takes precedence over its use in energy production.
- The Medium scenario involves stimulating bioenergy production while improving cropping and forest management practices, all within the framework of sustainable biomass use. Biomass types with high sustainability risks are avoided, and adequate space is allocated for non-energy uses of biomass. This scenario aligns with existing bioenergy policies under the RED provisional agreement but incorporates assumptions specific to each feedstock type.
- The High bioenergy scenario envisions extensive stimulation measures for rapid technological advancements in agriculture, forestry, and biofuel technologies. High demand for biomass and a willingness to pay premium prices drive increased mobilization of biomass production and harvesting, prioritizing biomass over alternative uses.

Figure C.1 illustrates the study results regarding the biomass potentials for different scenarios for 2030 and 2050.

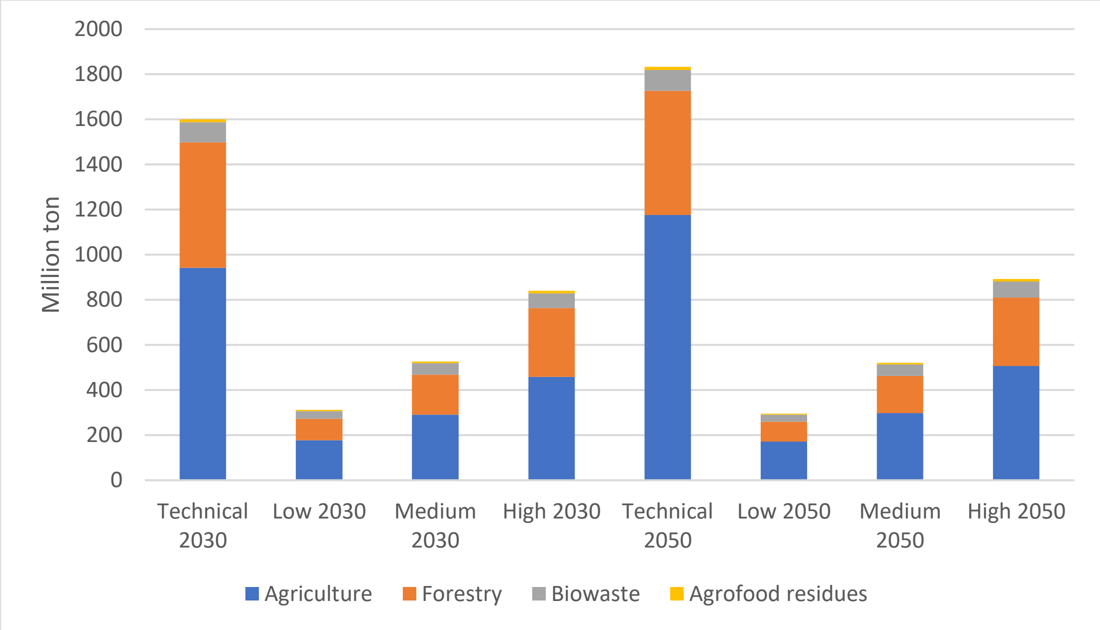

Figure C.1: Biomass potentials in technical, low, medium and high potentials in 2030 and 2050 and distribution over sectors delivering biomass.

As the most recent European biomass potential update, this study results have been used to determine the biomass import potential to the Netherlands. Among the different scenarios, the high mobilisation scenario is selected as the primary reference. This decision stems from achieving a carbon neutral energy system in the Netherlands and Europe, which will necessitate significant quantities of renewable energy resources, including biomass. Additionally, compared to other studies on biomass potential, the results of this study appear relatively conservative.

To determine the supply potential for the Netherlands, the following steps were implemented.

- Data from (European Commission, 2023) was detailed to include specific feedstock categories at Member States level. To avoid duplication, the biomass potential within the Netherlands was excluded from the total EU potential.
- The import potential was calculated based on datasets including lignocellulosic crops, primary forest biomass (including stem wood and primary residues), solid waste (including secondary agricultural & forestry residues). It is assumed that 10% of these selected biomass categories are available for the Dutch market, corresponding to 551 PJ. This figure is considered as base potential for both ADAPT and TRANSFORM. This 10% aligns with the assumption that renewable refineries will serve to at least the 10% of the EU market.
- Other biomass categories, such as agricultural primary residues, all gaseous biomass resources, such as manure, sewage sludge, and non-agricultural oils are excluded from consideration. Additionally, the possibility to import black liquor is not considered.
- The excluded categories collectively represent more than 50% of the total biomass potential. Thus, the 10% import potential to the Netherlands relates to less than 5% of the total EU biomass potential.

Import potential from outside EU
Woody biomass can also be imported from outside the EU. In fact, wood pellet net imports to the Netherlands have been highest in 2020, reaching to almost 2.1 MTonne (around 45 PJ[26]) of which 20% was from the US.[27]

For this study, we used the import potential data included in (Panoutsou & Maniatis, 2021) (which was derived from a BioTrade2020 plus and Biomass Policies) (see figure C.2Figure2). The import potential estimate for the Netherlands is based on the wood pellet import potential, where approximately 10% was assumed to be export to the Netherlands. This corresponds to 98.6 PJ.

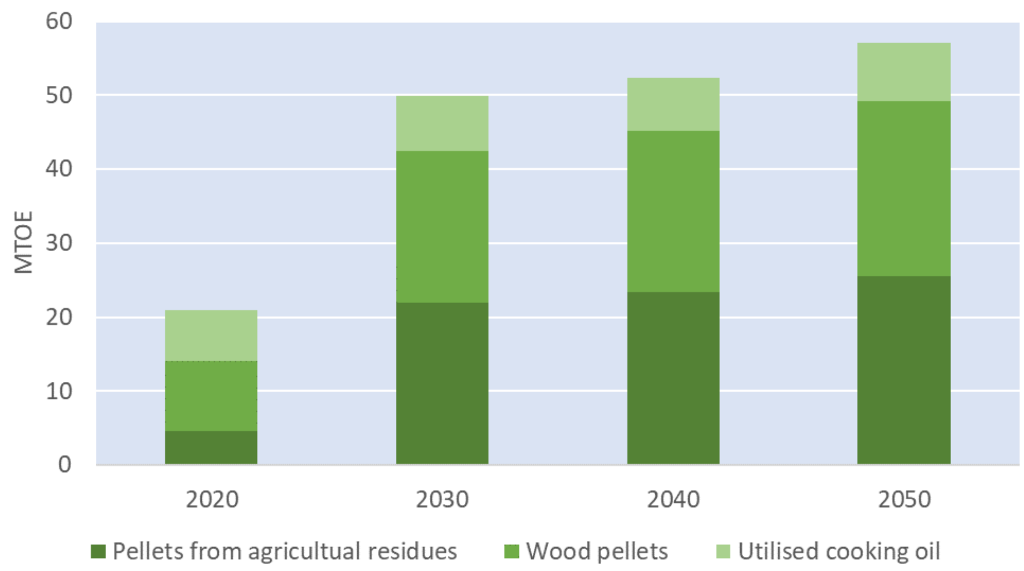

Figure2 C.2: Biomass import potential for the years between 2020 and 2050 (Spöttle, et al., 2013) (1 MTOE = 41.9 PJ)

Import of used cooking oil (UCO) and animal fats (AF)
Same approach is implemented for the UCO & AF import potentials. 10% of the supply potential within EU and from outside was considered. This resulted in an estimate of 48 PJ.

[26] Applied 18 GJ.t
[27] DownloadReportByFileName (usda.gov) THE NETHERLANDS (unece.org)

Appendix D
Plastics recycling assumptions

By Paul Stegmann, Carina Oliveira and Ayla Uslu

D.1 Sorting & recycling impacts on HVC production

Current situation in the Netherlands and Europe
According to PlasticEurope (Plastics Eruope, 2022), in 2020 plastics converter demand was 50,300 kt in EU27+3 and 2112.6 kt in the Netherlands. Waste generation was estimated at 29,500 kt in the European Union and at 1057.5 kt in the Netherlands. This data excludes non-plastics such as textiles, adhesives, sealants, coatings, etc.

About 32% of collected plastic waste in Europe is sent to recycling, but less than 17% of collected plastic waste is actually recycled (Plastics Europe, 2019). In 2020, 45% of Dutch plastic waste was sent to recycling and 55% to incineration with energy recovery (Plastics Eruope, 2022). However, there are further processing losses downstream so that a smaller part actually ends up as recyclate. In the EU 65% of the plastic waste sent to recycling ends up as recyclate (Plastics Europe, 2019). Assuming the same efficiency for the Netherlands, that means that only 29% (0.45*0.65) of all collected plastic waste in the Netherlands is actually recycled. This number is also in line with outcome of TNO's PRISM model, estimating that 31% of the Dutch plastic waste of 2018 ended up as recyclate (Wijngaard, et al., 2020).

Scenarios description
Projections for a business as usual scenario (ADAPT)
Starting from the current plastic data of Plastics Europe (Plastics Eruope, 2022) mentioned above, we assume the growth rates from Stegmann (Stegmann, Daioglou, Londo, & Junginger, 2022) for the business as usual scenario. These are based on the historic relationship of chemical and plastic production and GDP and population development and are using GDP and population projections from the second shared socioeconomic pathway (SSP2) (O'Neill, et al., 2017). These project a plastic demand growth of 46% and plastic waste growth of 41% until 2050 for Europe. For the Netherlands, the slightly lower growth of Western Europe was assumed (for further information on included countries in Western and Central Europe regions, see (PBL, 2018)). For comparison, the OECD plastics demand projections estimate a growth of 64% for OECD EU countries until 2050 (OECD, 2022).

Projections for the TRANSFORM and variants scenarios
Circular strategies such as the so called R strategies (Potting, Hekkert, Worrell, & Hanemaaijer, 2017) have the potential to substantially reduce the demand for new plastics. In the TRANSFORM and alternative scenarios, we assume substantial changes in the ways the society demands and uses plastics. These material demand reductions are the result of changes in consumption patterns, policy measures (e.g., bans, right to repair), changes in product design (design for longer life, repair, recycling), new business models (sharing economy, repair services, reuse systems) and requires pulling all circular levers of the so-called R-strategies throughout all sectors:

- *Refuse*: Refusing plastics use, e.g. by banning certain plastic types such as single use plastics or by changing our consumption patterns (e.g. less m^2 housing per person, less individual transport, less demand for fast fashion).
- *Rethink*: For example, intensifying the use of products through sharing products, such as car sharing concepts.
- *Reduce*: Reducing the material use per product through more efficient product design and production lines.
- *Re-use*: Reusing products, e.g. refillable bottles, reusable business to business packaging; increasing popularity of second hand products such as clothing
- *Repair*: We assume a substantial increase in repairing and refurbishing products, following the European's commissions plans to establish a right to repair (Šajn, 2022).
- *Remanufacture and repurpose*: Reusing parts of a discarded product in a new product.

To increase the efficiency and attractiveness of recycling, substantial efforts in policy, product design and consumer behaviour are required. While ADAPT scenario follows business as usual, in TRANSFORM and the industry variants, there is a strong shift to circular economy strategies in the Netherlands.

Some strategies mentioned by the Ellen MacArthur Foundation (Ellen MacArthur Foundation, 2017) should be considered to improve recycling rates and allow such shift towards circularity:

- standardization of types of plastics used: Phasing out small plastic fractions that are not economically recyclable;
- avoid multi-material (plastic) products, using more mono-materials that are easier to sort and recycle;
- avoid additives and opaque colours;
- more suitable format design of plastics products to enable easier separation and recycling;
- introduce material markers to improve identification of plastic types.

Those measures would allow for a significant increase in sorting & recycling yields. This could be further reinforced by streamlining and applying best practices in collection & sorting systems, which vary significantly by region or even municipality (Ellen MacArthur Foundation, 2017). This would also support a better consumer behaviour when collecting and separating plastics. Policy could push for better sorting systems via enforcing extended producer responsibility and fostering the use of deposit systems. Furthermore, innovations in sorting & recycling could improve the performance and efficiency of those processing steps.

Improvements in the collection and sorting of plastics would increase the quality of the input streams to recycling processes, leading to higher recycling yields and better quality recyclates that could substitute larger parts of primary plastics (substitution factor). This would decrease the demand for virgin materials. For the TRANSFORM scenario, a 40% reduction in high value chemicals (olefins and aromatics) production compared to ADAPT scenario, in 2050. For the less competitive variants, the production of HVCs is halved compared to TRANSFORM (70% reduction when compared to ADAPT); the competitive variant follows the same production rates of HVCs as TRANSFORM.

D.2 Waste treatment shares and recycling efficiencies

Current situation in the Netherlands and Europe and ADAPT assumptions
Currently, 35% of the collected post-consumer plastic waste in the EU27+3 is sent to recycling, 42% to energy recovery and 23% to landfilling (Plastics Eruope, 2022). In the Netherlands, 45% of post-consumer plastic waste is sent to recycling and 55% to energy recovery (Plastics Europe 2022). For the ADAPT scenario we assume that these shares barely change. We only assume a small uptake of chemical recycling via gasification and pyrolysis.

Assumptions for the TRANSFORM and variants scenarios
For the TRANSFORM scenarios we assume a substantial uptake of recycling, a strong reduction in energy recovery and a phase out of landfilling. It is considered that energy recovery (incineration) is just applied to non-recyclable waste in 2050, due to changes in product design, collection and separation. From the plastic waste available in the country, it is considered that 90% would be separately collected, drastically reducing their shares in mixed solid waste. The role of chemical recycling technologies would become more prominent, due to the need for recyclate that meets virgin plastic quality. The main characteristics of TRANSFORM and its variants are summarized as following:

- *TRANSFORM and Less Competitive variant:* it is considered that mixed plastic policy is on lead, which largely keeps the current mixture of plastics (in product design) but with almost fully separate collection of plastics and improved separation. This leads to a strong uptake of pyrolysis and gasification as treatment methods as they can deal better with such mixed streams (e.g. mixed polyolefins for pyrolysis).
  - By 2050, we assume 50% of plastic waste available goes to pyrolysis and gasification, which is around the current maximum potential of suitable plastic types, assuming that current impurities (glass fibres, additives) will be avoided in future product design or separated before recycling.
  - By 2050, 40% is sent to mechanical recycling and 10% goes to energy recovery via incineration.
- *Competitive & Import and Less Competitive & Import variants:* it is considered a more ambitious approach regarding circularity, in which policies incentive monoplastic streams recycling. Here we assume a more substantial change in product design (more mono materials are used) and in collection and separation of plastic waste (deposit system, separate collection). This allows for a substantial increase in mechanical recycling of the separated plastic streams.
  - We assume that most plastic waste serve as input to mechanical recycling (70%) and the remainder (30%) goes to pyrolysis and gasification, as a different plastic mix is present (less polyolefins) which are not suitable for pyrolysis and gasification or which would be preferably recycled by other technologies.
  - The amount of plastic waste sent to energy recovery is dependent on the recycling processes efficiencies, which are discussed in the next sub-section.

Recycling efficiencies
Mechanical recycling
As ADAPT is the business as usual scenario, the mechanical recycling efficiency is kept as it is currently (65% of plastic input is converted to recyclate). For TRANSFORM and industry variants, a strong push towards a more circular economy for plastics is assumed, therefore the mechanical recycling efficiency is considered to improve and be around 80-90% in 2050. For both TRANSFORM and Less Competitive variant the mixed plastic policy is considered,

therefore the efficiency considered is 80%, mainly due to the plastic waste streams available be less pure and more difficult to recycle mechanically. For the variants which mono-plastic policy is considered (Competitive Import and Less Competitive & Import) an efficiency of 90% for mechanical recycling is assumed. The recycling efficiency of 90% represents current best available technologies for certain plastic types like PET recycling (when also partly using deposit systems).

Chemical Recycling
Literature indicate current efficiency for mixed plastic waste pyrolysis of around 67 (Fivga & Dimitriou, 2018) and 68% for plastic waste gasification (Borgogna, A. et al., 2021) (Borgogna, Iaquaniello, Salladini, Agostini, & Boccacci, 2021). For ADAPT, these efficiencies are kept until 2050, while for TRANSFORM and variants the efficiencies are assumed to increase to 75% in 2050. In all scenarios, it is also considered that the rejected waste from mechanical recycling can be used as input for chemical recycling, being a choice by the model which technology (pyrolysis or gasification) the reject is used at.

D.3 Plastic waste availability

The assumptions for each scenario regarding availability of plastic waste for recycling is explained is this section. For ADAPT, TRANSFORM and the variant Less Competitive, only domestic plastic waste is considered. ADAPT domestic plastic waste volumes are based on the projections for the Netherlands derived from (Stegmann, Daioglou, Londo, & Junginger, 2022). For TRANSFORM and Less Competitive, the total plastic waste available is considered to be 40% less than in ADAPT, mainly due to the behavioural changes regarding consume of plastic products already mentioned in this study. For the variants Competitive & Import and Less Competitive & Import, the domestic plastic waste availability are supplemented by imported volumes. The imported volumes are assumed to be 10% of the total plastic waste generated in the EU. The projections for the total EU plastic waste generated are also extracted from (Stegmann, Daioglou, Londo, & Junginger, 2022).

Table D.1: Summary of scenario data input in kton for ADAPT

	2020	2030	2040	2050
Domestic plastic waste availability	1058	1161	1302	1437
Plastic waste import	0	0	0	0
Plastic waste sent to mechanical recycling	476	522	586	647
Plastic waste sent to chemical recycling	0	0	296	442
Mechanical recycling efficiency	65%	65%	65%	65%
Plastic waste pyrolysis efficiency	N/A	67%	67%	67%
Gasification pyrolysis efficiency	N/A	68%	68%	68%

Energy content assumed for plastic waste is 35 (GJ/t) (Stegmann, Daioglou, Londo, & Junginger, 2022)

Table D.2: Summary of scenario data input in kton for TRANSFORM

	2020	2030	2040	2050
Domestic plastic waste availability	1058	1088	1119	1150
Plastic waste import	0	0	0	0
Plastic waste sent to mechanical recycling	476	490	504	460
Plastic waste sent to chemical recycling	0	201	436	621
Mechanical recycling efficiency	65%	70%	80%	90%
Plastic waste pyrolysis efficiency	N/A	67%	67%	75%
Gasification pyrolysis efficiency	N/A	68%	68%	75%

Energy content assumed for plastic waste is 35 (GJ/t) (Stegmann, Daioglou, Londo, & Junginger, 2022)

Table D.3: Summary of scenario data input in kton for industry variants

	2020	2030	2040	2050
Competitive & import				
Domestic plastic waste availability	1058	1088	1119	1150
Plastic waste import	0	733	1467	2200
Plastic waste sent to mechanical recycling	476	544	671	805
Plastic waste sent to chemical recycling	0	218	358	425
Mechanical recycling efficiency	65%	70%	80%	90%
Plastic waste pyrolysis efficiency	N/A	67%	67%	75%
Less competitive				
Domestic plastic waste availability	1058	1088	1119	1150
Plastic waste import	0	0	0	0
Plastic waste sent to mechanical recycling	476	490	504	460
Plastic waste sent to chemical recycling	0	226	462	667
Mechanical recycling efficiency	65%	65%	75%	80%
Plastic waste pyrolysis efficiency	N/A	67%	67%	75%
Gasification pyrolysis efficiency	N/A	68%	68%	75%
Less Competitive & Import				
Domestic plastic waste availability	1058	1088	1119	1150
Plastic waste import	0	733	1467	2200
Plastic waste sent to mechanical recycling	476	544	671	805
Plastic waste sent to chemical recycling	0	218	358	425
Mechanical recycling efficiency	65%	70%	80%	90%
Plastic waste pyrolysis efficiency	N/A	67%	67%	75%
Gasification pyrolysis efficiency	N/A	68%	68%	75%
Gasification pyrolysis efficiency	N/A	68%	68%	75%

Energy content assumed for plastic waste is 35 (GJ/t) (Stegmann, Daioglou, Londo, & Junginger, 2022)

Appendix E
Techno economic parameters model

E.1 List of abbreviations

ATR	Autothermal Reforming
CC	Carbon Capture
DF	Direct Firing
GFA	Gross Floor Area
HD	High Density
HDV	Heavy Duty Vehicle
LD	Low Density
LDV	Light Duty Vehicle
MD	Medium Density
MWT	Mobile machinery
NG	Natural Gas
REF	Reference (or conventional)

E.2 Energy technologies

Technology ID	Technology name	Sector	UoC	UoA	2030	2040	2050	2030	2040	2050	2030	2040	2050	Fulfills Service demand (yes/no)?	2030	2040	2050	Life-time [yr]	Data source
913	Mono manure AD Green gas	Agriculture	PJ/yr	PJ	93.0	85.8	78.7	19.70	19.70	19.70	0.000	0.000	0.000	N	1.445	1.445	1.445	20	SDE++ 2023 Eindadvies
985	Lignocellulosic ethanol production	Refinery	PJ/yr	PJ	114.6	94.9	76.9	12.80	12.10	11.40	3.000	3.000	3.000	N	2.595	2.273	1.951	20	ADVANCEFUEL (2020), SDE++ 2021 Eindadvies
986	Ethanol from biomass (starch)	Refinery	PJ/yr	PJ	62.3	60.7	59.0	29.97	29.97	29.97	0.000	0.000	0.000	N	1.835	1.835	1.835	20	ECN & PBL, E-design model (2011)
987	Ethanol from biomass (sugar)	Refinery	PJ/yr	PJ	79.6	69.8	60.1	22.95	22.95	22.95	0.000	0.000	0.000	N	2.237	2.237	2.237	20	ECN & PBL, E-design model (2011)
998	H2 from Biomass gasification	H2 supply	PJ/yr	PJ	93.4	80.8	68.9	5.77	5.20	4.62	0.000	0.000	0.000	N	1.457	1.457	1.457	20	ECN & PBL, E-design model (2011)
1003	Micro-CHP Fuel cell (WB existing buildings)	Residential	PJ/yr	PJ	405.7	374.2	274.2	4.27	3.84	3.41	0.000	0.000	0.000	N	1.058	1.058	1.058	15	ECN & PBL, E-design model (2011)
1012	Solar-PV Residential	Residential	GW	PJ	871.8	731.5	591.2	12.00	10.70	9.40	0.000	0.000	0.000	N	1.000	1.000	1.000	25	
1013	Biomass gasification with CC	Electricity generation	GW	PJ	13,010.2	11,279.9	9,645.0	0.00	0.00	0.00	14.269	14.269	14.269	N	2.435	2.435	2.435	25	ECN & PBL, E-design model (2011)
1016	ATR with CC	H2 supply	PJ/yr	PJ	38.1	38.1	38.1	1.27	1.27	1.27	0.000	0.000	0.000	N	1.250	1.250	1.250	20	TNO datasheet
1020	Solar thermal - Services	Services	PJ/yr	PJ	18.0	18.4	15.2	0.06	0.06	0.06	0.000	0.000	0.000	N	1.000	1.000	1.000	15	ECN & PBL, E-design model (2011)
1021	Micro CHP fuel cel Services buildings	Services	PJ/yr	PJ	342.8	316.2	231.7	4.27	3.84	3.41	0.000	0.000	0.000	N	1.058	1.058	1.058	10	ECN & PBL, E-design model (2011)
1022	Soil heat pump - Services	Services	PJ/yr	PJ	62.4	62.7	50.7	1.74	1.75	1.76	0.000	0.000	0.000	N	1.000	1.000	1.000	15	TNO datasheet
1023	Ground water heat pump - Services	Services	PJ/yr	PJ	43.8	44.1	35.6	1.59	1.59	1.60	0.000	0.000	0.000	N	1.000	1.000	1.000	15	TNO datasheet
1024	Hybride WP boiler Services buildings	Services	PJ/yr	PJ	475.5	487.4	401.8	6.86	6.86	6.86	0.000	0.000	0.000	N	1.000	1.000	1.000	10	ECN & PBL, E-design model (2011)
1027	REF HR-107 - Services	Services	PJ/yr	PJ	2.4	2.4	2.4	0.11	0.11	0.11	0.000	0.000	0.000	N	1.085	1.099	1.099	10	Vesta model PBL, TNO datasheet
1029	Solar thermal - Newly built - Residential	Residential	PJ/yr	PJ	18.0	18.4	15.2	0.06	0.06	0.06	0.000	0.000	0.000	N	1.000	1.000	1.000	15	SDE++ 2021 Eindadvies
1035	REF HR-107 - Existing - Residential	Residential	PJ/yr	PJ	2.1	2.1	2.1	0.10	0.10	0.10	0.000	0.000	0.000	N	1.048	1.071	1.071	10	
1037	REF HR-107 - Newly built - Residential	Residential	PJ/yr	PJ	2.7	2.5	2.3	0.10	0.10	0.10	0.000	0.000	0.000	N	1.048	0.964	0.859	10	
1039	Solar thermal - Existing - Residential	Residential	PJ/yr	PJ	18.0	18.4	15.2	0.06	0.06	0.06	0.000	0.000	0.000	N	1.000	1.000	1.000	15	SDE++ 2021 Eindadvies
1042	Wind offshore	Electricity generation	GW	PJ	1,620.0	1,555.0	1,490.0	23.40	22.90	22.40	1.667	1.667	1.667	N	1.000	1.000	1.000	30	TNO datasheet
1043	REF H2 from SMR	H2 supply	PJ/yr	PJ	25.7	23.1	20.6	1.04	0.94	0.83	0.000	0.000	0.000	N	1.350	1.350	1.350	20	ECN & PBL, E-design model (2011)
1044	Boilers SHT coal	Other industry	PJ/yr	PJ	7.0	7.0	7.0	0.10	0.10	0.10	0.040	0.040	0.040	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
1045	Hydrogen Medium Temp Boilers - Industry	Other industry	PJ/yr	PJ	4.5	4.8	4.2	0.56	0.56	0.56	0.000	0.000	0.000	N	1.110	1.110	1.110	25	Danish Energy Agency (2021)
1046	Hot water electric boiler - Industry	Other industry	PJ/yr	PJ	2.1	2.2	1.8	0.03	0.03	0.03	0.139	0.125	0.111	N	1.010	1.010	1.010	25	Danish Energy Agency (2021)
1047	Electric Industrial Heat Pump - Industry	Other industry	PJ/yr	PJ	24.7	23.1	17.2	0.89	0.80	0.71	0.000	0.000	0.000	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
1048	Natural Gas Industrial Heat Pump - Industry	Other industry	PJ/yr	PJ	146.8	146.8	146.8	7.34	7.34	7.34	0.000	0.000	0.000	N	1.364	1.364	1.364	25	Danish Energy Agency (2021)
1049	CHP biomass (liquid)	Other industry	PJ/yr	PJ	73.1	73.1	73.1	8.39	8.39	8.39	0.000	0.000	0.000	N	1.515	1.515	1.515	15	ECN & PBL, E-design model (2011)
1050	CHP biomass (liquid) CC	Other industry	PJ/yr	PJ	77.0	77.0	77.0	21.00	21.00	21.00	3.551	3.551	3.551	N	1.595	1.595	1.595	15	ECN & PBL, E-design model (2011)
1051	CHP biomass (solid) CC	Other industry	PJ/yr	PJ	96.0	96.0	96.0	2.00	2.00	2.00	0.000	0.000	0.000	N	1.387	1.387	1.387	25	Danish Energy Agency (2021)
1052	CHP gas CC	Other industry	PJ/yr	PJ	46.7	46.7	46.7	0.48	0.48	0.48	0.000	0.000	0.000	N	1.276	1.276	1.276	25	Danish Energy Agency (2021)
1053	CHP biomass (solid) Industry	Other industry	PJ/yr	PJ	31.8	31.8	31.8	1.36	1.36	1.36	2.010e-05	2.010e-05	2.010e-05	N	1.176	1.176	1.176	25	Danish Energy Agency (2021)
1054	CHP gas	Other industry	PJ/yr	PJ	10.7	11.8	10.6	0.40	0.40	0.40	0.000	0.000	0.000	N	1.176	1.176	1.176	25	Danish Energy Agency (2021)
1055	Boilers LT biomass CC	Other industry	PJ/yr	PJ	64.4	64.4	64.4	1.25	1.25	1.25	0.000	0.000	0.000	N	1.437	1.437	1.437	25	Danish Energy Agency (2021)
1056	Coal boiler 100-200C - Industry	Other industry	PJ/yr	PJ	14.8	14.4	14.0	1.03	1.00	0.97	0.306	0.306	0.306	N	1.136	1.136	1.136	25	Danish Energy Agency (2021)
1057	Boilers LT natural gas CC	Other industry	PJ/yr	PJ	24.8	24.8	24.8	0.11	0.11	0.11	0.000	0.000	0.000	N	1.205	1.205	1.205	25	Danish Energy Agency (2021)
1059	Boilers LT coal	Other industry	PJ/yr	PJ	14.8	14.4	14.0	1.03	1.00	0.97	0.306	0.306	0.306	N	1.136	1.136	1.136	25	Danish Energy Agency (2021)

	UoC: unit of capacity UoA: unit of activity				Investment cost [Mln €(2015)/UoC]			Fixed O&M cost [Mln euro(2015)/UoC/yr]			Variable cost [Mln euro(2015)/UoA]				Energy input [PJ] per UoA				
Technology ID	Technology name	Sector	UoC	UoA	2030	2040	2050	2030	2040	2050	2030	2040	2050	Fulfills Service demand (yes/no)?	2030	2040	2050	Life-time [yr]	Data source
1060	Natural Gas Low Temp Boilers - Industry	Other industry	PJ/yr	PJ	1.3	1.4	1.3	0.06	0.06	0.05	0.139	0.125	0.111	N	1.111	1.111	1.111	25	Danish Energy Agency (2021)
1061	Boilers HT biomass CC	Other industry	PJ/yr	PJ	63.9	63.9	63.9	1.24	1.24	1.24	0.000	0.000	0.000	N	1.421	1.421	1.421	25	Danish Energy Agency (2021)
1062	Boilers HT coal CC	Other industry	PJ/yr	PJ	53.8	53.8	53.8	1.13	1.13	1.13	0.000	0.000	0.000	N	1.379	1.379	1.379	25	Danish Energy Agency (2021)
1063	NG DF 200-400C - Industry	Other industry	PJ/yr	PJ	0.5	0.5	0.5	0.01	0.01	0.01	0.025	0.025	0.025	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
1064	Biomass Medium Temp Boilers - Industry	Other industry	PJ/yr	PJ	18.4	19.0	15.8	1.14	1.10	1.07	0.306	0.306	0.306	N	1.124	1.124	1.124	25	Danish Energy Agency (2021)
1065	Natural Gas Medium Temp Boilers - Industry	Other industry	PJ/yr	PJ	1.3	1.4	1.3	0.06	0.06	0.05	0.139	0.125	0.111	N	1.111	1.111	1.111	25	Danish Energy Agency (2021)
1066	Boilers HT coal	Other industry	PJ/yr	PJ	14.8	14.4	14.0	1.03	1.00	0.97	0.306	0.306	0.306	N	1.136	1.136	1.136	25	Danish Energy Agency (2021)
1067	Boilers SHT biomass CC	Other industry	PJ/yr	PJ	63.9	63.9	63.9	1.24	1.24	1.24	0.000	0.000	0.000	N	1.421	1.421	1.421	25	Danish Energy Agency (2021)
1068	Boilers SHT coal CC	Other industry	PJ/yr	PJ	7.0	7.0	7.0	0.10	0.10	0.10	0.040	0.040	0.040	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
1069	NG DF 200-400C - Industry	Other industry	PJ/yr	PJ	0.5	0.5	0.5	0.01	0.01	0.01	0.025	0.025	0.025	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
1070	Natural Gas DF > 400 C - Industry	Other industry	PJ/yr	PJ	0.4	0.5	0.4	0.01	0.01	0.01	0.025	0.025	0.025	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
1071	Biomass High Temp Boilers - Industry	Other industry	PJ/yr	PJ	18.4	19.0	15.8	1.14	1.10	1.07	0.306	0.306	0.306	N	1.124	1.124	1.124	25	Danish Energy Agency (2021)
1072	REF Boilers natural gas Industry	Other industry	PJ/yr	PJ	1.4	1.4	1.4	0.06	0.06	0.05	0.139	0.125	0.111	N	1.111	1.111	1.111	25	Danish Energy Agency (2021)
1073	REF CHP gas	Other industry	PJ/yr	PJ	11.6	11.6	11.6	0.40	0.40	0.40	0.000	0.000	0.000	N	1.176	1.176	1.176	25	Danish Energy Agency (2021)
1083	REF Steam Cracking (conventional)	Chemical industry	Mton olefins/yr	Mton olefins	599.7	599.6	599.6	30.07	30.07	30.07	0.000	0.000	0.000	Y	72.647	72.647	76.525	15	ECN & PBL, E-design model (2011)
1090	Wind onshore	Electricity generation	GW	PJ	1,103.0	1,076.0	1,049.0	10.00	10.00	10.00	2.570	2.505	2.440	N	1.000	1.000	1.000	25	RESolve-E model
1096	Gas Combustion STEG CC	Electricity generation	GW	PJ	856.3	843.5	830.7	0.00	0.00	0.00	2.204	2.204	2.204	N	1.938	1.895	1.852	20	ECN & PBL, E-design model (2011)
1098	Biomass gasification	Electricity generation	GW	PJ	1,423.6	1,383.6	1,343.6	0.00	0.00	0.00	4.530	4.530	4.530	N	2.191	2.191	2.191	20	ECN & PBL, E-design model (2011)
1101	REF natural gas CCGT	Electricity generation	GW	PJ	7.0	675.1	650.0	0.01	0.01	0.01	0.417	0.417	0.417	N	1.565	1.408	1.124	20	COMPETES model
1108	Natural gas CCGT	Electricity generation	GW	PJ	700.1	675.1	650.0	0.01	0.01	0.01	0.417	0.417	0.417	N	1.639	1.639	1.639	20	COMPETES model
1111	Agriculture Geothermal	Agriculture	PJ/yr	PJ	74.9	69.1	63.2	0.80	0.80	0.80	0.000	0.000	0.000	N	1.000	1.000	1.000	20	ECN & PBL, E-design model (2011)
1113	Agriculture Biomassboiler	Agriculture	PJ/yr	PJ	20.4	17.9	17.0	1.14	1.10	1.07	0.306	0.306	0.306	N	1.111	1.111	1.111	25	Danish Energy Agency (2021)
1114	Agriculture WKO with warmtepomp	Agriculture	PJ/yr	PJ	88.3	81.5	74.6	1.23	1.23	1.23	0.000	0.000	0.000	N	1.212	1.222	1.220	20	ECN & PBL, E-design model (2011)
1117	Kleinschalige biomass Combustion	Electricity generation	GW	PJ	3,430.7	3,334.3	3,237.8	0.00	0.00	0.00	7.583	7.583	7.583	N	1.136	1.137	1.136	15	ECN & PBL, E-design model (2011)
1118	Gasturbine 250u	Electricity generation	GW	PJ	393.9	393.9	393.9	0.00	0.00	0.00	0.906	0.906	0.906	N	2.632	2.632	2.632	15	ECN & PBL, E-design model (2011)
1159	REF Boilers rest Industry ebalans	Other industry	PJ/yr	PJ	7.4	7.4	7.4	0.43	0.43	0.43	0.000	0.000	0.000	N	1.129	1.129	1.129	15	
1213	REF Electricity MT transmissielijn	Electricity generation	GW	PJ	690.0	690.0	690.0	17.25	17.25	17.25	0.000	0.000	0.000	N	1.020	1.020	1.020	25	
1214	REF Electricity HT to MT transformer	Electricity generation	GW	PJ	28.7	28.7	28.7	0.00	0.00	0.00	0.000	0.000	0.000	N	1.020	1.020	1.020	30	TNO datasheet
1215	REF Electricity MT to HT transformer	Electricity generation	GW	PJ	28.7	28.7	28.7	0.00	0.00	0.00	0.000	0.000	0.000	N	1.020	1.020	1.020	30	TNO datasheet
1219	REF Boilers rest Residential ebalans	Residential	PJ/yr	PJ	2.1	2.1	2.1	0.10	0.10	0.10	0.000	0.000	0.000	N	1.250	1.250	1.250	15	
1220	REF Boilers natural gas Residential ebalans	Residential	PJ/yr	PJ	2.1	2.1	2.1	0.10	0.10	0.10	0.000	0.000	0.000	N	1.950	1.984	2.069	15	
1225	REF Boilers rest Services ebalans	Services	PJ/yr	PJ	2.7	2.8	2.8	0.13	0.12	0.12	0.000	0.000	0.000	N	1.126	1.126	1.118	15	
1226	REF Boilers natural gas Services ebalans	Services	PJ/yr	PJ	2.7	2.6	2.5	0.13	0.12	0.12	0.000	0.000	0.000	N	1.073	1.110	1.110	15	
1231	REF Boilers rest Agriculture ebalans	Agriculture	PJ/yr	PJ	2.7	2.6	2.5	0.13	0.12	0.12	0.000	0.000	0.000	N	1.150	1.153	1.153	15	
1232	REF Boilers natural gas Agriculture ebalans	Agriculture	PJ/yr	PJ	2.7	2.6	2.5	0.13	0.12	0.12	0.000	0.000	0.000	N	1.111	1.111	1.111	15	ECN & PBL, E-design model (2011)
1244	REF Electricity LT distribution grid	Electricity generation	GW	PJ	916.0	916.0	916.0	22.90	22.90	22.90	0.000	0.000	0.000	N	1.020	1.020	1.020	30	TNO datasheet
1245	REF Electricity MT to LT transformer	Electricity generation	GW	PJ	118.8	118.8	118.8	0.00	0.00	0.00	0.000	0.000	0.000	N	1.020	1.020	1.020	30	TNO datasheet
1246	REF Electricity LT to MT transformer	Electricity generation	GW	PJ	118.8	118.8	118.8	0.00	0.00	0.00	0.000	0.000	0.000	N	1.020	1.020	1.020	25	
1248	REF CHP gas Agriculture ebalans	Agriculture	PJ/yr	PJ	57.8	57.8	57.8	1.69	1.69	1.69	0.000	0.000	0.000	N	1.129	1.138	1.138	15	
1261	REF Natural gas MD to HD connector	Gas supply	PJ/yr	PJ	0.0	0.0	0.0	0.00	0.00	0.00	0.000	0.000	0.000	N	1.000	1.000	1.000	25	
1262	REF Natural gas HD to MD connector	Gas supply	PJ/yr	PJ	0.0	0.0	0.0	0.00	0.00	0.00	0.000	0.000	0.000	N	1.000	1.000	1.000	25	
1263	REF Natural gas MD Pipeline	Gas supply	GW	PJ	116.9	116.9	116.9	2.92	2.92	2.92	0.000	0.000	0.000	N	1.000	1.000	1.000	25	
1265	REF Natural gas LD to MD connector	Gas supply	PJ/yr	PJ	0.0	0.0	0.0	0.00	0.00	0.00	0.000	0.000	0.000	N	1.000	1.000	1.000	25	
1266	REF Natural gas MD to LD connector	Gas supply	PJ/yr	PJ	0.0	0.0	0.0	0.00	0.00	0.00	0.000	0.000	0.000	N	1.000	1.000	1.000	25	
1267	REF Natural gas LD distribution grid	Gas supply	GW	PJ	474.1	474.1	474.1	11.85	11.85	11.85	0.000	0.000	0.000	N	1.000	1.000	1.000	25	
1284	REF fossil refinery	Refinery	PJ/yr	PJ	5.5	5.5	5.5	0.21	0.21	0.21	0.000	0.000	0.000	N	1.078	1.076	1.076	25	
1285	REF CHP gas refineries ebalans	Refinery	PJ/yr	PJ	11.6	11.6	11.6	0.40	0.40	0.40	0.000	0.000	0.000	N	1.176	1.176	1.176	25	Danish Energy Agency (2021)
1286	REF Boilers natural gas refineries ebalans	Refinery	PJ/yr	PJ	4.0	4.0	4.0	0.38	0.38	0.38	0.000	0.000	0.000	N	1.112	1.111	1.111	15	
1289	REF Boilers rest refineries ebalans	Refinery	PJ/yr	PJ	4.8	4.8	4.8	0.45	0.45	0.45	0.000	0.000	0.000	N	1.167	1.158	1.106	15	
1290	REF CHP rest refineries ebalans	Refinery	PJ/yr	PJ	21.2	21.2	21.2	0.76	0.76	0.76	0.000	0.000	0.000	N	1.131	1.128	1.161	15	

	UoC: unit of capacity UoA: unit of activity				Investment cost [Mln €(2015)/UoC]			Fixed O&M cost [Mln euro(2015)/UoC/yr]			Variable cost [Mln euro(2015)/UoA]				Energy input [PJ] per UoA				
Technology ID	Technology name	Sector	UoC	UoA	2030	2040	2050	2030	2040	2050	2030	2040	2050	Fulfills Service demand (yes/no)?	2030	2040	2050	Life-time [yr]	Data source
1327	H2 Methanation process	Gas supply	PJ/yr	PJ	13.9	13.9	13.9	1.39	1.39	1.39	0.000	0.000	0.000	N	1.000	1.000	1.000	10	
1335	H2 solar reformer	H2 supply	GW	PJ	402.0	402.0	402.0	22.11	22.11	22.11	0.000	0.000	0.000	N	1.885	1.885	1.885	20	
1339	H2 connector pipeline naar distribution grid	H2 supply	PJ/yr	PJ	0.0	0.0	0.0	0.00	0.00	0.00	0.000	0.000	0.000	N	1.000	1.000	1.000	20	
1340	H2 connector distribution grid naar filling station	H2 supply	PJ/yr	PJ	0.0	0.0	0.0	0.00	0.00	0.00	0.000	0.000	0.000	N	1.000	1.000	1.000	20	
1351	REF ICE personencar	Mobility	M vehicles	G vkm car	20,147.7	20,147.7	20,147.7	388.25	374.57	360.88	0.000	0.000	0.000	Y	1.904	1.823	1.823	10	PRIMES TREMOVE
1352	REF PI hybride car	Mobility	M vehicles	G vkm car	24,846.1	24,060.4	23,274.7	334.26	317.86	301.46	0.000	0.000	0.000	Y	1.448	1.389	1.365	10	PRIMES TREMOVE
1353	REF elektrische car	Mobility	M vehicles	G vkm car	24,037.5	23,144.6	22,251.6	249.45	239.58	229.71	0.000	0.000	0.000	Y	1.026	0.715	0.525	10	PRIMES TREMOVE
1354	CNG car	Mobility	M vehicles	G vkm car	21,004.1	21,004.1	21,004.1	363.31	352.24	341.17	0.000	0.000	0.000	Y	1.928	1.863	1.799	10	PRIMES TREMOVE
1355	Elektrische car	Mobility	M vehicles	G vkm car	28,958.0	26,763.5	24,569.0	300.51	277.07	253.64	0.000	0.000	0.000	Y	0.513	0.499	0.485	10	PRIMES TREMOVE
1356	REF H2 car	Mobility	M vehicles	G vkm car	37,995.8	33,563.1	29,130.5	449.62	398.54	347.46	0.000	0.000	0.000	Y	1.136	1.136	1.136	10	PRIMES TREMOVE
1357	Diesel hybrid car with high fuel reduction	Mobility	M vehicles	G vkm car	24,840.5	24,840.5	24,840.5	478.68	461.81	444.94	0.000	0.000	0.000	Y	0.663	0.663	0.663	10	PRIMES TREMOVE
1358	PI car	Mobility	M vehicles	G vkm car	25,170.3	24,337.5	23,504.7	338.62	321.53	304.44	0.000	0.000	0.000	Y	1.267	1.180	1.094	10	
1359	Flex boiler waste gasses	Other industry	PJ/yr	PJ	4.8	4.8	4.8	0.45	0.45	0.45	0.000	0.000	0.000	N	1.333	1.333	1.333	15	
1360	Flex CHP waste gasses	Other industry	PJ/yr	PJ	21.2	21.2	21.2	0.76	0.76	0.76	0.000	0.000	0.000	N	2.804	2.804	2.804	15	
1363	E85 flex-fuel car	Mobility	M vehicles	G vkm car	19,587.0	19,587.0	19,587.0	398.15	389.19	380.23	0.000	0.000	0.000	Y	2.087	2.087	2.087	10	PRIMES TREMOVE
1364	REF HDV truck	Mobility	M vehicles	Bn vkm HDV	145,779.7	146,982.0	148,073.0	1,733.36	1,747.65	1,760.62	0.000	0.000	0.000	Y	13.273	11.669	11.084	8	PRIMES TREMOVE
1365	LNG truck	Mobility	M vehicles	Bn vkm HDV	178,162.3	178,162.3	178,162.3	1,532.44	1,532.44	1,532.44	0.000	0.000	0.000	Y	18.212	18.143	18.074	8	PRIMES TREMOVE
1366	H2 HDV truck	Mobility	M vehicles	Bn vkm HDV	424,034.8	298,318.4	263,862.7	2,238.35	1,870.81	1,503.28	0.000	0.000	0.000	Y	7.967	7.937	7.907	8	PRIMES TREMOVE
1370	Heat transmission grid	Central heat supply	GW	PJ	435.0	435.0	435.0	10.50	10.50	10.50	0.000	0.000	0.000	N	1.333	1.333	1.333	25	Afman (2017)
1371	Natural Gas Medium Temp Boilers - Chemical	Chemical industry	PJ/yr	PJ	1.4	1.4	1.4	0.06	0.06	0.05	0.139	0.125	0.111	N	1.111	1.111	1.111	25	Danish Energy Agency (2021)
1372	Natural Gas Medium Temp Boilers - Refineries	Refinery	PJ/yr	PJ	1.4	1.4	1.4	0.06	0.06	0.05	0.139	0.125	0.111	N	1.111	1.111	1.111	25	Danish Energy Agency (2021)
1373	Natural Gas CHP - Chemical	Chemical industry	PJ/yr	PJ	11.6	11.6	11.6	0.40	0.40	0.40	0.000	0.000	0.000	N	1.176	1.176	1.176	25	Danish Energy Agency (2021)
1374	Natural Gas CHP - Refineries	Refinery	PJ/yr	PJ	11.6	11.6	11.6	0.40	0.40	0.40	0.000	0.000	0.000	N	1.176	1.176	1.176	25	Danish Energy Agency (2021)
1375	REF ammonia production	Fertilizer industry	Mton NH3/yr	Mton NH3	356.3	356.3	356.3	0.00	0.00	0.00	12.167	12.167	12.167	Y	29.709	29.756	29.998	20	
1387	REF Natural Gas CHP - Basic metals	Basic metal ferro	PJ/yr	PJ	11.6	11.6	11.6	0.40	0.40	0.40	0.000	0.000	0.000	N	1.176	1.176	1.176	25	Danish Energy Agency (2021)
1388	Natural Gas Medium Temp Boilers - Basic Metals	Basic metal ferro	PJ/yr	PJ	1.4	1.4	1.4	0.06	0.06	0.05	0.139	0.125	0.111	N	1.111	1.111	1.111	25	Danish Energy Agency (2021)
1391	REF CHP rest chemical ebalans	Chemical industry	PJ/yr	PJ	21.2	21.2	21.2	0.76	0.76	0.76	0.000	0.000	0.000	N	1.137	1.118	1.114	15	
1392	REF Boilers rest chemical ebalans	Chemical industry	PJ/yr	PJ	0.5	0.5	0.5	0.45	0.45	0.45	0.000	0.000	0.000	N	1.111	1.111	1.111	15	
1395	REF CHP rest basic metal ebalans	Basic metal ferro	PJ/yr	PJ	21.2	21.2	21.2	0.76	0.76	0.76	0.000	0.000	0.000	N	1.000	1.071	1.071	15	
1396	REF Boilers rest basic metal ebalans	Basic metal ferro	PJ/yr	PJ	0.5	0.5	0.5	0.45	0.45	0.45	0.000	0.000	0.000	N	1.000	1.000	1.000	15	

	UoC: unit of capacity UoA: unit of activity				Investment cost [Mln €(2015)/UoC]			Fixed O&M cost [Mln euro(2015)/UoC/yr]			Variable cost [Mln euro(2015)/UoA]				Energy input [PJ] per UoA				
Technology ID	Technology name	Sector	UoC	UoA	2030	2040	2050	2030	2040	2050	2030	2040	2050	Fulfills Service demand (yes/no)?	2030	2040	2050	Life-time [yr]	Data source
1422	Flex CHP waste gasses refineries	Refinery	PJ/yr	PJ	21.2	21.2	21.2	0.76	0.76	0.76	0.000	0.000	0.000	N	2.804	2.804	2.804	15	
1423	Flex boiler waste gasses refineries	Refinery	PJ/yr	PJ	4.8	4.8	4.8	0.45	0.45	0.45	0.000	0.000	0.000	N	1.333	1.333	1.333	15	
1425	Flex CHP waste gasses chemical	Chemical industry	PJ/yr	PJ	21.2	21.2	21.2	0.76	0.76	0.76	0.000	0.000	0.000	N	2.804	2.804	2.804	15	
1426	Flex boiler waste gasses chemical	Chemical industry	PJ/yr	PJ	4.8	4.8	4.8	0.45	0.45	0.45	0.000	0.000	0.000	N	1.333	1.333	1.333	15	
1428	Flex CHP waste gasses basic metal	Basic metal ferro	PJ/yr	PJ	21.2	21.2	21.2	0.76	0.76	0.76	0.000	0.000	0.000	N	2.804	2.804	2.804	15	
1429	Flex boiler waste gasses basic metal	Basic metal ferro	PJ/yr	PJ	4.8	4.8	4.8	0.45	0.45	0.45	0.000	0.000	0.000	N	1.333	1.333	1.333	15	
1430	Hydrogen Medium Temp Boilers - Basic Metals	Basic metal ferro	PJ/yr	PJ	4.4	4.4	4.4	0.56	0.56	0.56	0.000	0.000	0.000	N	1.110	1.110	1.110	25	Danish Energy Agency (2021)
1431	CHP biomass (solid) CC basic metal	Basic metal ferro	PJ/yr	PJ	96.0	96.0	96.0	2.00	2.00	2.00	0.000	0.000	0.000	N	1.387	1.387	1.387	25	Danish Energy Agency (2021)
1432	CHP gas CC basic metal	Basic metal ferro	PJ/yr	PJ	46.7	46.7	46.7	0.48	0.48	0.48	0.000	0.000	0.000	N	1.276	1.276	1.276	25	Danish Energy Agency (2021)
1434	Biomass Medium Temp Boilers with CC - Basic Metals	Basic metal ferro	PJ/yr	PJ	63.9	63.9	63.9	1.24	1.24	1.24	0.000	0.000	0.000	N	1.421	1.421	1.421	25	Danish Energy Agency (2021)
1435	Boilers HT biomass basic metal	Basic metal ferro	PJ/yr	PJ	7.0	7.0	7.0	0.10	0.10	0.10	0.040	0.040	0.040	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
1436	Hydrogen Medium Temp Boilers - Chemical	Chemical industry	PJ/yr	PJ	4.4	4.4	4.4	0.56	0.56	0.56	0.000	0.000	0.000	N	1.110	1.110	1.110	25	Danish Energy Agency (2021)
1437	CHP biomass (solid) CC chemical	Chemical industry	PJ/yr	PJ	96.0	96.0	96.0	2.00	2.00	2.00	0.000	0.000	0.000	N	1.387	1.387	1.387	25	Danish Energy Agency (2021)
1438	CHP gas CC chemical	Chemical industry	PJ/yr	PJ	46.7	46.7	46.7	0.48	0.48	0.48	0.000	0.000	0.000	N	1.276	1.276	1.276	25	Danish Energy Agency (2021)
1439	CHP biomass (solid) chemical	Chemical industry	PJ/yr	PJ	31.8	31.8	31.8	1.36	1.36	1.36	2.010e-05	2.010e-05	2.010e-05	N	1.176	1.176	1.176	25	Danish Energy Agency (2021)
1440	Biomass DF 200-400C - Chemical	Chemical industry	PJ/yr	PJ	7.0	7.0	7.0	0.10	0.10	0.10	0.040	0.040	0.040	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
1441	Biomass Medium Temp Boilers - Chemical	Chemical industry	PJ/yr	PJ	18.7	17.9	17.0	1.14	1.10	1.07	0.306	0.306	0.306	N	1.124	1.124	1.124	25	Danish Energy Agency (2021)
1442	Hydrogen Medium Temp Boilers - Refineries	Refinery	PJ/yr	PJ	4.4	4.4	4.4	0.56	0.56	0.56	0.000	0.000	0.000	N	1.110	1.110	1.110	25	Danish Energy Agency (2021)
1443	CHP biomass (solid) CC refineries	Refinery	PJ/yr	PJ	96.0	96.0	96.0	2.00	2.00	2.00	0.000	0.000	0.000	N	1.387	1.387	1.387	25	Danish Energy Agency (2021)
1444	CHP gas CC refineries	Refinery	PJ/yr	PJ	46.7	46.7	46.7	0.48	0.48	0.48	0.000	0.000	0.000	N	1.276	1.276	1.276	25	Danish Energy Agency (2021)
1446	Biomass DF 200-400C - refineries	Refinery	PJ/yr	PJ	7.0	7.0	7.0	0.10	0.10	0.10	0.040	0.040	0.040	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
1447	Biomass Medium Temp Boilers - Refineries	Refinery	PJ/yr	PJ	18.7	17.9	17.0	1.14	1.10	1.07	0.306	0.306	0.306	N	1.124	1.124	1.124	25	Danish Energy Agency (2021)
1448	CHP biomass (solid) basic metal	Basic metal ferro	PJ/yr	PJ	31.8	31.8	31.8	1.36	1.36	1.36	2.010e-05	2.010e-05	2.010e-05	N	1.176	1.176	1.176	25	Danish Energy Agency (2021)
1449	CHP biomass (solid) refineries	Refinery	PJ/yr	PJ	31.8	31.8	31.8	1.36	1.36	1.36	2.010e-05	2.010e-05	2.010e-05	N	1.176	1.176	1.176	25	Danish Energy Agency (2021)
1461	Onshore substation and trafo offshore to onshore grid	Electricity generation	GW	PJ	167.5	167.5	167.5	0.00	0.00	0.00	0.000	0.000	0.000	N	1.015	1.015	1.015	30	
1462	Solar-PV Vertical (incl. bif noise barriers)	Services	GW	PJ	1,002.7	893.0	783.3	13.04	11.62	10.21	0.000	0.000	0.000	N	1.000	1.000	1.000	25	
1463	Solar-PV Bifacial vertical	Agriculture	GW	PJ	1,002.7	893.0	783.3	13.04	11.62	10.21	0.000	0.000	0.000	N	1.000	1.000	1.000	25	
1464	Solar-PV Services	Services	GW	PJ	523.0	436.7	385.5	8.60	7.65	6.70	0.000	0.000	0.000	N	1.000	1.000	1.000	25	
1465	Solar-PV large scale utilities	Electricity generation	GW	PJ	463.7	387.4	311.0	11.15	10.83	10.51	0.000	0.000	0.000	N	1.000	1.000	1.000	25	TNO datasheet
1466	CC add on to Haber-Bosch NH3 production	Fertilizer industry	Mton/yr	Mton	33.5	33.5	33.5	1.00	1.00	1.00	5.600	5.600	5.600	N	0.450	0.450	0.450	20	MIDDEN
1467	NG DF 200-400C refineries	Refinery	PJ/yr	PJ	0.5	0.5	0.5	0.01	0.01	0.01	0.025	0.025	0.025	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
1468	NG DF 200-400C - Basic Metals Ferro	Basic metal ferro	PJ/yr	PJ	0.5	0.5	0.5	0.01	0.01	0.01	0.025	0.025	0.025	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
1469	NG DF 200-400C - Chemical	Chemical industry	PJ/yr	PJ	0.5	0.5	0.5	0.01	0.01	0.01	0.025	0.025	0.025	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
1497	STEG H2	Electricity generation	GW	PJ	599.0	599.0	479.9	0.00	0.00	0.00	1.010	1.010	1.010	N	1.851	1.759	1.667	20	COMPETES model
1509	E85 flex-fuel car with high efficiency	Mobility	M vehicles	G vkm car	23,096.2	23,096.0	23,096.0	398.15	380.23	380.23	0.000	0.000	0.000	Y	1.189	1.189	1.189	10	PRIMES TREMOVE
1511	CO2 from air capture	Gas supply	Mton/yr	Mton	600.0	450.0	300.0	34.00	28.00	22.00	0.000	0.000	0.000	N	9.900	9.900	9.900	15	
1512	CO2 storage component after capture	Gas supply	Mton/yr	Mton	278.0	278.0	278.0	0.00	0.00	0.00	0.000	0.000	0.000	N	0.000	0.000	0.000	20	SDE++ 2021 Eindadvies
1561	H2 from Oil gasification with CC plus	H2 supply	PJ/yr	PJ	26.6	26.6	26.6	4.01	4.01	4.01	0.915	0.915	0.915	N	1.441	1.441	1.441	20	
1581	CHP biomass (liquid) Industry CC plus	Other industry	PJ/yr	PJ	115.4	115.4	115.4	31.49	31.49	31.49	5.327	5.327	5.327	N	1.693	1.693	1.693	15	
1582	Biomass CHP with CC - Industry	Other industry	PJ/yr	PJ	125.3	124.2	98.3	2.00	2.00	2.00	0.000	0.000	0.000	N	1.387	1.387	1.387	25	Danish Energy Agency (2021)

	UoC: unit of capacity UoA: unit of activity				Investment cost [Mln €(2015)/UoC]			Fixed O&M cost [Mln euro(2015)/UoC/yr]			Variable cost [Mln euro(2015)/UoA]				Energy input [PJ] per UoA				
Technology ID	Technology name	Sector	UoC	UoA	2030	2040	2050	2030	2040	2050	2030	2040	2050	Fulfills Service demand (yes/no)?	2030	2040	2050	Life-time [yr]	Data source
1583	Natural Gas CHP with CC - Industry	Other industry	PJ/yr	PJ	45.8	49.5	43.3	0.48	0.48	0.48	0.000	0.000	0.000	N	1.276	1.276	1.276	25	Danish Energy Agency (2021)
1584	Biomass Low Temp Boilers with CC - Industry	Other industry	PJ/yr	PJ	63.3	68.3	59.7	1.25	1.25	1.25	0.000	0.000	0.000	N	1.437	1.437	1.437	25	Danish Energy Agency (2021)
1585	Boilers LT coal Industry CC plus	Other industry	PJ/yr	PJ	41.5	41.5	41.5	1.16	1.16	1.16	0.000	0.000	0.000	N	1.410	1.410	1.410	25	Danish Energy Agency (2021)
1586	Natural Gas Low Temp Boilers with CC - Industry	Other industry	PJ/yr	PJ	24.3	26.3	23.0	0.11	0.11	0.11	0.000	0.000	0.000	N	1.205	1.205	1.205	25	Danish Energy Agency (2021)
1587	Biomass Medium Temp Boilers with CC - Industry	Other industry	PJ/yr	PJ	62.8	67.8	59.2	1.24	1.24	1.24	0.000	0.000	0.000	N	1.421	1.421	1.421	25	Danish Energy Agency (2021)
1588	Boilers HT coal industry CC plus	Other industry	PJ/yr	PJ	53.8	53.8	53.8	1.13	1.13	1.13	0.000	0.000	0.000	N	1.379	1.379	1.379	25	Danish Energy Agency (2021)
1589	Natural Gas Medium Temp Boilers with CC - Industry	Other industry	PJ/yr	PJ	23.6	25.5	22.3	0.11	0.11	0.11	0.000	0.000	0.000	N	1.166	1.166	1.166	25	Danish Energy Agency (2021)
1590	Biomass High Temp Boilers with CC - Industry	Other industry	PJ/yr	PJ	62.8	67.8	59.2	1.24	1.24	1.24	0.000	0.000	0.000	N	1.421	1.421	1.421	25	Danish Energy Agency (2021)
1591	Boilers SHT coal Industry CC plus	Other industry	PJ/yr	PJ	7.0	7.0	7.0	0.10	0.10	0.10	0.040	0.040	0.040	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
1592	NG DF 200-400C- Industry	Other industry	PJ/yr	PJ	0.5	0.5	0.4	0.01	0.01	0.01	0.025	0.025	0.025	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
1594	H2 from SMR with CC plus	H2 supply	PJ/yr	PJ	20.2	19.4	18.6	3.90	3.90	3.90	0.737	0.737	0.737	N	1.421	1.421	1.421	20	
1595	Biomass gasification BVSTEG with CC plus	Electricity generation	GW	PJ	19,515.3	18,799.8	18,084.4	0.00	0.00	0.00	21.404	21.404	21.404	N	2.678	2.678	2.678	20	
1599	Natural gas CCGT wCC	Electricity generation	GW	PJ	1,455.1	1,258.0	1,066.2	0.03	0.03	0.03	1.697	1.697	1.697	N	1.768	1.768	1.768	20	COMPETES model
1607	H2 from Biomass gasification CC plus	H2 supply	PJ/yr	PJ	141.6	141.6	141.6	14.14	14.14	14.14	1.442	1.442	1.442	N	1.543	1.543	1.543	20	
1611	Biomass CHP with CC - Basic metals	Basic metal ferro	PJ/yr	PJ	96.0	96.0	96.0	2.00	2.00	2.00	0.000	0.000	0.000	N	1.387	1.387	1.387	25	Danish Energy Agency (2021)
1612	Natural Gas CHP with CC - Basic metals	Basic metal ferro	PJ/yr	PJ	46.7	46.7	46.7	0.48	0.48	0.48	0.000	0.000	0.000	N	1.276	1.276	1.276	25	Danish Energy Agency (2021)
1613	Biomass boiler 200-400C - Basic Metals Ferro	Basic metal ferro	PJ/yr	PJ	18.7	17.9	17.0	1.14	1.10	1.07	0.306	0.306	0.306	N	1.124	1.124	1.124	25	Danish Energy Agency (2021)
1614	Biomass CHP with CC - Chemical	Chemical industry	PJ/yr	PJ	96.0	96.0	96.0	2.00	2.00	2.00	0.000	0.000	0.000	N	1.387	1.387	1.387	25	Danish Energy Agency (2021)
1615	Natural Gas CHP with CC - Chemical	Chemical industry	PJ/yr	PJ	46.7	46.7	46.7	0.48	0.48	0.48	0.000	0.000	0.000	N	1.276	1.276	1.276	25	Danish Energy Agency (2021)
1616	Biomass Medium Temp Boilers with CC - Chemical	Chemical industry	PJ/yr	PJ	63.9	63.9	63.9	1.24	1.24	1.24	0.000	0.000	0.000	N	1.421	1.421	1.421	25	Danish Energy Agency (2021)
1619	Natural Gas CHP with CC - Refineries	Refinery	PJ/yr	PJ	46.7	46.7	46.7	0.48	0.48	0.48	0.000	0.000	0.000	N	1.276	1.276	1.276	25	Danish Energy Agency (2021)
1620	Biomass Medium Temp Boilers with CC - Refineries	Refinery	PJ/yr	PJ	63.9	63.9	63.9	1.24	1.24	1.24	0.000	0.000	0.000	N	1.421	1.421	1.421	25	Danish Energy Agency (2021)
1622	Natural Gas Medium Temp Boilers with CC - Refineries	Refinery	PJ/yr	PJ	24.0	24.0	24.0	0.11	0.11	0.11	0.000	0.000	0.000	N	1.166	1.166	1.166	25	Danish Energy Agency (2021)
1623	Natural Gas Medium Temp Boilers with CC - Basic Metals	Basic metal ferro	PJ/yr	PJ	24.0	24.0	24.0	0.11	0.11	0.11	0.000	0.000	0.000	N	1.166	1.166	1.166	25	Danish Energy Agency (2021)
1624	Natural Gas Medium Temp Boilers with CC - Chemical	Chemical industry	PJ/yr	PJ	24.0	24.0	24.0	0.11	0.11	0.11	0.000	0.000	0.000	N	1.166	1.166	1.166	25	Danish Energy Agency (2021)
1626	Biomass CHP with CC - Refineries	Refinery	PJ/yr	PJ	96.0	96.0	96.0	2.00	2.00	2.00	0.000	0.000	0.000	N	1.387	1.387	1.387	25	Danish Energy Agency (2021)
1627	Hydropower	Electricity generation	GW	PJ	1,183.1	1,183.1	1,183.1	0.00	0.00	0.00	0.938	0.938	0.938	N	1.000	1.000	1.000	20	
1630	Heat savings - Basic metals ferro	Basic metal ferro	PJ/yr	PJ	138.9	138.9	138.9	0.00	0.00	0.00	0.000	0.000	0.000	N	1.000	1.000	1.000	10	Menkveld (2023)
1631	Heat savings level 1 - Other industry	Other industry	PJ/yr	PJ	18.9	18.9	18.9	0.00	0.00	0.00	0.000	0.000	0.000	N	1.000	1.000	1.000	10	Menkveld (2023)
1633	Electricity savings level 1 - Basic metals ferro	Basic metal ferro	PJ/yr	PJ	51.7	51.7	51.7	0.00	0.00	0.00	0.000	0.000	0.000	N	1.000	1.000	1.000	10	Menkveld (2023)
1648	Diesel truck with 5% fuel consumption reduction	Mobility	M vehicles	Bn vkm HDV	146,559.1	148,074.0	150,764.0	1,742.62	1,760.64	1,792.62	0.000	0.000	0.000	Y	12.609	11.028	10.372	8	PRIMES TREMOVE
1650	Hybrid bus	Mobility	M vehicles	G vkm bus	16,694.0	16,694.0	16,694.0	0.00	0.00	0.00	0.000	0.000	0.000	Y	8.728	8.728	8.728	10	PRIMES TREMOVE
1651	REF Fuel cell bus	Mobility	M vehicles	G vkm bus	111,286.0	53,807.0	38,800.0	0.00	0.00	0.00	0.000	0.000	0.000	Y	8.280	8.280	8.280	10	PRIMES TREMOVE
1652	CNG bus	Mobility	M vehicles	G vkm bus	24,192.0	24,192.0	24,192.0	0.00	0.00	0.00	0.000	0.000	0.000	Y	9.226	9.226	9.226	10	PRIMES TREMOVE
1653	REF BEV bus	Mobility	M vehicles	G vkm bus	59,333.0	31,297.0	19,013.0	0.00	0.00	0.00	0.000	0.000	0.000	Y	4.140	4.140	4.140	10	PRIMES TREMOVE

	UoC: unit of capacity UoA: unit of activity				Investment cost [Mln €(2015)/UoC]			Fixed O&M cost [Mln euro(2015)/UoC/yr]			Variable cost [Mln euro(2015)/UoA]				Energy input [PJ] per UoA				
Technology ID	Technology name	Sector	UoC	UoA	2030	2040	2050	2030	2040	2050	2030	2040	2050	Fulfills Service demand (yes/no)?	2030	2040	2050	Life-time [yr]	Data source
1654	ICE hybrid diesel van	Mobility	M vehicles	G vkm LDV	24,469.3	24,469.3	24,469.3	0.00	0.00	0.00	0.000	0.000	0.000	Y	1.246	1.246	1.246	12	PRIMES TREMOVE
1656	Gasoline hybrid car with high fuel reduction	Mobility	M vehicles	G vkm car	22,343.3	22,343.3	22,343.3	397.74	386.40	375.07	0.000	0.000	0.000	Y	0.755	0.755	0.755	10	PRIMES TREMOVE
1705	Biomass DF > 400 C Boilers - Industry	Other industry	PJ/yr	PJ	6.9	7.4	6.5	0.10	0.10	0.10	0.040	0.040	0.040	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
1721	REF MSW incineration	Waste	GW	PJ	3,670.0	3,670.0	3,670.0	65.63	65.63	65.63	0.000	0.000	0.000	Y	62.655	62.655	62.655	15	
1722	Natural Gas Industrial Heat Pump - Chemical	Chemical industry	PJ/yr	PJ	146.8	146.8	146.8	7.34	7.34	7.34	0.000	0.000	0.000	N	1.364	1.364	1.364	25	Danish Energy Agency (2021)
1723	Natural Gas Industrial Heat Pump - Basic Metals	Basic metal ferro	PJ/yr	PJ	162.6	169.1	141.8	7.34	7.34	7.34	0.000	0.000	0.000	N	1.364	1.364	1.364	25	Danish Energy Agency (2021)
1724	Geothermal Industrial Heat Pump - Industry	Other industry	PJ/yr	PJ	86.8	72.1	58.7	3.88	3.49	3.10	0.000	0.000	0.000	N	1.000	1.016	1.036	20	ECN & PBL, E-design model (2011)
1725	REF WP Services	Services	PJ/yr	PJ	48.6	40.4	25.5	1.20	0.96	0.72	0.000	0.000	0.000	N	1.000	1.000	1.000	15	TNO datasheet
1726	REF WP Residential	Residential	PJ/yr	PJ	480.5	492.5	406.0	0.00	0.00	0.00	0.000	0.000	0.000	N	0.999	1.000	1.000	15	ECN & PBL, E-design model (2011)
1741	REF Boilers natural gas gas supply	Gas supply	PJ/yr	PJ	4.0	4.0	4.0	0.38	0.38	0.38	0.000	0.000	0.000	N	1.087	1.087	1.087	15	ECN & PBL, E-design model (2011)
1742	REF CHP gas gas supply	Gas supply	GW	PJ	3,000.5	3,000.3	3,000.2	0.64	0.64	0.64	0.000	0.000	0.000	N	1.211	1.208	1.214	15	ECN & PBL, E-design model (2011)
1743	Mono manure CHP	Agriculture	GW	PJ	5,235.7	5,235.7	5,235.7	433.20	433.20	433.20	0.000	0.000	0.000	N	2.257	2.257	2.257	15	SDE++ 2023 Eindadvies
1744	REF AD of waste and sewage water - CHP	Waste	GW	PJ	1,593.2	1,593.2	1,593.2	0.00	0.00	0.00	0.000	0.000	0.000	N	1.176	1.176	1.176	15	
1745	Green gas from allesvergister (GFT)	Waste	PJ/yr	PJ	46.4	46.4	46.4	4.08	4.08	4.08	0.530	0.530	0.530	N	1.010	1.010	1.010	15	SDE++ 2021 Eindadvies
1747	Biomass CHP - Refineries	Refinery	PJ/yr	PJ	31.8	31.8	31.8	1.36	1.36	1.36	2.010e-05	2.010e-05	2.010e-05	N	1.176	1.176	1.176	25	Danish Energy Agency (2021)
1748	Biomass CHP - Basic metals	Basic metal ferro	PJ/yr	PJ	31.8	31.8	31.8	1.36	1.36	1.36	2.010e-05	2.010e-05	2.010e-05	N	1.176	1.176	1.176	25	Danish Energy Agency (2021)
1749	Biomass CHP - Chemical	Chemical industry	PJ/yr	PJ	31.8	31.8	31.8	1.36	1.36	1.36	2.010e-05	2.010e-05	2.010e-05	N	1.176	1.176	1.176	25	Danish Energy Agency (2021)
1750	Biomass CHP - Industry	Other industry	PJ/yr	PJ	31.8	31.8	31.8	1.36	1.36	1.36	2.010e-05	2.010e-05	2.010e-05	N	1.176	1.176	1.176	25	Danish Energy Agency (2021)
1754	CHP biomass (solid) Services	Services	PJ/yr	PJ	45.5	44.9	44.3	2.48	2.48	2.48	0.000	0.000	0.000	N	1.389	1.379	1.368	15	ECN & PBL, E-design model (2011)
1756	Solar -PV industry	Other industry	GW	PJ	523.0	436.7	368.0	6.96	6.83	6.70	0.000	0.000	0.000	N	1.000	1.000	1.000	15	
1757	Geothermal HP - LT Heat for FB Industry < 100C	Food and Beverage Industry	PJ/yr	PJ	57.9	57.9	57.9	0.80	0.80	0.80	0.000	0.000	0.000	N	1.000	1.000	1.000	20	Danish Energy Agency (2021)
1758	REF AD of waste and sewage water - Green gas	Waste	PJ/yr	PJ	33.0	33.0	33.0	2.38	2.38	2.38	0.000	0.000	0.000	N	1.010	1.010	1.010	15	
1760	H2 car	Mobility	M vehicles	G vkm car	38,677.7	34,173.1	29,668.6	457.69	405.78	353.88	0.000	0.000	0.000	Y	0.789	0.765	0.742	10	
1763	REF BOF steel making	Basic metal ferro	Mton steel/yr	Mton steel	527.9	527.9	527.9	33.18	33.18	33.18	9.000	9.000	9.000	Y	16.573	16.573	16.573	30	TNO datasheet
1764	Steel making TGR-BF wCC	Basic metal ferro	Mton steel/yr	Mton steel	779.9	779.9	779.9	65.03	65.03	65.03	0.000	0.000	0.000	Y	19.020	19.020	19.020	30	TNO datasheet
1765	Steelmaking DR with natural gas	Basic metal ferro	Mton steel/yr	Mton steel	737.0	737.0	737.0	22.11	22.11	22.11	0.000	0.000	0.000	Y	10.550	10.550	10.550	30	MIDDEN
1766	Steelmaking DR with ext. H2	Basic metal ferro	Mton steel/yr	Mton steel	414.0	414.0	414.0	12.42	12.42	12.42	0.000	0.000	0.000	Y	11.928	11.928	11.928	30	TNO datasheet
1767	Hisarna	Basic metal ferro	Mton steel/yr	Mton steel	356.0	332.2	308.3	60.00	50.25	40.50	0.000	0.000	0.000	Y	14.600	14.600	14.600	30	TNO datasheet
1768	Hisarna wCC	Basic metal ferro	Mton steel/yr	Mton steel	520.0	437.5	355.0	355.00	210.25	65.50	0.000	0.000	0.000	Y	18.830	18.830	18.830	30	TNO datasheet
1769	REF MWT Agriculture	Mobile machinery	PJ/yr	PJ	287.9	287.9	287.9	0.00	0.00	0.00	0.000	0.000	0.000	Y	1.000	1.000	1.000	15	
1770	REF MWT Services	Mobile machinery	PJ/yr	PJ	287.9	287.9	287.9	0.00	0.00	0.00	0.000	0.000	0.000	Y	1.000	1.000	1.000	15	
1771	REF MWT Industry	Mobile machinery	PJ/yr	PJ	287.9	287.9	287.9	0.00	0.00	0.00	0.000	0.000	0.000	Y	1.000	1.000	1.000	15	
1772	Hybride MWT Agriculture	Mobile machinery	PJ/yr	PJ	619.2	619.2	619.2	0.00	0.00	0.00	0.000	0.000	0.000	Y	0.825	0.825	0.825	15	
1773	Hybride MWT Services	Mobile machinery	PJ/yr	PJ	619.2	619.2	619.2	0.00	0.00	0.00	0.000	0.000	0.000	Y	0.900	0.893	0.887	15	
1774	Electric MWT Services	Mobile machinery	PJ/yr	PJ	619.2	619.2	619.2	0.00	0.00	0.00	0.000	0.000	0.000	Y	0.438	0.438	0.438	12	

	UoC: unit of capacity UoA: unit of activity				Investment cost [Mln €(2015)/UoC]			Fixed O&M cost [Mln euro(2015)/UoC/yr]			Variable cost [Mln euro(2015)/UoA]				Energy input [PJ] per UoA				
Technology ID	Technology name	Sector	UoC	UoA	2030	2040	2050	2030	2040	2050	2030	2040	2050	Fulfills Service demand (yes/no)?	2030	2040	2050	Life-time [yr]	Data source
1775	REF wood stove residential	Residential	PJ/yr	PJ	22.5	22.5	22.5	0.80	0.80	0.80	0.000	0.000	0.000	N	1.604	1.604	1.604	15	Biomass Futures project (2012)
1776	REF AD boiler - Other Industry	Other industry	PJ/yr	PJ	26.1	26.1	26.1	1.30	1.30	1.30	0.000	0.000	0.000	N	1.000	1.000	1.000	15	SDE++ 2021 Eindadvies
1780	REF rest non energetic and other conversions	Chemical industry	PJ/yr	PJ	0.0	0.0	0.0	0.00	0.00	0.00	0.000	0.000	0.000	Y	177.710	278.62	215.833	25	
1781	Hybride MWT Industry	Mobile machinery	PJ/yr	PJ	619.2	619.2	619.2	0.00	0.00	0.00	0.000	0.000	0.000	Y	0.825	0.825	0.825	15	
1782	Electric MWT Industry	Mobile machinery	PJ/yr	PJ	619.2	619.2	619.2	0.00	0.00	0.00	0.000	0.000	0.000	Y	0.400	0.400	0.400	15	
1783	ULCOWIN	Basic metal ferro	Mton steel/yr	Mton steel	0.0	768.0	640.0	0.00	54.00	45.00	0.000	0.000	0.000	Y	14.010	14.010	14.010	30	TNO datasheet
1784	ULCOLYSIS	Basic metal ferro	Mton steel/yr	Mton steel	0.0	858.0	715.0	0.00	69.60	58.00	0.000	0.000	0.000	Y	14.540	14.540	14.540	30	TNO datasheet
1795	Electric Medium Temp Boilers	Other industry	PJ/yr	PJ	2.2	2.2	2.2	0.03	0.03	0.03	0.025	0.025	0.025	N	1.010	1.010	1.010	25	Danish Energy Agency (2021)
1798	MSW incineration CC	Waste	GW	PJ	5,176.3	5,176.3	5,176.3	65.67	65.67	65.67	0.000	0.000	0.000	Y	62.655	62.655	62.655	25	
1799	Post-Combustion CC in Refineries	Refinery	Mton/yr	Mton	270.0	270.0	270.0	12.09	12.09	12.09	4.960	4.960	4.960	N	4.290	4.290	4.290	20	TNO datasheet
1800	CO2-afvang chemical add-on	Chemical industry	Mton/yr	Mton	266.5	266.5	266.5	8.00	8.00	8.00	0.000	0.000	0.000	N	5,766	5,766	5,766	20	SDE++ 2023 Eindadvies
1801	CO2-afvang basic metal add-on	Basic metal ferro	Mton/yr	Mton	266.5	266.5	266.5	8.00	8.00	8.00	0.000	0.000	0.000	N	5,766	5,766	5,766	20	SDE++ 2023 Eindadvies
1818	Hybride WP boiler (boilerdeel, existing buildings)	Residential	PJ/yr	PJ	23.6	19.9	16.2	0.86	0.86	0.86	0.000	0.000	0.000	N	1.087	1.087	1.087	15	TNO datasheet
1819	Hybride WP boiler (WP-deel, existing buildings)	Residential	PJ/yr	PJ	0.0	0.0	0.0	0.00	0.00	0.00	0.000	0.000	0.000	N	0.974	0.974	0.974	15	TNO datasheet
1834	CNG van	Mobility	M vehicles	G vkm LDV	19,508.8	19,508.8	19,508.8	331.65	331.65	331.65	0.000	0.000	0.000	Y	2.700	2.700	2.700	12	PRIMES TREMOVE
1835	H2 van	Mobility	M vehicles	G vkm LDV	36,490.7	32,068.6	27,646.5	713.47	627.01	540.55	0.000	0.000	0.000	Y	1.200	1.200	1.200	12	PRIMES TREMOVE
1836	BEV van	Mobility	M vehicles	G vkm LDV	25,220.7	23,803.7	22,386.7	261.73	247.02	232.32	0.000	0.000	0.000	Y	0.612	0.612	0.612	12	PRIMES TREMOVE
1837	PI van	Mobility	M vehicles	G vkm LDV	23,821.5	23,351.7	22,881.9	365.64	358.43	351.22	0.000	0.000	0.000	Y	0.894	0.894	0.894	12	PRIMES TREMOVE
1838	LNG inland navigation freight	Mobility	1000 vessels	G tkm	3,537.5	3,537.5	3,537.5	0.00	0.00	0.00	0.000	0.000	0.000	Y	0.117	0.106	0.096	30	PRIMES TREMOVE
1841	REF ICE van	Mobility	M vehicles	G vkm LDV	21,231.4	21,231.4	21,231.4	636.94	636.94	636.94	0.000	0.000	0.000	Y	2.938	3.128	4.031	12	PRIMES TREMOVE
1852	REF Nuclear power plant	Electricity generation	GW	PJ	7,104.1	7,104.1	7,104.1	157.76	157.76	157.76	0.000	0.000	0.000	N	2.864	2.857	2.857	50	
1853	Nuclear energy Gen IV - Electricity production	Electricity generation	GW	PJ	6,318.0	6,318.0	6,318.0	77.00	77.00	77.00	2.470	2.470	2.470	N	2.941	2.941	2.941	60	Scheepers (2021)
1855	SNG from lignocellulosics	Gas supply	PJ/yr	PJ	87.0	78.5	70.0	5.00	4.50	4.00	3.000	3.000	3.000	N	1.531	1.531	1.531	35	SDE++ 2021 Eindadvies
1859	SNG from lignocellulosics with CC	Gas supply	PJ/yr	PJ	90.0	81.0	72.0	5.00	4.50	4.00	4.000	3.500	3.000	N	1.554	1.554	1.554	35	SDE++ 2021 Eindadvies
1860	Bio-DME production	Refinery	PJ/yr	PJ	68.0	61.0	54.0	4.00	3.50	3.00	3.000	2.500	2.000	N	1.522	1.522	1.522	35	
1862	Biomass gasification + FT towards diesel	Refinery	PJ/yr	PJ	77.0	69.5	62.0	5.00	4.50	4.00	3.000	3.000	3.000	N	1.580	1.580	1.580	35	SDE++ 2022 Eindadvies
1864	Biobenzine from biomass	Refinery	PJ/yr	PJ	97.8	97.8	97.8	3.91	3.91	3.91	0.000	0.000	0.000	N	1.602	1.602	1.602	35	Hannula (2013)
1879	Biobenzine from biomass LP	Refinery	PJ/yr	PJ	96.6	96.6	96.6	3.86	3.86	3.86	0.000	0.000	0.000	N	1.221	1.221	1.221	35	Hannula (2013)
1881	H2 from SMR CC from shifted syngas low	H2 supply	PJ/yr	PJ	27.8	25.2	22.7	0.85	0.77	0.69	0.000	0.000	0.000	N	1.354	1.354	1.354	25	
1882	H2 from SMR CC from shifted syngas high	H2 supply	PJ/yr	PJ	31.4	28.6	25.7	1.00	0.91	0.82	0.000	0.000	0.000	N	1.429	1.429	1.429	25	

	UoC: unit of capacity UoA: unit of activity				Investment cost [Mln €(2015)/UoC]			Fixed O&M cost [Mln euro(2015)/UoC/yr]			Variable cost [Mln euro(2015)/UoA]				Energy input [PJ] per UoA				
Technology ID	Technology name	Sector	UoC	UoA	2030	2040	2050	2030	2040	2050	2030	2040	2050	Fulfills Service demand (yes/no)?	2030	2040	2050	Life-time [yr]	Data source
1883	H2 from SMR CC from PSA tail gas low	H2 supply	PJ/yr	PJ	32.0	28.8	25.6	1.06	1.06	1.06	0.000	0.000	0.000	N	1.375	1.375	1.375	25	
1884	H2 from SMR CC from PSA tail gas high	H2 supply	PJ/yr	PJ	34.2	30.8	27.3	1.09	1.09	1.09	0.000	0.000	0.000	N	1.313	1.313	1.313	25	
1885	H2 from SMR CC from flue gas	H2 supply	PJ/yr	PJ	46.1	41.5	36.9	1.34	1.34	1.34	0.000	0.000	0.000	N	1.445	1.445	1.445	25	
1888	H2 from Biomass gasification Fast Internally Circulating Fluidized Bed' (FICFB) gasifier centraal	H2 supply	PJ/yr	PJ	120.7	120.7	120.7	5.96	5.96	5.96	0.000	0.000	0.000	N	1.668	1.668	1.668	20	
1891	H2 from thermochemical water splitting centraal	H2 supply	PJ/yr	PJ	363.6	327.3	290.9	25.95	23.35	20.76	0.000	0.000	0.000	N	3.472	3.472	3.472	20	
1892	H2 from photocatalysis PEC centraal	H2 supply	PJ/yr	PJ	218.4	196.5	174.7	21.02	18.91	16.81	0.000	0.000	0.000	N	12.216	12.216	12.216	20	
1893	H2 from supercritical waterelktrolysis of biomass lokaal	H2 supply	PJ/yr	PJ	199.2	179.3	159.4	79.70	71.73	63.76	0.000	0.000	0.000	N	2.722	2.722	2.722	20	
1939	P2L FT pathway, external H2, incl direct air capture	Refinery	PJ/yr	PJ	65.0	51.0	37.0	3.00	2.00	1.00	0.000	0.000	0.000	N	2.094	2.055	1.925	20	
1940	P2L FT pathway, external H2, external CO2	Refinery	PJ/yr	PJ	15.0	13.5	12.0	1.00	0.00	0.00	0.000	0.000	0.000	N	1.508	1.495	1.391	20	
1956	P2L FT pathway, low temp electrolysis, direct air capture	Refinery	PJ/yr	PJ	115.0	84.5	54.0	5.00	3.50	2.00	0.000	0.000	0.000	N	2.717	2.570	2.545	20	
1957	P2L FT pathway, low temp electrolysis, external CO2	Refinery	PJ/yr	PJ	65.0	47.0	29.0	3.00	2.00	1.00	0.000	0.000	0.000	N	2.131	2.011	1.817	20	
1960	P2L FT pathway, high temp electrolysis, direct air capture	Refinery	PJ/yr	PJ	97.2	91.1	64.6	4.86	4.56	3.23	0.000	0.000	0.000	N	2.371	2.301	2.226	20	
1961	P2L FT pathway, high temp electrolysis, external CO2	Refinery	PJ/yr	PJ	67.3	61.3	32.3	3.37	3.06	1.62	0.000	0.000	0.000	N	1.785	1.741	1.691	20	
1996	Marine fuel vessel	Bunkers	PJ/yr	PJ	50.0	50.0	50.0	0.00	0.00	0.00	0.000	0.000	0.000	Y	1.000	1.000	1.000	20	
2005	Pyrolysis fuel production	Refinery	PJ/yr	PJ	39.6	34.2	28.8	4.17	3.60	3.03	0.000	0.000	0.000	N	2.110	2.110	2.110	20	Sierk de Jong (2017)
2006	Alcohol-to-jet	Refinery	PJ/yr	PJ	8.9	7.0	5.1	1.14	0.90	0.66	0.000	0.000	0.000	N	1.209	1.209	1.209	20	Sierk de Jong (2017)
2007	HEFA	Refinery	PJ/yr	PJ	11.3	11.3	11.3	1.81	1.81	1.81	0.000	0.000	0.000	N	1.139	1.139	1.138	20	S. de Jong (2017)
2010	Natural Gas Direct Firing HT400 - Ferro	Basic metal ferro	PJ/yr	PJ	0.5	0.5	0.5	0.01	0.01	0.01	0.025	0.025	0.025	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
2011	Electric Direct Firing HT400 - Ferro	Basic metal ferro	PJ/yr	PJ	1.9	1.9	1.9	0.00	0.00	0.00	0.000	0.000	0.000	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
2012	Hydrogen DF > 400 C - Basic Metals Ferro	Basic metal ferro	PJ/yr	PJ	1.5	1.5	1.5	0.05	0.05	0.05	0.000	0.000	0.000	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
2013	Biomass DF 200-400C - Basic Metals Ferro	Basic metal ferro	PJ/yr	PJ	7.0	7.0	7.0	0.10	0.10	0.10	0.040	0.040	0.040	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
2014	Biomass DF > 400C - Basic Metals	Basic metal ferro	PJ/yr	PJ	7.0	7.0	7.0	0.10	0.10	0.10	0.040	0.040	0.040	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
2015	Electric High Temp Boilers - Basic Metals	Basic metal ferro	PJ/yr	PJ	2.2	2.2	2.2	0.03	0.03	0.03	0.025	0.025	0.025	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
2016	Electric Medium Temp Boilers - Basic Metals	Basic metal ferro	PJ/yr	PJ	2.2	2.2	2.2	0.03	0.03	0.03	0.025	0.025	0.025	N	1.010	1.010	1.010	25	Danish Energy Agency (2021)
2020	Electrification of Steam Crackers	Chemical industry	Mton olefins/yr	Mton olefins	422.9	422.9	422.9	30.07	30.07	30.07	0.000	0.000	0.000	Y	85.832	85.832	85.832	20	
2023	Waste Gas CHP - Chemical	Chemical industry	PJ/yr	PJ	11.6	11.6	11.6	0.40	0.40	0.40	0.000	0.000	0.000	N	1.176	1.176	1.176	25	Danish Energy Agency (2021)
2024	Waste Gas CHP with CC - Chemical	Chemical industry	PJ/yr	PJ	52.9	52.9	52.9	0.48	0.48	0.48	0.000	0.000	0.000	N	1.294	1.294	1.294	25	Danish Energy Agency (2021)
2025	Natural Gas DF > 400 C - Chemical	Chemical industry	PJ/yr	PJ	0.5	0.5	0.5	0.01	0.01	0.01	0.025	0.025	0.025	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
2026	NG DF 100-200C- chemical	Chemical industry	PJ/yr	PJ	0.5	0.5	0.5	0.01	0.01	0.01	0.025	0.025	0.025	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
2027	Hydrogen High Temp Boilers - Chemical	Chemical industry	PJ/yr	PJ	4.4	4.4	4.4	0.56	0.56	0.56	0.000	0.000	0.000	N	1.110	1.110	1.110	25	Danish Energy Agency (2021)
2028	Biomass DF > 400 C - Chemical	Chemical industry	PJ/yr	PJ	7.0	7.0	7.0	0.10	0.10	0.10	0.040	0.040	0.040	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
2029	Biomass DF > 400C - Chemical	Chemical industry	PJ/yr	PJ	7.0	7.0	7.0	0.10	0.10	0.10	0.040	0.040	0.040	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
2030	Waste Gas High Temp Boilers - Chemical	Chemical industry	PJ/yr	PJ	1.4	1.4	1.4	0.06	0.06	0.05	0.139	0.125	0.111	N	1.111	1.111	1.111	25	Danish Energy Agency (2021)
2031	Waste Gas Medium Temp Boilers - Chemical	Chemical industry	PJ/yr	PJ	1.4	1.4	1.4	0.06	0.06	0.05	0.139	0.125	0.111	N	1.111	1.111	1.111	25	Danish Energy Agency (2021)
2032	Waste Gas High Temp Boilers with CC - Chemical	Chemical industry	PJ/yr	PJ	28.9	28.9	28.9	0.11	0.11	0.11	0.000	0.000	0.000	N	1.184	1.184	1.184	25	Danish Energy Agency (2021)

	UoC: unit of capacity UoA: unit of activity				Investment cost [Mln €(2015)/UoC]			Fixed O&M cost [Mln euro(2015)/UoC/yr]			Variable cost [Mln euro(2015)/UoA]				Energy input [PJ] per UoA				
Technology ID	Technology name	Sector	UoC	UoA	2030	2040	2050	2030	2040	2050	2030	2040	2050	Fulfills Service demand (yes/no)?	2030	2040	2050	Life-time [yr]	Data source
2033	Waste Gas Medium Temp Boilers with CC - Chemical	Chemical industry	PJ/yr	PJ	28.1	28.1	28.1	0.11	0.11	0.11	0.000	0.000	0.000	N	1.219	1.219	1.219	25	Danish Energy Agency (2021)
2034	Electric High Temp Boilers - Chemical	Chemical industry	PJ/yr	PJ	2.2	2.2	2.2	0.03	0.03	0.03	0.025	0.025	0.025	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
2035	Electric Medium Temp Boilers - Chemical	Chemical industry	PJ/yr	PJ	2.2	2.2	2.2	0.03	0.03	0.03	0.025	0.025	0.025	N	1.010	1.010	1.010	25	Danish Energy Agency (2021)
2036	Electric Industrial Heat Pump - Chemical	Chemical industry	PJ/yr	PJ	22.3	20.1	17.8	0.89	0.80	0.71	0.000	0.000	0.000	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
2037	Mechanical Vapour Recompression - Chemical	Chemical industry	PJ/yr	PJ	40.2	36.2	32.1	0.03	0.01	1.14e-03	0.000	0.000	0.000	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
2040	Natural Gas CHP - Fertilizers	Fertilizer industry	PJ/yr	PJ	11.6	11.6	11.6	0.40	0.40	0.40	0.000	0.000	0.000	N	1.176	1.176	1.176	25	Danish Energy Agency (2021)
2041	Natural Gas CHP with CC - Fertilizers	Fertilizer industry	PJ/yr	PJ	46.7	46.7	46.7	0.48	0.48	0.48	0.000	0.000	0.000	N	1.276	1.276	1.276	25	Danish Energy Agency (2021)
2042	Biomass CHP - Fertilizers	Fertilizer industry	PJ/yr	PJ	31.8	31.8	31.8	1.36	1.36	1.36	2.010e-05	2.010e-05	2.010e-05	N	1.176	1.176	1.176	25	Danish Energy Agency (2021)
2043	Biomass CHP with CC - Fertilizers	Fertilizer industry	PJ/yr	PJ	96.0	96.0	96.0	2.00	2.00	2.00	0.000	0.000	0.000	N	1.387	1.387	1.387	25	Danish Energy Agency (2021)
2044	REF NG Steam 200-400 boiler - Fertilizer	Fertilizer industry	PJ/yr	PJ	3.7	3.7	3.7	0.35	0.35	0.35	0.000	0.000	0.000	N	1.111	1.111	1.111	15	
2045	REF NG Steam 100-200 boiler - Fertilizer	Fertilizer industry	PJ/yr	PJ	3.7	3.7	3.7	0.35	0.35	0.35	0.000	0.000	0.000	N	1.111	1.111	1.111	15	
2046	Natural Gas High Temp Boilers with CC - Fertilizers	Fertilizer industry	PJ/yr	PJ	24.0	24.0	24.0	0.11	0.11	0.11	0.000	0.000	0.000	N	1.166	1.166	1.166	25	Danish Energy Agency (2021)
2047	Natural Gas Medium Temp Boilers with CC - Fertilizers	Fertilizer industry	PJ/yr	PJ	24.8	24.8	24.8	0.11	0.11	0.11	0.000	0.000	0.000	N	1.205	1.205	1.205	25	Danish Energy Agency (2021)
2048	Hydrogen High Temp Boilers - Fertilizers	Fertilizer industry	PJ/yr	PJ	4.4	4.4	4.4	0.56	0.56	0.56	0.000	0.000	0.000	N	1.110	1.110	1.110	25	Danish Energy Agency (2021)
2049	Hydrogen Medium Temp Boilers - Fertilizers	Fertilizer industry	PJ/yr	PJ	4.4	4.4	4.4	0.56	0.56	0.56	0.000	0.000	0.000	N	1.110	1.110	1.110	25	Danish Energy Agency (2021)
2050	Biomass High Temp Boilers - Fertilizers	Fertilizer industry	PJ/yr	PJ	18.7	17.9	17.0	1.14	1.10	1.07	0.306	0.306	0.306	N	1.124	1.124	1.124	25	Danish Energy Agency (2021)
2051	Biomass Medium Temp Boilers - Fertilizers	Fertilizer industry	PJ/yr	PJ	18.7	17.9	17.0	1.14	1.10	1.07	0.306	0.306	0.306	N	1.124	1.124	1.124	25	Danish Energy Agency (2021)
2052	Biomass High Temp Boilers with CC - Fertilizers	Fertilizer industry	PJ/yr	PJ	63.9	63.9	63.9	1.24	1.24	1.24	0.000	0.000	0.000	N	1.421	1.421	1.421	25	Danish Energy Agency (2021)
2053	Biomass Medium Temp Boilers with CC - Fertilizers	Fertilizer industry	PJ/yr	PJ	64.4	64.4	64.4	1.25	1.25	1.25	0.000	0.000	0.000	N	1.437	1.437	1.437	25	Danish Energy Agency (2021)
2054	Electric High Temp Boilers - Fertilizers	Fertilizer industry	PJ/yr	PJ	2.2	2.2	2.2	0.03	0.03	0.03	0.025	0.025	0.025	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
2055	Electric Medium Temp Boilers - Fertilizers	Fertilizer industry	PJ/yr	PJ	2.2	2.2	2.2	0.03	0.03	0.03	0.025	0.025	0.025	N	1.010	1.010	1.010	25	Danish Energy Agency (2021)
2056	Natural Gas Industrial Heat Pump - Fertilizers	Fertilizer industry	PJ/yr	PJ	146.8	146.8	146.8	7.34	7.34	7.34	0.000	0.000	0.000	N	1.364	1.364	1.364	25	Danish Energy Agency (2021)
2057	Electric Industrial Heat Pump - Fertilizers	Fertilizer industry	PJ/yr	PJ	22.3	20.1	17.8	0.89	0.80	0.71	0.000	0.000	0.000	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
2058	Mechanical Vapour Recompression - Fertilizers	Fertilizer industry	PJ/yr	PJ	40.2	36.2	32.1	0.03	0.01	1.14e-03	0.000	0.000	0.000	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
2059	Hydrogen DF > 400 C - Industry	Other industry	PJ/yr	PJ	1.5	1.5	1.5	0.05	0.05	0.05	0.000	0.000	0.000	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
2060	Hydrogen Low Temp Boilers - Industry	Other industry	PJ/yr	PJ	4.4	4.4	4.4	0.56	0.56	0.56	0.000	0.000	0.000	N	1.110	1.110	1.110	25	Danish Energy Agency (2021)
2061	Electric High Temp Boilers - Industry	Other industry	PJ/yr	PJ	2.2	2.2	2.2	0.03	0.03	0.03	0.025	0.025	0.025	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
2062	Mechanical Vapour Recompression - Industry	Other industry	PJ/yr	PJ	40.2	36.2	32.1	0.03	0.01	1.14e-03	0.000	0.000	0.000	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
2067	NG DF 200-400C - Industry	Other industry	PJ/yr	PJ	0.5	0.5	0.5	0.01	0.01	0.01	0.025	0.025	0.025	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
2072	Biomass DF > 400C - Industry	Other industry	PJ/yr	PJ	7.0	7.0	7.0	0.10	0.10	0.10	0.040	0.040	0.040	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
2081	Naphtha from pyrolysis biooil gasification and FT process	Refinery	PJ/yr	PJ	79.0	79.0	79.0	3.16	3.16	3.16	0.000	0.000	0.000	N	1.751	1.751	1.751	15	
2086	10% Co-processing in Conventional Refinery	Refinery	PJ/yr	PJ	5.5	5.5	5.5	0.21	0.21	0.21	0.000	0.000	0.000	N	1.076	1.078	1.079	25	
2089	Fast Pirolysis with upgrading	Refinery	PJ/yr	PJ	11.0	10.7	10.4	0.58	0.56	0.54	0.000	0.000	0.000	N	1.993	1.993	1.993	15	
2090	Electrification of Refineries	Refinery	PJ/yr	PJ	5.7	5.7	5.7	0.11	0.11	0.11	0.000	0.000	0.000	N	0.882	0.882	0.882	15	
2091	Natural Gas DF > 400 C- Refineries	Refinery	PJ/yr	PJ	0.5	0.5	0.5	0.01	0.01	0.01	0.025	0.025	0.025	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
2092	NG DF 200-400C - Refineries	Refinery	PJ/yr	PJ	0.5	0.5	0.5	0.01	0.01	0.01	0.025	0.025	0.025	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
2093	Hydrogen DF > 400 C - Refineries	Refinery	PJ/yr	PJ	1.5	1.5	1.5	0.05	0.05	0.05	0.000	0.000	0.000	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
2094	Biomass DF > 400 C - Refineries	Refinery	PJ/yr	PJ	7.0	7.0	7.0	0.10	0.10	0.10	0.040	0.040	0.040	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
2095	Biomass DF > 400C - Refineries	Refinery	PJ/yr	PJ	7.0	7.0	7.0	0.10	0.10	0.10	0.040	0.040	0.040	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
2097	Electric Medium Temp Boilers - Refinery	Refinery	PJ/yr	PJ	2.2	2.2	2.2	0.03	0.03	0.03	0.025	0.025	0.025	N	1.010	1.010	1.010	25	Danish Energy Agency (2021)

	UoC: unit of capacity UoA: unit of activity				Investment cost [Mln €(2015)/UoC]			Fixed O&M cost [Mln euro(2015)/UoC/yr]			Variable cost [Mln euro(2015)/UoA]				Energy input [PJ] per UoA				
Technology ID	Technology name	Sector	UoC	UoA	2030	2040	2050	2030	2040	2050	2030	2040	2050	Fulfills Service demand (yes/no)?	2030	2040	2050	Life-time [yr]	Data source
2100	Mechanical Vapour Recompression - Refinery	Refinery	PJ/yr	PJ	40.2	36.2	32.1	0.03	0.01	1.14e-03	0.000	0.000	0.000	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
2104	Electric High Temp Boilers - Refinery	Refinery	PJ/yr	PJ	2.2	2.2	2.2	0.03	0.03	0.03	0.025	0.025	0.025	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
2114	Aquathermal	Central heat supply	PJ/yr	PJ	199.1	177.8	156.5	3.98	3.56	3.13	0.000	0.000	0.000	N	1.325	1.325	1.325	30	TNO datasheet
2115	Solar thermal for district heating without storage (all sectors)	Central heat supply	PJ/yr	PJ	23.8	21.4	19.0	0.31	0.28	0.25	0.000	0.000	0.000	N	1.024	1.024	1.024	25	TNO datasheet
2117	Solar PV floating > 1 MWp	Electricity generation	GW	PJ	579.7	484.2	388.8	13.90	13.58	13.26	0.000	0.000	0.000	N	1.000	1.000	1.000	25	TNO datasheet
2118	SOEC small-scale	H2 supply	GW	PJ	2,110.0	1,825.0	1,540.0	10.00	10.00	10.00	0.000	0.000	0.000	N	1.130	1.130	1.130	20	TNO datasheet
2119	H2 Alkaline small-scale	H2 supply	GW	PJ	1,380.0	1,320.0	1,260.0	110.00	100.00	90.00	0.000	0.000	0.000	N	1.500	1.485	1.470	30	TNO datasheet
2120	H2 Large-scale electrolyser	H2 supply	GW	PJ	700.0	700.0	700.0	20.00	15.00	10.00	0.000	0.000	0.000	N	1.500	1.485	1.470	30	TNO datasheet
2121	REF AD of waste and sewage water - Heat	Waste	PJ/yr	PJ	25.0	24.7	24.3	0.69	0.69	0.69	0.000	0.000	0.000	N	1.176	1.176	1.176	15	TNO datasheet
2122	Geothermal heat production, ultradeep, baseload	Other industry	PJ/yr	PJ	67.2	60.5	53.7	3.88	3.49	3.10	0.000	0.000	0.000	N	1.030	1.030	1.030	25	Danish Energy Agency (2021)
2124	Solar thermal for process hot water without storage	Other industry	PJ/yr	PJ	31.7	28.6	25.4	0.15	0.14	0.12	0.000	0.000	0.000	N	1.024	1.024	1.024	25	TNO datasheet
2125	Biomass boiler for built environment > 5MWth	Central heat supply	PJ/yr	PJ	17.3	17.3	17.3	0.91	0.91	0.91	0.000	0.000	0.000	N	1.111	1.111	1.111	15	TNO datasheet
2126	Air source heat pumps - households	Residential	PJ/yr	PJ	43.3	35.1	27.0	0.67	0.53	0.40	0.000	0.000	0.000	N	1.000	1.000	1.000	20	TNO datasheet
2127	Rooftop PV agriculture	Agriculture	GW	PJ	520.0	435.0	350.0	12.57	12.21	11.85	0.000	0.000	0.000	N	1.000	1.000	1.000	15	
2128	H2 PEM small-scale	H2 supply	GW	PJ	1,430.0	1,345.0	1,260.0	80.00	70.00	60.00	0.000	0.000	0.000	N	1.530	1.475	1.420	25	TNO datasheet
2132	Heat savings level 2 - Other industry	Other industry	PJ/yr	PJ	61.7	61.7	61.7	0.00	0.00	0.00	0.000	0.000	0.000	N	1.000	1.000	1.000	10	Menkveld (2023)
2133	Electricity savings level 2 - Other industry	Other industry	PJ/yr	PJ	61.7	61.7	61.7	0.00	0.00	0.00	0.000	0.000	0.000	N	1.000	1.000	1.000	10	Menkveld (2023)
2143	Pyrolysis Oil Production from biomass	Refinery	PJ/yr	PJ	74.8	72.1	69.4	4.11	3.97	3.82	0.000	0.000	0.000	N	1.133	1.133	1.133	20	
2145	Electric truck with 600 km range	Mobility	M vehicles	Bn vkm	385,486.2	271,198.5	239,875.2	2,695.69	1,896.48	1,677.44	0.000	0.000	0.000	Y	5.896	5.873	5.851	8	PRIMES TREMOVE
2146	SMR with cryogenic membrane PSA CC	H2 supply	GW	PJ	951.1	864.7	778.2	29.77	27.06	24.36	0.000	0.000	0.000	N	1.372	1.372	1.372	20	
2148	Mono manure AD for heat	Agriculture	GW	PJ	800.0	788.9	777.8	22.22	22.22	22.22	0.000	0.000	0.000	N	1.110	1.110	1.110	15	SDE++ 2019 Eindadvies
2149	H2 Boilers - Households	Residential	PJ/yr	PJ	2.4	2.3	2.2	0.12	0.11	0.11	0.000	0.000	0.000	N	1.031	1.031	1.031	15	Vesta model PBL
2150	H2 Low Temp Boilers - Services	Services	PJ/yr	PJ	2.7	2.6	2.5	0.13	0.12	0.12	0.000	0.000	0.000	N	0.990	0.990	0.990	25	Danish Energy Agency (2021)
2162	Geothermal diep district heating	Central heat supply	GW	PJ	1,523.0	1,370.7	1,218.4	105.00	99.50	94.00	0.001	0.001	0.001	N	1.000	1.000	1.000	25	SDE++ 2021 Eindadvies
2163	Geothermal shallow district heating	Central heat supply	GW	PJ	1,259.0	1,133.1	1,007.2	125.00	112.50	100.00	0.001	0.001	0.001	N	1.000	1.000	1.000	25	
2165	H-B NH3 with external H2	Fertilizer industry	Mton	Mton	302.8	302.8	302.8	10.00	10.00	10.00	0.000	0.000	0.000	Y	29.160	29.160	29.160	20	
2166	Electrolyse H-B NH3	Fertilizer industry	Mton	Mton	979.0	881.1	783.2	22.88	22.88	22.88	0.000	0.000	0.000	Y	38.757	38.757	38.757	20	
2169	HVO from UCO	Refinery	PJ/yr	PJ	11.3	11.3	11.3	1.81	1.81	1.81	0.000	0.000	0.000	N	1.065	1.065	1.065	20	S. de Jong (2015)
2170	Terraced houses - startlabel B or DC retrofitted to B	Residential	M terraced houses	M terraced houses	16,290.0	16,290.0	16,290.0	0.00	0.00	0.00	0.000	0.000	0.000	Y	33.688	33.688	33.688	25	TNO datasheet
2171	Terraced houses - startlabel A+	Residential	M terraced houses	M terraced houses	0.0	0.0	0.0	0.00	0.00	0.00	0.000	0.000	0.000	Y	8.860	8.860	8.860	25	TNO datasheet
2172	Apartments - startlabel B or DC retrofitted to B	Residential	M apartments	M apartmen ts	10,763.4	10,763.4	10,763.4	0.00	0.00	0.00	0.000	0.000	0.000	Y	0.000	0.000	0.000	25	TNO datasheet
2173	Other dwelllings - startlabel B or DC retrofitted to B	Residential	M other dwellings	M other dwellings	18,891.1	18,891.1	18,891.1	0.00	0.00	0.00	0.000	0.000	0.000	Y	0.000	0.000	0.000	25	TNO datasheet
2174	Terraced houses - startlabel GFE	Residential	M terraced houses	M terraced houses	0.0	0.0	0.0	0.00	0.00	0.00	0.000	0.000	0.000	Y	0.000	0.000	0.000	5	TNO datasheet
2175	Terraced houses - startlabel DC	Residential	M terraced houses	M terraced houses	0.0	0.0	0.0	0.00	0.00	0.00	0.000	0.000	0.000	Y	0.000	0.000	0.000	5	TNO datasheet
2176	Terraced houses - startlabel A	Residential	M terraced houses	M terraced houses	0.0	0.0	0.0	0.00	0.00	0.00	0.000	0.000	0.000	Y	0.000	0.000	0.000	5	TNO datasheet

UoC: unit of capacity UoA: unit of activity					Investment cost [Mln €(2015)/UoC]			Fixed O&M cost [Mln euro(2015)/UoC/yr]			Variable cost [Mln euro(2015)/UoA]				Energy input [PJ] per UoA				
Technology ID	Technology name	Sector	UoC	UoA	2030	2040	2050	2030	2040	2050	2030	2040	2050	Fulfills Service demand (yes/no)?	2030	2040	2050	Life-time [yr]	Data source
2177	Apartments - startlabel GFE	Residential	M apartments	M apartments	0.0	0.0	0.0	0.00	0.00	0.00	0.000	0.000	0.000	Y	0.000	0.000	0.000	5	TNO datasheet
2178	Apartments - startlabel DC	Residential	M apartments	M apartments	0.0	0.0	0.0	0.00	0.00	0.00	0.000	0.000	0.000	Y	0.000	0.000	0.000	5	TNO datasheet
2179	Apartments - startlabel DC/B retrofitted to A	Residential	M apartments	M apartments	22,727.9	22,727.9	22,727.9	0.00	0.00	0.00	0.000	0.000	0.000	Y	0.000	0.000	0.000	25	TNO datasheet
2180	Apartments - startlabel A/A+	Residential	M apartments	M apartments	0.0	0.0	0.0	0.00	0.00	0.00	0.000	0.000	0.000	Y	0.000	0.000	0.000	25	TNO datasheet
2181	Other dwellings - startlabel GFE	Residential	M other dwellings	M other dwellings	0.0	0.0	0.0	0.00	0.00	0.00	0.000	0.000	0.000	Y	0.000	0.000	0.000	5	TNO datasheet
2182	Other dwelllings - startlabel DC	Residential	M other dwellings	M other dwellings	0.0	0.0	0.0	0.00	0.00	0.00	0.000	0.000	0.000	Y	0.000	0.000	0.000	5	TNO datasheet
2183	Other dwelllings - startlabel A	Residential	M other dwellings	M other dwellings	0.0	0.0	0.0	0.00	0.00	0.00	0.000	0.000	0.000	Y	0.000	0.000	0.000	5	TNO datasheet
2184	Other dwelllings - startlabel A+	Residential	M other dwellings	M other dwellings	0.0	0.0	0.0	0.00	0.00	0.00	0.000	0.000	0.000	Y	0.000	0.000	0.000	25	TNO datasheet
2185	Offices - B label	Services	km2 GFA	km2 GFA	115.0	115.0	115.0	0.00	0.00	0.00	0.000	0.000	0.000	Y	0.000	0.000	0.000	25	
2186	Offices - GFE label	Services	km2 GFA	km2 GFA	0.0	0.0	0.0	0.00	0.00	0.00	0.000	0.000	0.000	Y	0.783	0.783	0.783	5	
2187	Offices - DC label	Services	km2 GFA	km2 GFA	25.0	25.0	25.0	0.00	0.00	0.00	0.000	0.000	0.000	Y	0.000	0.000	0.000	25	
2188	Offices - A label	Services	km2 GFA	km2 GFA	140.0	140.0	140.0	0.00	0.00	0.00	0.000	0.000	0.000	Y	0.000	0.000	0.000	25	
2189	Offices - A+ label	Services	km2 GFA	km2 GFA	170.0	170.0	170.0	0.00	0.00	0.00	0.000	0.000	0.000	Y	0.000	0.000	0.000	25	
2190	Energy in education - GFE label	Services	km2 GFA	km2 GFA	0.0	0.0	0.0	0.00	0.00	0.00	0.000	0.000	0.000	Y	0.386	0.386	0.386	5	
2191	Energy in education - DC label	Services	km2 GFA	km2 GFA	30.0	30.0	30.0	0.00	0.00	0.00	0.000	0.000	0.000	Y	0.000	0.000	0.000	25	
2192	Energy in education - B label	Services	km2 GFA	km2 GFA	135.0	135.0	135.0	0.00	0.00	0.00	0.000	0.000	0.000	Y	0.000	0.000	0.000	25	
2193	Energy in education - A label	Services	km2 GFA	km2 GFA	165.0	165.0	165.0	0.00	0.00	0.00	0.000	0.000	0.000	Y	0.000	0.000	0.000	25	
2194	Energy in education - A+ label	Services	km2 GFA	km2 GFA	195.0	195.0	195.0	0.00	0.00	0.00	0.000	0.000	0.000	Y	0.000	0.000	0.000	25	
2195	Energy in industrial halls - GFE label	Services	km2 GFA	km2 GFA	0.0	0.0	0.0	0.00	0.00	0.00	0.000	0.000	0.000	Y	0.322	0.322	0.322	5	
2196	Energy in industrial halls - DC label	Services	km2 GFA	km2 GFA	20.0	20.0	20.0	0.00	0.00	0.00	0.000	0.000	0.000	Y	0.000	0.000	0.000	25	
2197	Energy in industrial halls - B label	Services	km2 GFA	km2 GFA	80.0	80.0	80.0	0.00	0.00	0.00	0.000	0.000	0.000	Y	0.000	0.000	0.000	25	
2198	Energy in industrial halls - A label	Services	km2 GFA	km2 GFA	105.0	105.0	105.0	0.00	0.00	0.00	0.000	0.000	0.000	Y	0.000	0.000	0.000	25	
2199	Energy in industrial halls - A+ label	Services	km2 GFA	km2 GFA	125.0	125.0	125.0	0.00	0.00	0.00	0.000	0.000	0.000	Y	0.000	0.000	0.000	25	
2200	Energy in hospitals - GFE label	Services	km2 GFA	km2 GFA	0.0	0.0	0.0	0.00	0.00	0.00	0.000	0.000	0.000	Y	0.825	0.825	0.825	5	
2201	Energy in hospitals - DC label	Services	km2 GFA	km2 GFA	30.0	30.0	30.0	0.00	0.00	0.00	0.000	0.000	0.000	Y	0.000	0.000	0.000	25	
2202	Energy in hospitals - B label	Services	km2 GFA	km2 GFA	135.0	135.0	135.0	0.00	0.00	0.00	0.000	0.000	0.000	Y	0.000	0.000	0.000	25	
2203	Energy in hospitals - A label	Services	km2 GFA	km2 GFA	165.0	165.0	165.0	0.00	0.00	0.00	0.000	0.000	0.000	Y	0.000	0.000	0.000	25	
2204	Energy in hospitals - A+ label	Services	km2 GFA	km2 GFA	190.0	190.0	190.0	0.00	0.00	0.00	0.000	0.000	0.000	Y	0.000	0.000	0.000	25	
2205	Energy in rest services - GFE label	Services	km2 GFA	km2 GFA	0.0	0.0	0.0	0.00	0.00	0.00	0.000	0.000	0.000	Y	0.571	0.571	0.571	5	
2206	Energy in rest services - DC label	Services	km2 GFA	km2 GFA	30.0	30.0	30.0	0.00	0.00	0.00	0.000	0.000	0.000	Y	0.000	0.000	0.000	25	
2207	Energy in rest services - B label	Services	km2 GFA	km2 GFA	135.0	135.0	135.0	0.00	0.00	0.00	0.000	0.000	0.000	Y	0.000	0.000	0.000	25	
2208	Energy in rest services - A label	Services	km2 GFA	km2 GFA	165.0	165.0	165.0	0.00	0.00	0.00	0.000	0.000	0.000	Y	0.000	0.000	0.000	25	
2209	Energy in rest services - A+ label	Services	km2 GFA	km2 GFA	195.0	195.0	195.0	0.00	0.00	0.00	0.000	0.000	0.000	Y	0.000	0.000	0.000	25	
2219	REF Natural gas boilers - Low Temp - FBI	Food and Beverage Industry	PJ/yr	PJ	1.4	1.4	1.4	0.06	0.06	0.05	0.139	0.125	0.111	N	1.111	1.111	1.111	25	Danish Energy Agency (2021)
2220	REF Natural gas CHP - Low Temp - FBI	Food and Beverage Industry	PJ/yr	PJ	17.7	17.7	17.7	0.64	0.64	0.64	0.000	0.000	0.000	N	1.250	1.191	1.124	15	

UoC: unit of capacity UoA: unit of activity					Investment cost [Mln €(2015)/UoC]			Fixed O&M cost [Mln euro(2015)/UoC/yr]			Variable cost [Mln euro(2015)/UoA]				Energy input [PJ] per UoA				
Technology ID	Technology name	Sector	UoC	UoA	2030	2040	2050	2030	2040	2050	2030	2040	2050	Fulfills Service demand (yes/no)?	2030	2040	2050	Life-time [yr]	Data source
2221	REF rest boilers - Low Temp - FBI	Food and Beverage Industry	PJ/yr	PJ	7.4	7.4	7.4	0.43	0.43	0.43	0.000	0.000	0.000	N	1.163	1.163	1.163	15	
2222	REF Anaerobic Digestion to Green Gas - FBI	Food and Beverage Industry	PJ/yr	PJ	46.3	46.3	46.3	4.08	4.08	4.08	0.527	0.527	0.527	N	1.010	1.010	1.010	15	SDE++ 2021 Eindadvies
2224	Deep geothermal heat - FBI	Food and Beverage Industry	PJ/yr	PJ	67.2	60.5	53.7	3.88	3.49	3.10	0.000	0.000	0.000	N	1.030	1.030	1.030	25	Danish Energy Agency (2021)
2231	Electric boiler - Low Temp - FBI	Food and Beverage Industry	PJ/yr	PJ	2.2	2.2	2.2	0.03	0.03	0.03	0.025	0.025	0.025	N	1.010	1.010	1.010	25	Danish Energy Agency (2021)
2232	Electric Heat Pump - Low Temp - FBI	Food and Beverage Industry	PJ/yr	PJ	22.3	20.1	17.8	0.89	0.80	0.71	0.000	0.000	0.000	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
2233	Biomass boilers - Low Temp - FBI	Food and Beverage Industry	PJ/yr	PJ	18.7	17.9	17.0	1.14	1.10	1.07	0.306	0.306	0.306	N	1.124	1.124	1.124	25	Danish Energy Agency (2021)
2234	Natural Gas boilers - Low Temp - FBI	Food and Beverage Industry	PJ/yr	PJ	1.4	1.4	1.4	0.06	0.06	0.05	0.139	0.125	0.111	N	1.111	1.111	1.111	25	Danish Energy Agency (2021)
2235	Hydrogen boilers - Low Temp - FBI	Food and Beverage Industry	PJ/yr	PJ	4.4	4.4	4.4	0.56	0.56	0.56	0.000	0.000	0.000	N	1.110	1.110	1.110	25	Danish Energy Agency (2021)
2236	Anaerobic Digestion boilers - Low Temp - FBI	Food and Beverage Industry	PJ/yr	PJ	25.0	24.7	24.3	0.69	0.69	0.69	0.000	0.000	0.000	N	1.133	1.133	1.133	15	TNO datasheet
2237	REF process_salt	Chemical industry	Mton salt/yr	Mton salt	0.0	0.0	0.0	0.00	0.00	0.00	0.000	0.000	0.000	Y	1.860	1.860	1.860	15	
2238	MVR brine vaporization_salt	Chemical industry	Mton salt/yr	Mton salt	30.2	30.2	30.2	1.50	1.50	1.50	0.000	0.000	0.000	Y	1.640	1.640	1.640	15	
2239	REF Natural Gas Medium Temp Boilers - Salt	Chemical industry	PJ/yr	PJ	1.4	1.4	1.4	0.06	0.06	0.05	0.139	0.125	0.111	N	1.111	1.111	1.111	25	Danish Energy Agency (2021)
2240	Hydrogen Medium Temp Boilers - Salt	Chemical industry	PJ/yr	PJ	4.4	4.4	4.4	0.56	0.56	0.56	0.000	0.000	0.000	N	1.110	1.110	1.110	25	Danish Energy Agency (2021)
2241	Electric Medium Temp Boilers - Salt	Chemical industry	PJ/yr	PJ	2.2	2.2	2.2	0.03	0.03	0.03	0.025	0.025	0.025	N	1.010	1.010	1.010	25	Danish Energy Agency (2021)
2243	REF Membrane Electrolysis_chlorine	Chemical industry	Mton Chlorine/yr	Mton Chlorine	0.0	0.0	0.0	0.00	0.00	0.00	0.000	0.000	0.000	Y	10.120	10.120	10.120	15	
2244	Zero gap membrane electrolyser_chlorine	Chemical industry	Mton Chlorine/yr	Mton Chlorine	3.6	3.6	3.6	0.55	0.55	0.55	0.000	0.000	0.000	Y	9.496	9.496	9.496	15	
2245	REF Natural Gas Medium Temp Boilers - Chlorine	Chemical industry	PJ/yr	PJ	1.4	1.4	1.4	0.06	0.06	0.05	0.139	0.125	0.111	N	1.111	1.111	1.111	25	Danish Energy Agency (2021)
2246	Electric Medium Temp Boilers - Chlorine	Chemical industry	PJ/yr	PJ	2.2	2.2	2.2	0.03	0.03	0.03	0.025	0.025	0.025	N	1.010	1.010	1.010	25	Danish Energy Agency (2021)
2247	Biomass Medium Temp Boilers - Chlorine	Chemical industry	PJ/yr	PJ	18.7	17.9	17.0	1.14	1.10	1.07	0.306	0.306	0.306	N	1.124	1.124	1.124	25	Danish Energy Agency (2021)
2248	Deep geothermal heat - Chlorine	Chemical industry	PJ/yr	PJ	67.2	60.5	53.7	3.88	3.49	3.10	0.000	0.000	0.000	N	1.030	1.030	1.030	25	Danish Energy Agency (2021)
2288	Electric boiler - 200-400C - FBI	Food and Beverage Industry	PJ/yr	PJ	2.2	2.2	2.2	0.03	0.03	0.03	0.025	0.025	0.025	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
2289	Biomass boiler - 200-400C - FBI	Food and Beverage Industry	PJ/yr	PJ	18.7	17.9	17.0	1.14	1.10	1.07	0.306	0.306	0.306	N	1.124	1.124	1.124	25	Danish Energy Agency (2021)
2290	Natural Gas boiler - 200-400C - FBI	Food and Beverage Industry	PJ/yr	PJ	1.4	1.4	1.4	0.06	0.06	0.05	0.139	0.125	0.111	N	1.111	1.111	1.111	25	Danish Energy Agency (2021)
2291	Hydrogen boiler - 200-400C - FBI	Food and Beverage Industry	PJ/yr	PJ	4.4	4.4	4.4	0.56	0.56	0.56	0.000	0.000	0.000	N	1.110	1.110	1.110	25	Danish Energy Agency (2021)
2293	Waste Heat Industrial Heat Pump - Industry	Other industry	PJ/yr	PJ	22.3	20.1	17.8	0.89	0.80	0.71	0.000	0.000	0.000	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
2294	Waste Heat Industrial Heat Pump - chemical	Chemical industry	PJ/yr	PJ	22.3	20.1	17.8	0.89	0.80	0.71	0.000	0.000	0.000	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
2295	Waste Heat Industrial Heat Pump - fertilizer	Fertilizer industry	PJ/yr	PJ	22.3	20.1	17.8	0.89	0.80	0.71	0.000	0.000	0.000	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
2296	Waste Heat Industrial Heat Pump - FBI	Food and Beverage Industry	PJ/yr	PJ	22.3	20.1	17.8	0.89	0.80	0.71	0.000	0.000	0.000	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
2297	Hot water electric boiler - Industry	Other industry	PJ/yr	Pj	1.9	1.9	1.9	0.03	0.03	0.03	0.139	0.125	0.111	N	1.010	1.010	1.010	25	Danish Energy Agency (2021)
2298	Hot water electric boiler - FBI	Food and Beverage Industry	PJ/yr	PJ	1.9	1.9	1.9	0.03	0.03	0.03	0.139	0.125	0.111	N	1.010	1.010	1.010	25	Danish Energy Agency (2021)

	UoC: unit of capacity UoA: unit of activity				Investment cost [Mln €(2015)/UoC]			Fixed O&M cost [Mln euro(2015)/UoC/yr]			Variable cost [Mln euro(2015)/UoA]				Energy input [PJ] per UoA				
Technology ID	Technology name	Sector	UoC	UoA	2030	2040	2050	2030	2040	2050	2030	2040	2050	Fulfills Service demand (yes/no)?	2030	2040	2050	Life-time [yr]	Data source
2299	Hot water NG boiler - Industry	Other industry	PJ/yr	PJ	1.2	1.2	1.2	0.06	0.06	0.05	0.253	0.255	0.257	N	1.064	1.064	1.064	25	Danish Energy Agency (2021)
2300	Hot water Biomass boiler - Industry	Other industry	PJ/yr	PJ	18.7	17.9	17.0	1.14	1.10	1.07	0.306	0.306	0.306	N	1.111	1.111	1.111	25	Danish Energy Agency (2021)
2301	Hot water H2 boiler - Industry	Other industry	PJ/yr	PJ	2.7	2.6	2.5	0.13	0.12	0.12	0.000	0.000	0.000	N	0.990	0.990	0.990	25	Danish Energy Agency (2021)
2302	Hot water waste gasses boiler - Chemical	Chemical industry	PJ/yr	PJ	4.8	4.8	4.8	0.45	0.45	0.45	0.000	0.000	0.000	N	1.176	1.176	1.176	15	
2307	Electric boiler HT100to200 - Waste	Waste	PJ/yr	PJ	2.2	2.2	2.2	0.03	0.03	0.03	0.025	0.025	0.025	N	1.010	1.010	1.010	25	Danish Energy Agency (2021)
2308	NG boiler HT100to200- Waste	Waste	PJ/yr	PJ	1.4	1.4	1.4	0.06	0.06	0.05	0.139	0.125	0.111	N	1.111	1.111	1.111	25	Danish Energy Agency (2021)
2309	Biomass boiler HT100to200 - Waste	Waste	PJ/yr	PJ	18.7	17.9	17.0	1.14	1.10	1.07	0.306	0.306	0.306	N	1.124	1.124	1.124	25	Danish Energy Agency (2021)
2310	H2 boiler HT100to200 - Waste	Waste	PJ/yr	PJ	4.4	4.4	4.4	0.56	0.56	0.56	0.000	0.000	0.000	N	1.110	1.110	1.110	25	Danish Energy Agency (2021)
2314	NG Direct Firing - Basic metal non-ferro	Basic metal non-ferro	PJ/yr	PJ	0.5	0.5	0.5	0.01	0.01	0.01	0.025	0.025	0.025	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
2315	Electric Direct Firing - Basic metal non-ferro	Basic metal non-ferro	PJ/yr	PJ	1.9	1.9	1.9	0.00	0.00	0.00	0.000	0.000	0.000	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
2316	Hydrogen DF > 400 C - Basic metal non-ferro	Basic metal non-ferro	PJ/yr	PJ	1.5	1.5	1.5	0.05	0.05	0.05	0.000	0.000	0.000	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
2319	Biomass Hotwater Boiler - Services	Services	PJ/yr	PJ	18.7	17.9	17.0	1.14	1.10	1.07	0.306	0.306	0.306	N	1.111	1.111	1.111	25	Danish Energy Agency (2021)
2320	H2 boiler - District heating	Central heat supply	PJ/yr	PJ	2.7	2.6	2.5	0.13	0.12	0.12	0.000	0.000	0.000	N	0.990	0.990	0.990	25	Danish Energy Agency (2021)
2321	NG boiler - District heating	Central heat supply	PJ/yr	PJ	1.2	1.2	1.2	0.06	0.06	0.05	0.253	0.255	0.257	N	1.064	1.064	1.064	25	Danish Energy Agency (2021)
2322	e - boiler - District heating	Central heat supply	PJ/yr	PJ	1.9	1.9	1.9	0.03	0.03	0.03	0.139	0.125	0.111	N	1.010	1.010	1.010	25	Danish Energy Agency (2021)
2323	NG CHP - District heating	Central heat supply	PJ/yr	PJ	31.7	31.4	31.1	1.59	1.59	1.59	0.951	0.951	0.951	N	1.111	1.111	1.111	25	TNO datasheet
2324	Ground source heat pumps - households	Residential	PJ/yr	PJ	30.7	30.1	29.5	0.32	0.32	0.32	0.000	0.000	0.000	N	1.000	1.000	1.000	20	TNO datasheet
2325	Hybrid heat pumps (boiler part) households	Residential	PJ/yr	PJ	23.6	19.9	16.2	0.86	0.86	0.86	0.000	0.000	0.000	N	1.390	1.390	1.390	20	TNO datasheet
2328	Hybrid heat pumps (HP part) households	Residential	PJ/yr	PJ	0.0	0.0	0.0	0.00	0.00	0.00	0.000	0.000	0.000	N	1.000	1.006	1.011	20	TNO datasheet
2329	REF NG Direct Firing - High Temp - Fertilizer	Fertilizer industry	PJ/yr	PJ	15.0	15.0	15.0	0.18	0.17	0.15	0.000	0.000	0.000	N	1.111	1.111	1.111	15	Danish Energy Agency (2021)
2330	Direct Firing NG 200-400 C - Chemicals	Chemical industry	PJ/yr	PJ	0.5	0.5	0.5	0.01	0.01	0.01	0.025	0.025	0.025	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
2331	Direct Firing Elec 200-400 C - Chemicals	Chemical industry	PJ/yr	PJ	1.9	1.9	1.9	0.00	0.00	0.00	0.000	0.000	0.000	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
2332	Direct Firing NG 200-400 C - Ferro	Basic metal ferro	PJ/yr	PJ	0.5	0.5	0.5	0.01	0.01	0.01	0.025	0.025	0.025	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
2333	Direct Firing Elec 200-400 C - Ferro	Basic metal ferro	PJ/yr	PJ	1.9	1.9	1.9	0.00	0.00	0.00	0.000	0.000	0.000	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
2338	Direct Firing NG 200-400 C - non ferro	Basic metal non-ferro	PJ/yr	PJ	0.5	0.5	0.5	0.01	0.01	0.01	0.025	0.025	0.025	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
2339	Direct Firing Elec 200-400 C - non ferro	Basic metal non-ferro	PJ/yr	PJ	1.9	1.9	1.9	0.00	0.00	0.00	0.000	0.000	0.000	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
2340	Natural Gas Boilers 200-400 C - non ferro	Basic metal non-ferro	PJ/yr	PJ	1.4	1.4	1.4	0.06	0.06	0.05	0.139	0.125	0.111	N	1.111	1.111	1.111	25	Danish Energy Agency (2021)
2341	Electric Boilers 200-400 C- non ferro	Basic metal non-ferro	PJ/yr	PJ	2.2	2.2	2.2	0.03	0.03	0.03	0.025	0.025	0.025	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
2342	Hydrogen Boilers 200-400 C- non ferro	Basic metal non-ferro	PJ/yr	PJ	4.4	4.4	4.4	0.56	0.56	0.56	0.000	0.000	0.000	N	1.110	1.110	1.110	25	Danish Energy Agency (2021)
2343	Electric Boilers 100-200C - non ferro	Basic metal non-ferro	PJ/yr	PJ	2.2	2.2	2.2	0.03	0.03	0.03	0.025	0.025	0.025	N	1.010	1.010	1.010	25	Danish Energy Agency (2021)
2344	Electric HP < 100 C non ferro	Basic metal non-ferro	PJ/yr	PJ	22.3	20.1	17.8	0.89	0.80	0.71	0.000	0.000	0.000	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
2346	Post-Combustion CC Add on - Fertilizer	Fertilizer industry	Mton/yr	Mton	283.5	220.1	156.6	0.00	0.00	0.00	0.000	0.000	0.000	N	1.130	1.295	1.460	20	MIDDEN
2349	Direct Firing NG 200-400 C - Industry	Other industry	PJ/yr	PJ	0.5	0.5	0.5	0.01	0.01	0.01	0.025	0.025	0.025	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
2350	Direct Firing Elec 200-400 C -Industry	Other industry	PJ/yr	PJ	1.9	1.9	1.9	0.00	0.00	0.00	0.000	0.000	0.000	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
2351	Direct Firing NG 200-400 C - Refinery	Refinery	PJ/yr	PJ	0.5	0.5	0.5	0.01	0.01	0.01	0.025	0.025	0.025	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
2352	Direct Firing Elec 200-400 C - Refinery	Refinery	PJ/yr	PJ	1.9	1.9	1.9	0.00	0.00	0.00	0.000	0.000	0.000	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
2353	Direct Firing WG 200-400 C - Chemicals	Chemical industry	PJ/yr	PJ	0.5	0.5	0.5	0.01	0.01	0.01	0.025	0.025	0.025	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
2354	Direct Firing WG > 400 C - Chemicals	Chemical industry	PJ/yr	PJ	0.5	0.5	0.5	0.01	0.01	0.01	0.025	0.025	0.025	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
2356	REF methanol from NG	Chemical industry	PJ/yr	PJ	18.0	16.0	14.0	0.90	0.80	0.70	0.000	0.000	0.000	N	1.364	1.364	1.318	30	TNO datasheet, MIDDEN
2357	Methanol from lignocellulosics	Chemical industry	PJ/yr	PJ	64.0	57.5	51.0	4.00	3.50	3.00	3.000	2.500	2.000	N	1.606	1.606	1.606	20	Uslu (2020)
2359	Methanol to olefins	Chemical industry	Mton olefins/yr	Mton olefins	607.1	607.1	607.1	36.43	36.43	36.43	0.000	0.000	0.000	Y	41.140	41.140	41.140	20	Uslu (2020)
2360	Methanol from ext. H2 and ext. CO2	Chemical industry	PJ/yr	PJ	8.0	7.5	7.0	0.20	0.19	0.17	0.000	0.000	0.000	N	1.234	1.234	1.234	20	Uslu (2020)
2361	Methanol from ext. H2 and direct air capture	Chemical industry	PJ/yr	PJ	44.0	33.0	22.0	2.00	1.50	1.00	0.000	0.000	0.000	N	1.750	1.750	1.750	20	TNO datasheet
2362	Methanol to Gasoline	Refinery	PJ/yr	PJ	9.7	9.7	9.7	0.49	0.49	0.49	0.000	0.000	0.000	N	1.217	1.217	1.217	20	Hennig (2021)
2363	Natural Gas boilers - Low Temp - chemical	Chemical industry	PJ/yr	PJ	1.4	1.4	1.4	0.06	0.06	0.05	0.139	0.125	0.111	N	1.111	1.111	1.111	25	Danish Energy Agency (2021)

	UoC: unit of capacity UoA: unit of activity				Investment cost [Mln €(2015)/UoC]			Fixed O&M cost [Mln euro(2015)/UoC/yr]			Variable cost [Mln euro(2015)/UoA]				Energy input [PJ] per UoA				
Technology ID	Technology name	Sector	UoC	UoA	2030	2040	2050	2030	2040	2050	2030	2040	2050	Fulfills Service demand (yes/no)?	2030	2040	2050	Life-time [yr]	Data source
2364	REF Glass production conventional furnaces	Other industry	Mton glass/yr	Mton glass	147.9	147.9	147.9	4.44	4.44	4.44	0.000	0.000	0.000	Y	5.443	5.443	5.443	15	MIDDEN
2365	Glass production with electric cold-top furnaces	Other industry	Mton glass/yr	Mton glass	345.2	345.2	345.2	10.85	10.85	10.85	0.000	0.000	0.000	Y	6.090	6.090	6.090	15	MIDDEN
2366	Glass production with efficient furnaces	Other industry	Mton glass/yr	Mton glass	187.4	187.4	187.4	5.92	5.92	5.92	0.000	0.000	0.000	Y	4.720	4.720	4.720	15	MIDDEN
2367	REF Ceramics production in conventional kilns	Other industry	Mton ceramics/yr	Mton ceramics	147.9	147.9	147.9	7.40	7.40	7.40	0.000	0.000	0.000	Y	1.740	1.740	1.740	30	MIDDEN
2368	Ceramics production in electric kilns	Other industry	Mton ceramics/yr	Mton ceramics	0.0	271.2	271.2	0.00	13.61	13.61	0.000	0.000	0.000	Y	2.300	2.300	2.300	30	MIDDEN
2371	LNG truck with 13% energy consumption reduction	Mobility	M vehicles	Bn vkm HDV	185,678.5	185,678.5	185,678.5	1,597.10	1,597.10	1,597.10	0.000	0.000	0.000	Y	15.844	15.784	15.725	8	PRIMES TREMOVE
2372	H2 truck with energy consumption reduction	Mobility	M vehicles	Bn vkm HDV	426,861.1	300,846.8	266,093.2	2,259.66	1,889.88	1,520.10	0.000	0.000	0.000	Y	7.144	7.117	7.090	8	PRIMES TREMOVE
2374	Pyrolysis of plastic waste with hydrotreating	Chemical industry	PJ/yr	PJ	202.9	202.9	202.9	10.22	10.22	10.22	0.000	0.000	0.000	N	1.153	1.153	1.153	20	Fiviga (2018)
2375	Waste Gas 200-400C Boilers - Refineries	Refinery	PJ/yr	PJ	1.4	1.4	1.4	0.06	0.06	0.05	0.139	0.125	0.111	N	1.111	1.111	1.111	25	Danish Energy Agency (2021)
2376	Waste Gas 200-400C Boilers CC- Refineries	Refinery	PJ/yr	PJ	28.9	28.9	28.9	0.11	0.11	0.11	0.000	0.000	0.000	N	1.184	1.184	1.184	25	Danish Energy Agency (2021)
2377	Waste Gas 100-200C Boilers - Refineries	Refinery	PJ/yr	PJ	1.4	1.4	1.4	0.06	0.06	0.05	0.139	0.125	0.111	N	1.111	1.111	1.111	25	Danish Energy Agency (2021)
2378	Waste Gas 100-200C Boilers CC - Refineries	Refinery	PJ/yr	PJ	28.1	28.1	28.1	0.11	0.11	0.11	0.000	0.000	0.000	N	1.219	1.219	1.219	25	Danish Energy Agency (2021)
2380	DME truck	Mobility	M vehicles	Bn vkm HDV	160,845.2	160,845.2	160,845.2	1,912.49	1,912.49	1,912.49	0.000	0.000	0.000	Y	12.120	12.120	12.120	8	PRIMES TREMOVE
2381	DME truck with 18% energy consumption reduction	Mobility	M vehicles	Bn vkm HDV	163,810.0	163,810.0	163,810.0	1,947.74	1,947.74	1,947.74	0.000	0.000	0.000	Y	9.892	9.892	9.892	8	PRIMES TREMOVE
2382	Methanol for shipping from NG	Refinery	PJ/yr	PJ	18.0	16.0	14.0	0.90	0.80	0.70	0.000	0.000	0.000	N	1.364	1.341	1.318	30	TNO datasheet, MIDDEN
2383	Methanol vessel	Bunkers	PJ/yr	PJ	50.0	50.0	50.0	0.00	0.00	0.00	0.000	0.000	0.000	Y	1.000	1.000	1.000	20	
2384	NG to LNG for shipping	Gas supply	PJ/yr	PJ	16.2	14.5	12.9	0.48	0.44	0.39	0.000	0.000	0.000	N	1.097	1.097	1.097	20	SDE++ 2021 Eindadvies
2385	LNG vessel	Bunkers	PJ/yr	PJ	50.0	50.0	50.0	0.00	0.00	0.00	0.000	0.000	0.000	Y	1.000	1.000	1.000	20	PRIMES TREMOVE
2386	Biogas to Bio-LNG for shipping	Gas supply	PJ/yr	PJ	16.2	14.5	12.9	0.48	0.44	0.39	0.000	0.000	0.000	N	1.097	1.097	1.097	20	SDE++ 2021 Eindadvies
2387	Synthetic LNG production from ext. H2 and CO2	Gas supply	PJ/yr	PJ	30.1	28.5	26.9	1.87	1.83	1.78	0.000	0.000	0.000	N	1.081	1.081	1.081	20	
2388	Methanol from lignocellulosics with CC	Chemical industry	PJ/yr	PJ	71.0	64.0	57.0	4.00	3.50	3.00	3.000	2.500	2.000	N	1.547	1.547	1.547	20	Uslu (2020)
2389	Methanol from biogas	Chemical industry	PJ/yr	PJ	18.0	16.0	14.0	0.90	0.80	0.70	0.000	0.000	0.000	N	1.377	1.355	1.334	30	TNO datasheet, MIDDEN
2392	Lignocellulosic ethanol production with CC	Refinery	PJ/yr	PJ	87.0	78.5	70.0	5.00	4.50	4.00	3.000	3.000	3.000	N	2.495	2.495	2.495	20	ADVANCEFUEL (2020), SDE++ 2021 Eindadvies
2393	Bio-DME production with CC	Refinery	PJ/yr	PJ	73.0	65.5	58.0	4.00	3.50	3.00	3.000	2.500	2.000	N	1.552	1.552	1.552	35	SDE++ 2021 Eindadvies
2396	Other dwelllings - startlabel A retrofitted to A+	Residential	M other dwellings	M other dwellings	10,034.3	10,034.3	10,034.3	0.00	0.00	0.00	0.000	0.000	0.000	Y	0.000	0.000	0.000	25	TNO datasheet
2397	Terraced houses - startlabel A retrofitted to A+	Residential	M terraced houses	M terraced houses	10,004.5	10,004.5	10,004.5	0.00	0.00	0.00	0.000	0.000	0.000	Y	0.000	0.000	0.000	25	TNO datasheet
2398	Other dwelllings - startlabel DC/B retrofitted to A	Residential	M other dwellings	M other dwellings	31,443.0	31,443.0	31,443.0	0.00	0.00	0.00	0.000	0.000	0.000	Y	0.000	0.000	0.000	25	TNO datasheet
2399	Terraced houses - startlabel DC/B retrofitted to A	Residential	M terraced houses	M terraced houses	27,991.7	27,991.7	27,991.7	0.00	0.00	0.00	0.000	0.000	0.000	Y	0.000	0.000	0.000	25	TNO datasheet
2400	Apartments - startlabel GFE retrofitted to DC	Residential	M apartments	M apartmen ts	8,633.3	8,633.3	8,633.3	0.00	0.00	0.00	0.000	0.000	0.000	Y	0.000	0.000	0.000	25	TNO datasheet
2401	Apartments - startlabel GFE retrofitted to B	Residential	M apartments	M apartmen ts	14,628.1	14,628.1	14,628.1	0.00	0.00	0.00	0.000	0.000	0.000	Y	0.000	0.000	0.000	25	TNO datasheet

	UoC: unit of capacity UoA: unit of activity				Investment cost [Mln €(2015)/UoC]			Fixed O&M cost [Mln euro(2015)/UoC/yr]			Variable cost [Mln euro(2015)/UoA]				Energy input [PJ] per UoA				
Technology ID	Technology name	Sector	UoC	UoA	2030	2040	2050	2030	2040	2050	2030	2040	2050	Fulfills Service demand (yes/no)?	2030	2040	2050	Life-time [yr]	Data source
2402	Other dwelllings - startlabel GFE retrofitted to DC	Residential	M other dwellings	M other dwellings	15,352.8	15,352.8	15,352.8	0.00	0.00	0.00	0.000	0.000	0.000	Y	0.000	0.000	0.000	25	TNO datasheet
2403	Other dwelllings - startlabel GFE retrofitted to B	Residential	M other dwellings	M other dwellings	35,085.4	35,085.4	35,085.4	0.00	0.00	0.00	0.000	0.000	0.000	Y	0.000	0.000	0.000	25	TNO datasheet
2404	Terraced houses - startlabel GFE retrofitted to DC	Residential	M terraced houses	M terraced houses	10,280.7	10,280.7	10,280.7	0.00	0.00	0.00	0.000	0.000	0.000	Y	0.000	0.000	0.000	25	TNO datasheet
2405	Terraced houses - startlabel GFE retrofitted to B	Residential	M terraced houses	M terraced houses	19,678.9	19,678.9	19,678.9	0.00	0.00	0.00	0.000	0.000	0.000	Y	0.000	0.000	0.000	25	TNO datasheet
2407	Bioethylene via bioethanol	Chemical industry	Mton olefins/yr	Mton olefins	95.0	95.0	95.0	10.96	10.96	10.96	0.000	0.000	0.000	Y	86.890	86.890	86.890	20	Uslu (2020)
2408	Biomass gasification + FT towards diesel with CC	Refinery	PJ/yr	PJ	86.0	77.0	68.0	5.00	4.50	4.00	3.000	3.000	3.000	N	1.586	1.586	1.586	20	SDE++ 2022 Eindadvies.
2409	H2 from waste gas steam reforming with CC from flue gas	H2 supply	PJ/yr	PJ	46.1	41.5	36.9	1.34	1.34	1.34	0.000	0.000	0.000	N	1.346	1.346	1.346	25	
2410	Steam Cracking (adapted) for co-processing III (more pyoil)	Chemical industry	Mton olefins/yr	Mton olefins	599.6	599.6	599.6	30.07	30.07	30.07	0.000	0.000	0.000	Y	72.647	72.647	72.647	20	
2412	Nuclear energy EPR (Gen III+) - Electricity production	Electricity generation	GW	PJ	7,080.0	6,584.0	6,088.0	100.40	100.40	100.40	4.940	4.940	4.940	N	2.941	2.941	2.941	60	Scheepers (2021)
2418	Compression HP, air source, large 10MWth - District heating	Central heat supply	GW	PJ	760.0	760.0	760.0	2.00	2.00	2.00	0.473	0.473	0.473	N	1.000	1.000	1.000	25	
2419	Biomass (wood chips) CHP, small ~19 MWth - District heating	Central heat supply	GW	PJ	6,000.0	5,900.0	5,800.0	273.00	272.00	270.00	2.556	2.583	2.611	N	1.040	1.040	1.040	25	
2422	Compression HP, air source, IWH, medium 3 MW - Distict heating	Central heat supply	GW	PJ	860.0	860.0	860.0	2.00	2.00	2.00	0.695	0.612	0.750	N	1.000	1.000	1.000	25	
2428	REF BEV van	Mobility	M vehicles	G vkm LDV	23,838.8	22,136.5	21,506.1	247.39	229.72	223.18	0.000	0.000	0.000	Y	1.176	1.078	1.078	12	PRIMES TREMOVE
2429	REF electric truck	Mobility	M vehicles	Bn vkm HDV	385,486.2	271,198.5	239,875.2	2,695.69	1,896.48	1,677.44	0.000	0.000	0.000	Y	6.120	6.120	6.120	8	PRIMES TREMOVE
2430	REF ICE bus	Mobility	M vehicles	G vkm bus	0.0	0.0	0.0	0.00	0.00	0.00	0.000	0.000	0.000	Y	10.038	10.045	10.744	10	PRIMES TREMOVE
2431	REF ICE inland navigation freight	Mobility	1000 vessels	G tkm	0.0	0.0	0.0	0.00	0.00	0.00	0.000	0.000	0.000	Y	0.111	0.101	0.091	20	PRIMES TREMOVE
2432	ICE inland navigation freight - 15% fuel reduction	Mobility	1000 vessels	G tkm	1,418.4	1,418.4	1,418.4	0.00	0.00	0.00	0.000	0.000	0.000	Y	0.095	0.086	0.078	30	PRIMES TREMOVE
2433	Battery electric inland navigation freight	Mobility	1000 vessels	G tkm	8,874.1	6,407.7	5,670.5	0.00	0.00	0.00	0.000	0.000	0.000	Y	0.044	0.045	0.047	30	PRIMES TREMOVE
2434	Fuel cell inland navigation freight	Mobility	1000 vessels	G tkm	9,496.8	6,743.6	5,862.4	0.00	0.00	0.00	0.000	0.000	0.000	Y	0.061	0.062	0.065	30	PRIMES TREMOVE
2435	Electricity savings level 1 - FBI	Food and Beverage Industry	PJ/yr	PJ	42.6	42.6	42.6	0.00	0.00	0.00	0.000	0.000	0.000	N	1.000	1.000	1.000	10	Menkveld (2023)
2438	Heat savings level 2 - FBI	Food and Beverage Industry	PJ/yr	PJ	54.8	54.8	54.8	0.00	0.00	0.00	0.000	0.000	0.000	N	1.000	1.000	1.000	10	Menkveld (2023)
2439	Electricity savings level 2 - Chemical	Chemical industry	PJ/yr	PJ	92.9	92.9	92.9	0.00	0.00	0.00	0.000	0.000	0.000	N	1.000	1.000	1.000	10	Menkveld (2023)
2440	Electricity savings level 3 - Chemical	Chemical industry	PJ/yr	PJ	185.8	185.8	185.8	0.00	0.00	0.00	0.000	0.000	0.000	N	1.000	1.000	1.000	10	Menkveld (2023)
2442	Electricity savings level 2 - Fertilizer	Fertilizer industry	PJ/yr	PJ	104.2	104.2	104.2	0.00	0.00	0.00	0.000	0.000	0.000	N	1.000	1.000	1.000	10	Menkveld (2023)
2444	Electricity savings level 2 - Basic metals ferro	Basic metal ferro	PJ/yr	PJ	76.1	76.1	76.1	0.00	0.00	0.00	0.000	0.000	0.000	N	1.000	1.000	1.000	10	Menkveld (2023)

	UoC: unit of capacity UoA: unit of activity				Investment cost [Mln €(2015)/UoC]			Fixed O&M cost [Mln euro(2015)/UoC/yr]			Variable cost [Mln euro(2015)/UoA]				Energy input [PJ] per UoA				
Technology ID	Technology name	Sector	UoC	UoA	2030	2040	2050	2030	2040	2050	2030	2040	2050	Fulfills Service demand (yes/no)?	2030	2040	2050	Life-time [yr]	Data source
2445	Electricity savings level 3 - Fertilizer	Fertilizer industry	PJ/yr	PJ	208.3	208.3	208.3	0.00	0.00	0.00	0.000	0.000	0.000	N	1.000	1.000	1.000	10	Menkveld (2023)
2447	Electricity savings level 3 - Basic metals ferro	Basic metal ferro	PJ/yr	PJ	152.3	152.3	152.3	0.00	0.00	0.00	0.000	0.000	0.000	N	1.000	1.000	1.000	10	Menkveld (2023)
2448	Heat savings - Het Nieuwe Telen - Agriculture	Agriculture	PJ/yr	PJ	0.0	0.0	0.0	0.00	0.00	0.00	0.000	0.000	0.000	N	1.000	1.000	1.000	10	Menkveld (2023)
2449	Heat savings - Insulation package - Agriculture	Agriculture	PJ/yr	PJ	15.1	15.1	15.1	0.00	0.00	0.00	0.000	0.000	0.000	N	1.000	1.000	1.000	10	Menkveld (2023)
2450	Heat savings - 2e scherm - Agriculture	Agriculture	PJ/yr	PJ	48.3	48.3	48.3	0.00	0.00	0.00	0.000	0.000	0.000	N	1.000	1.000	1.000	10	Menkveld (2023)
2451	Heat savings - 3e scherm - Agriculture	Agriculture	PJ/yr	PJ	58.0	58.0	58.0	0.00	0.00	0.00	0.000	0.000	0.000	N	1.000	1.000	1.000	10	Menkveld (2023)
2452	Heat savings - selective ventilation - Agriculture	Agriculture	PJ/yr	PJ	543.5	543.5	543.5	0.00	0.00	0.00	0.000	0.000	0.000	N	1.000	1.000	1.000	10	Menkveld (2023)
2453	Heat savings - existing buildingskassen - Agriculture	Agriculture	PJ/yr	PJ	2,898.5	2,898.5	2,898.5	0.00	0.00	0.00	0.000	0.000	0.000	N	1.000	1.000	1.000	10	Menkveld (2023)
2454	Heat saving - Low temperature heating - Agriculture	Agriculture	PJ/yr	PJ	130.4	130.4	130.4	0.00	0.00	0.00	0.000	0.000	0.000	N	1.000	1.000	1.000	10	Menkveld (2023)
2455	Electricity savings - meet en regeltechniek - Agriculture	Agriculture	PJ/yr	PJ	28.0	28.0	28.0	0.00	0.00	0.00	0.000	0.000	0.000	N	1.000	1.000	1.000	10	Menkveld (2023)
2456	Electricity savings - distribution & feeding - Agriculture	Agriculture	PJ/yr	PJ	356.0	356.0	356.0	0.00	0.00	0.00	0.000	0.000	0.000	N	1.000	1.000	1.000	10	Menkveld (2023)
2457	Electricity savings - bevochtiging - Agriculture	Agriculture	PJ/yr	PJ	759.0	759.0	759.0	0.00	0.00	0.00	0.000	0.000	0.000	N	1.000	1.000	1.000	10	Menkveld (2023)
2458	Electricity savings - selective cooling - Agriculture	Agriculture	PJ/yr	PJ	762.0	762.0	762.0	0.00	0.00	0.00	0.000	0.000	0.000	N	1.000	1.000	1.000	10	Menkveld (2023)
2459	Electricity savings - LED lightning - Agriculture	Agriculture	PJ/yr	PJ	973.0	973.0	973.0	0.00	0.00	0.00	0.000	0.000	0.000	N	1.000	1.000	1.000	10	Menkveld (2023)
2461	External NH3 for fertilizer industry	Fertilizer industry	Mton NH3/yr	Mton NH3	0.0	0.0	0.0	0.00	0.00	0.00	0.000	0.000	0.000	Y	20.300	20.300	20.300	30	
2464	Ammonia vessel	Bunkers	PJ/yr	PJ	50.0	50.0	50.0	0.00	0.00	0.00	0.000	0.000	0.000	Y	1.000	1.000	1.000	20	
2465	ammonia production (energy carrier)	H2 supply	PJ/yr	PJ	19.2	19.2	19.2	0.00	0.00	0.00	0.654	0.654	0.654	N	1.600	1.594	1.588	20	
2467	H-B NH3 with external H2 (energy carrier)	H2 supply	PJ/yr	PJ	16.3	16.3	16.3	0.54	0.54	0.54	0.000	0.000	0.000	N	1.567	1.567	1.567	20	
2468	Electrolyse H-B NH3 (energy carrier)	H2 supply	PJ/yr	PJ	52.6	47.4	42.1	1.23	1.23	1.23	0.000	0.000	0.000	N	2.084	2.084	2.084	20	
2470	Ethylene from mechanical recycling (high yield)	Chemical industry	Mton olefins/yr	Mton olefins	967.0	967.0	967.0	48.50	48.50	48.50	0.000	0.000	0.000	Y	110.854	110.854	110.854	15	
2482	H2 from NH3 cracking	H2 supply	PJ/yr	PJ	12.5	12.5	12.5	0.50	0.50	0.50	0.000	0.000	0.000	N	1.535	1.535	1.535	30	IEA (2019)
2483	Ethylene from mechanical recycling (low yield)	Chemical industry	Mton olefins/yr	Mton olefins	967.0	967.0	967.0	48.50	48.50	48.50	0.000	0.000	0.000	N	0.000	0.000	0.000	15	
2484	Ethylene from plastic gasification	Chemical industry	Mton olefins/yr	Mton olefins	1,450.0	1,450.0	1,450.0	72.75	72.75	72.75	0.000	0.000	0.000	N	9.094	9.094	9.094	15	
2485	Waste heat - Heat Pump - Refinery	Refinery	PJ/yr	PJ	22.3	20.1	17.8	0.89	0.80	0.71	0.000	0.000	0.000	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)
2486	Heat<100C - Heat Pump - Refinery	Refinery	PJ/yr	PJ	22.3	20.1	17.8	0.89	0.80	0.71	0.000	0.000	0.000	N	1.000	1.000	1.000	25	Danish Energy Agency (2021)

	UoC: unit of capacity UoA: unit of activity				Investment cost [Mln €(2015)/UoC]			Fixed O&M cost [Mln euro(2015)/UoC/yr]			Variable cost [Mln euro(2015)/UoA]				Energy input [PJ] per UoA				
Technology ID	Technology name	Sector	UoC	UoA	2030	2040	2050	2030	2040	2050	2030	2040	2050	Fulfills Service demand (yes/no)?	2030	2040	2050	Life-time [yr]	Data source
2501	Steam network (100-200 degC)	Central heat supply	GW	PJ	125.0	125.0	125.0	0.00	0.00	0.00	0.000	0.000	0.000	N	1.053	1.053	1.053	25	
2502	Steam network (200-400 degC)	Central heat supply	GW	PJ	125.0	125.0	125.0	0.00	0.00	0.00	0.000	0.000	0.000	N	1.053	1.053	1.053	25	
2508	Aromatics production via biomass	Chemical industry	PJ/yr	PJ	17.5	17.5	17.5	0.88	0.88	0.88	0.000	0.000	0.000	N	2.782	2.782	2.782	20	
2509	Methanol to aromatics	Chemical industry	PJ/yr	PJ	2.5	2.5	2.5	0.12	0.12	0.12	0.000	0.000	0.000	N	1.152	1.152	1.152	20	
2511	Small Modular Reactor - electricity only modus	Electricity generation	GW	PJ	7,026.2	6,534.0	6,041.7	99.64	99.64	99.64	4.902	4.902	4.902	N	1.504	1.504	1.504	60	NRG/TNO Systeemstudies: eigenschappen van SMRs
2515	Gasification of mixed plastic waste to methanol	Chemical industry	PJ/yr	PJ	38.1	38.1	38.1	15.88	15.88	15.88	0.000	0.000	0.000	N	1.513	1.513	1.513	20	Afzal (2023)
2516	Mechanical recycling of plastic waste	Chemical industry	Mton olefins/yr	Mton olefins	384.0	384.0	384.0	19.00	19.00	19.00	0.000	0.000	0.000	Y	55.850	55.850	55.850	20	
2517	Offshore platform including converter	Electricity generation	GW	PJ	450.0	450.0	450.0	0.00	0.00	0.00	0.000	0.000	0.000	N	1.010	1.010	1.010	30	
2518	Mechanical recycling of plastic waste with high yield	Chemical industry	Mton olefins/yr	Mton olefins	384.0	333.0	312.0	19.00	17.00	16.00	0.000	0.000	0.000	Y	55.850	41.950	36.870	20	
2519	Gasification of mixed plastic waste to methanol with high yield	Chemical industry	PJ/yr	PJ	38.1	38.1	35.0	15.88	15.88	14.55	0.000	0.000	0.000	N	1.513	1.513	1.387	20	Afzal (2023)
2520	Pyrolysis of plastic waste with hydrotreating with high yield	Chemical industry	PJ/yr	PJ	202.9	202.9	187.9	10.22	10.22	9.39	0.000	0.000	0.000	N	1.153	1.153	1.090	20	Fiviga (2018)
2521	Biomethanol via direct gasification with ext H2	Chemical industry	PJ/yr	PJ	57.1	51.3	45.5	3.60	3.15	2.70	0.000	0.000	0.000	N	1.440	1.440	1.440	20	
2522	Steel making with AEF using imported HBI	Basic metal ferro	Mton steel/yr	Mton steel	283.0	283.0	283.0	8.49	8.49	8.49	0.000	0.000	0.000	Y	3.603	3.603	3.603	30	MIDDEN

E.3 Storage technologies

UoC: unit of capacity
UoA: unit of activity

					Investment cost [Mln €(2015)/UoC]			Fixed O&M cost [Mln €(2015)/UoC/yr]			Variable cost [Mln €(2015)/UoA]							
Tech-nology ID	Technology name	Sector	UoC	UoA	2030	2040	2050	2030	2040	2050	2030	2040	2050	Energy input [PJ] per UoA	Storage losses per hour [%]	Time to completely charge/discharge [hr]	Life-time [yr]	Datasource
1268	CAES storage	Electricity	PJ	PJ	23,148.0	21,990.5	20,833.0	375.00	375.00	375.00	0.140	0.140	0.140	1.000	0.00000		50	TNO datasheet
1269	CAES - charge component	Electricity	PJ	PJ	0.0	0.0	0.0	0.00	0.00	0.00	0.000	0.000	0.000	1.429		8.00	50	TNO datasheet
1270	CAES - discharge component	Electricity	PJ	PJ	0.0	0.0	0.0	0.00	0.00	0.00	0.000	0.000	0.000	1.000		12.00	50	TNO datasheet
1294	H2 vessels on pipeline charge	H2 supply	GW	PJ	192.1	158.7	125.3	0.46	0.34	0.22	0.000	0.000	0.000	1.000		1.00	20	TNO datasheet
1295	H2 vessels on pipeline discharge	H2 supply	GW	PJ	0.0	0.0	0.0	0.00	0.00	0.00	0.000	0.000	0.000	1.000		1.00	20	TNO datasheet
1296	H2 vessels on pipeline	H2 supply	PJ	PJ	4,166.7	3,333.3	2,500.0	83.33	66.67	50.00	0.000	0.000	0.000	1.000	0.00000		20	TNO datasheet
1297	H2 vessels on distribution net charge	H2 supply	GW	PJ	192.1	158.7	125.3	0.46	0.34	0.22	0.000	0.000	0.000	1.000		1.00	20	TNO datasheet
1298	H2 vessels on distribution net discharge	H2 supply	GW	PJ	0.0	0.0	0.0	0.00	0.00	0.00	0.000	0.000	0.000	1.000		1.00	20	TNO datasheet
1299	H2 vessels on distribution net	H2 supply	PJ	PJ	4,166.7	3,333.3	2,500.0	41.67	33.33	25.00	0.000	0.000	0.000	1.000	0.00000		20	TNO datasheet
1300	A-CAES - discharge component	Electricity	GW	PJ	0.0	0.0	0.0	0.00	0.00	0.00	0.000	0.000	0.000	1.000		5.00	40	TNO datasheet
1301	A-CAES - charge component	Electricity	GW	PJ	0.0	0.0	0.0	0.00	0.00	0.00	0.000	0.000	0.000	1.550		10.00	40	TNO datasheet
1302	A-CAES storage	Electricity	PJ	PJ	72,222.0	69,444.5	66,667.0	939.00	476.30	13.60	0.560	0.560	0.560	1.000	0.00000		40	TNO datasheet
1303	Pb battery - discharge component	Electricity	GW	PJ	0.0	0.0	0.0	0.00	0.00	0.00	0.000	0.000	0.000	1.000		4.00	5	TNO datasheet
1304	Pb battery - charge component	Electricity	GW	PJ	0.0	0.0	0.0	0.00	0.00	0.00	0.000	0.000	0.000	1.180		4.00	5	TNO datasheet
1305	Pb battery storage	Electricity	PJ	PJ	63,333.3	59,722.2	56,111.1	888.90	833.35	777.80	0.222	0.222	0.222	1.000	0.05000		5	TNO datasheet
1306	NiCd battery - discharge component	Electricity	GW	PJ	0.0	0.0	0.0	0.00	0.00	0.00	0.000	0.000	0.000	1.000		2.00	12	
1307	NiCd battery - charge component	Electricity	GW	PJ	0.0	0.0	0.0	0.00	0.00	0.00	0.000	0.000	0.000	1.333		4.00	12	
1308	NiCd battery storage	Electricity	PJ	PJ	78,125.0	70,312.5	62,500.0	1,562.50	1,406.25	1,250.00	0.781	0.625	0.469	1.000	0.05000		12	
1309	NaS battery - discharge component	Electricity	GW	PJ	0.0	0.0	0.0	0.00	0.00	0.00	0.000	0.000	0.000	1.000		4.00	10	
1310	NaS battery - charge component	Electricity	GW	PJ	0.0	0.0	0.0	0.00	0.00	0.00	0.000	0.000	0.000	1.124		6.00	10	
1311	NaS battery storage	Electricity	PJ	PJ	92,777.8	87,638.9	82,500.0	1,391.67	1,314.58	1,237.50	0.870	1.054	1.238	1.000	0.13440		10	
1312	Li ion battery - discharge component	Electricity	GW	PJ	0.0	0.0	0.0	0.00	0.00	0.00	0.000	0.000	0.000	1.000		2.50	15	TNO datasheet
1313	Li ion battery - charge component	Electricity	GW	PJ	0.0	0.0	0.0	0.00	0.00	0.00	0.000	0.000	0.000	1.180		2.50	15	TNO datasheet
1314	Li ion battery storage	Electricity	PJ	PJ	48,888.9	42,777.8	36,666.7	976.11	829.72	683.33	0.725	0.725	0.725	1.000	0.05000		15	TNO datasheet
1315	VRB battery - discharge component	Electricity	GW	PJ	0.0	0.0	0.0	0.00	0.00	0.00	0.000	0.000	0.000	1.000		6.00	10	TNO datasheet
1316	VRB battery - charge component	Electricity	GW	PJ	0.0	0.0	0.0	0.00	0.00	0.00	0.000	0.000	0.000	1.370		6.00	10	TNO datasheet
1317	VRB battery storage	Electricity	PJ	PJ	148,611.1	148,611.1	148,611.1	1,944.44	1,944.44	1,944.44	0.083	0.083	0.083	1.000	0.00000		10	TNO datasheet
1318	ZnBr battery - discharge component	Electricity	GW	PJ	0.0	0.0	0.0	0.00	0.00	0.00	0.000	0.000	0.000	1.000		10.00	12	
1319	ZnBr battery - charge component	Electricity	GW	PJ	0.0	0.0	0.0	0.00	0.00	0.00	0.000	0.000	0.000	1.299		12.50	12	
1320	ZnBr battery storage	Electricity	PJ	PJ	93,750.0	84,375.0	75,000.0	1,875.00	1,687.50	1,500.00	0.703	0.633	0.563	1.000	0.00000		12	
1321	H2 ondergronds - charge component	H2 supply	GW	PJ	40.0	40.0	40.0	2.80	2.80	2.80	0.000	0.000	0.000	1.000		1.00	20	TNO datasheet
1322	H2 ondergronds - discharge component	H2 supply	GW	PJ	48.5	48.5	48.5	1.94	1.94	1.94	0.000	0.000	0.000	1.000		1.00	20	TNO datasheet
1323	H2 ondergronds storage	H2 supply	PJ	PJ	50.0	50.0	50.0	2.25	2.25	2.25	0.000	0.000	0.000	1.000	0.00000		50	TNO datasheet
1329	H2 filling station - discharge component	Mobility	PJ	PJ	0.0	0.0	0.0	0.00	0.00	0.00	0.000	0.000	0.000	1.000		0.03	15	
1470	H2 tank PI FCEV car - charge component	Mobility	PJ	PJ	0.0	0.0	0.0	0.00	0.00	0.00	0.000	0.000	0.000	1.000		0.03	10	
1471	H2 storage medium in vehicle	Mobility	PJ	PJ	0.0	0.0	0.0	0.00	0.00	0.00	0.000	0.000	0.000	1.000	0.00000		10	

UoC: unit of capacity UoA: unit of activity					Investment cost [Mln €(2015)/UoC]			Fixed O&M cost [Mln €(2015)/UoC/yr]			Variable cost [Mln €(2015)/UoA]							
Tech-nology ID	Technology name	Sector	UoC	UoA	2030	2040	2050	2030	2040	2050	2030	2040	2050	Energy input [PJ] per UoA	Storage losses per hour [%]	Time to completely charge/discharge [hr]	Life-time [yr]	Datasource
1471	H2 storage medium in vehicle	Mobility	PJ	PJ	0.0	0.0	0.0	0.00	0.00	0.00	0.000	0.000	0.000	1.000	0.00000		10	
1472	H2 tank PI FCEV - discharge component	Mobility	PJ	PJ	0.0	0.0	0.0	0.00	0.00	0.00	0.000	0.000	0.000	1.000		6.67	10	
1473	H2 storage Filling Station - charge component	Mobility	GW	PJ	0.0	0.0	0.0	0.00	0.00	0.00	0.000	0.000	0.000	1.000		1.00	20	
1474	H2 storage filling station	Mobility	PJ	PJ	18,180.3	18,180.3	18,180.3	181.43	181.43	181.43	0.000	0.000	0.000	1.000	0.00000		20	
1478	Electricity from battery for EV driving	Mobility	GW	PJ	0.0	0.0	0.0	0.00	0.00	0.00	0.000	0.000	0.000	1.000		5.33	10	
1479	Battery in EV car/LDV	Mobility	PJ	PJ	0.0	0.0	0.0	0.00	0.00	0.00	0.000	0.000	0.000	1.000	0.10000		10	
1480	EV charging - home	Mobility	GW	PJ	0.0	0.0	0.0	0.00	0.00	0.00	0.000	0.000	0.000	1.000		8.00	10	
1481	EV charging - office	Mobility	GW	PJ	0.0	0.0	0.0	0.00	0.00	0.00	0.000	0.000	0.000	1.000		8.00	10	
1482	EV charging - car park	Mobility	GW	PJ	0.0	0.0	0.0	0.00	0.00	0.00	0.000	0.000	0.000	1.000		2.00	10	
1483	EV charging - Fast charging	Mobility	GW	PJ	0.0	0.0	0.0	0.00	0.00	0.00	0.000	0.000	0.000	1.000		1.00	10	
2151	Electricity from battery for EV truck driving	Mobility	GW	PJ	0.0	0.0	0.0	0.00	0.00	0.00	0.000	0.000	0.000	1.000		8.00	10	
2152	Battery in truck	Mobility	PJ	PJ	0.0	0.0	0.0	0.00	0.00	0.00	0.000	0.000	0.000	1.000	0.10000		10	
2153	EV truck charing - car park	Mobility	GW	PJ	0.0	0.0	0.0	0.00	0.00	0.00	0.000	0.000	0.000	1.000		2.00	10	
2154	EV truck charing - Fast charging	Mobility	GW	PJ	0.0	0.0	0.0	0.00	0.00	0.00	0.000	0.000	0.000	1.000		1.00	10	

E.4 Transmission technologies

UoC: unit of capacity UoA: unit of activity				Investment cost [Mln €(2015)/(UoC*km)]			Losses per km [%]				
Tech-n	Technology name	UoC	UoA	2030	2040	2050	2030	2040	2050	Life-time [yr]	Data source
1212	Onshore HV transmission line	GW	PJ	2.119	2.119	2.119	0,0350%	0,0350%	0,0350%	30	TNO datasheet
1264	HD natural gas transmission pipeline	GW	PJ	0.341	0.341	0.341	0,0002%	0,0002%	0,0002%	30	Based on Boots (2005)
1330	HD hydrogen transmission pipeline	GW	PJ	0.426	0.426	0.426	0,0003%	0,0003%	0,0003%	30	Based on ID 1264, but scaled by 80%
1456	Offshore HVDC grid	GW	PJ	1.133	1.133	1.133	0,0003%	0,0003%	0,0003%	30	North Sea Energy project
2506	CO2 network for CO2 storage	Mton/yr	Mton	0.014	0.014	0.014	0,0000%	0,0000%	0,0000%	25	ZEP

E.5 References

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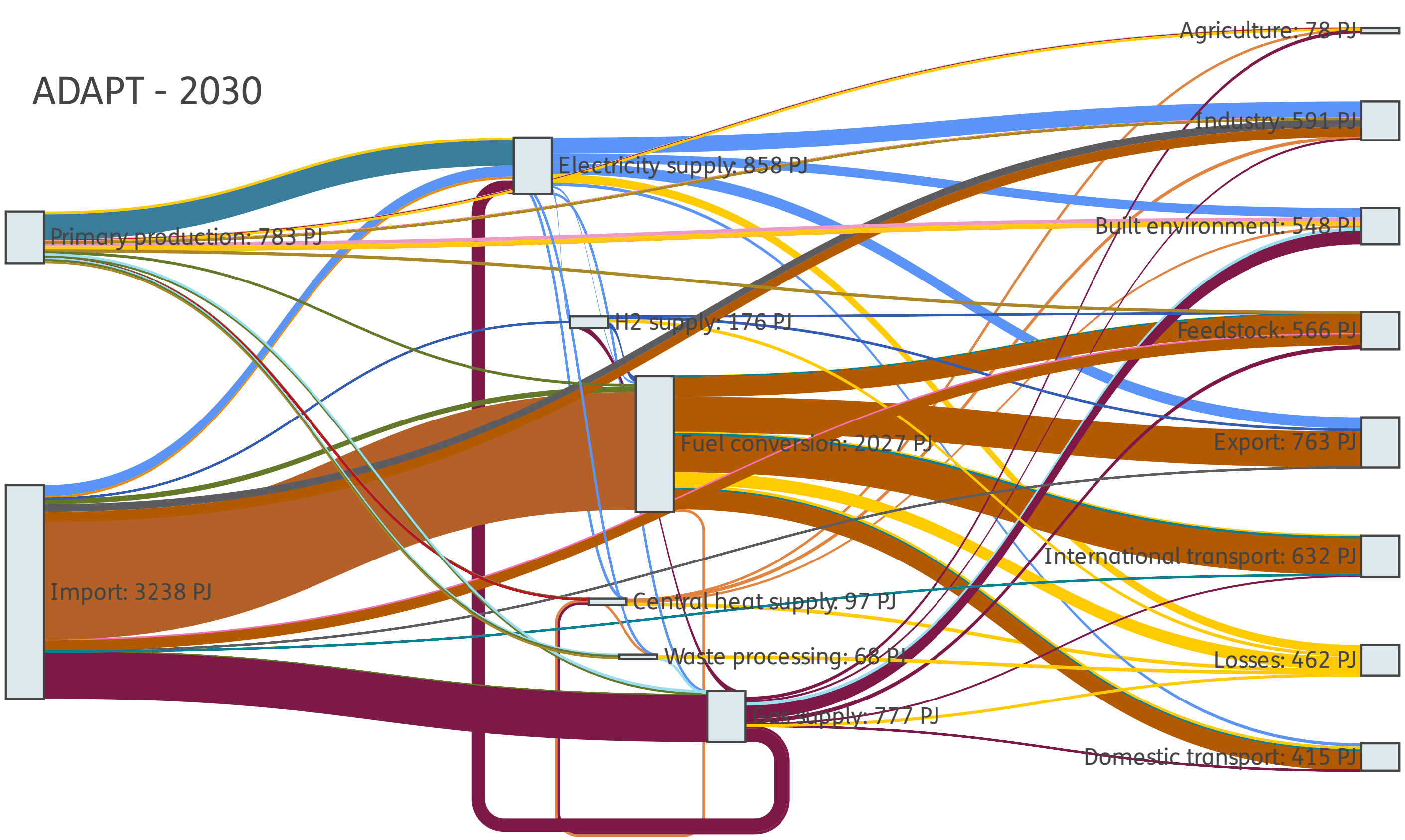
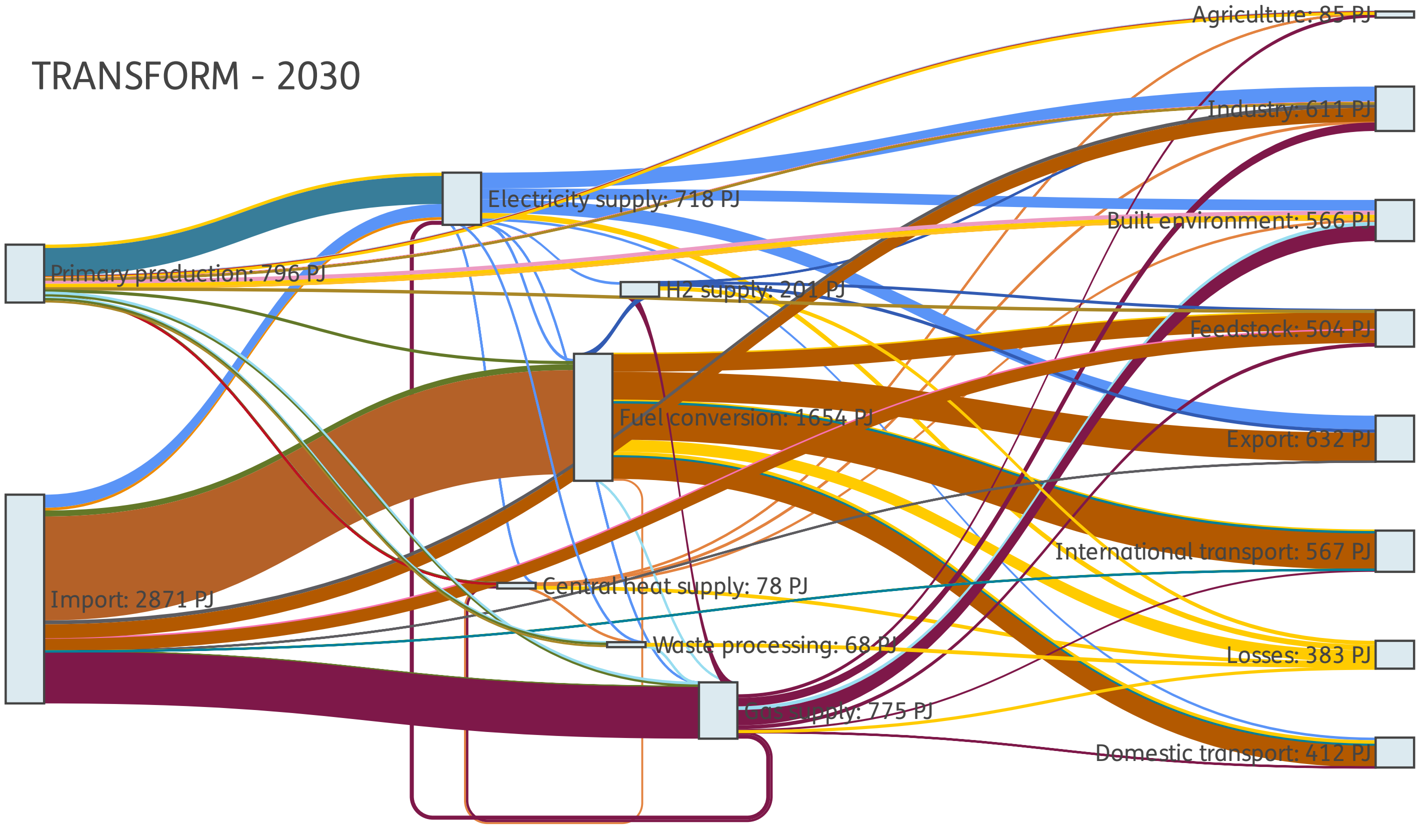
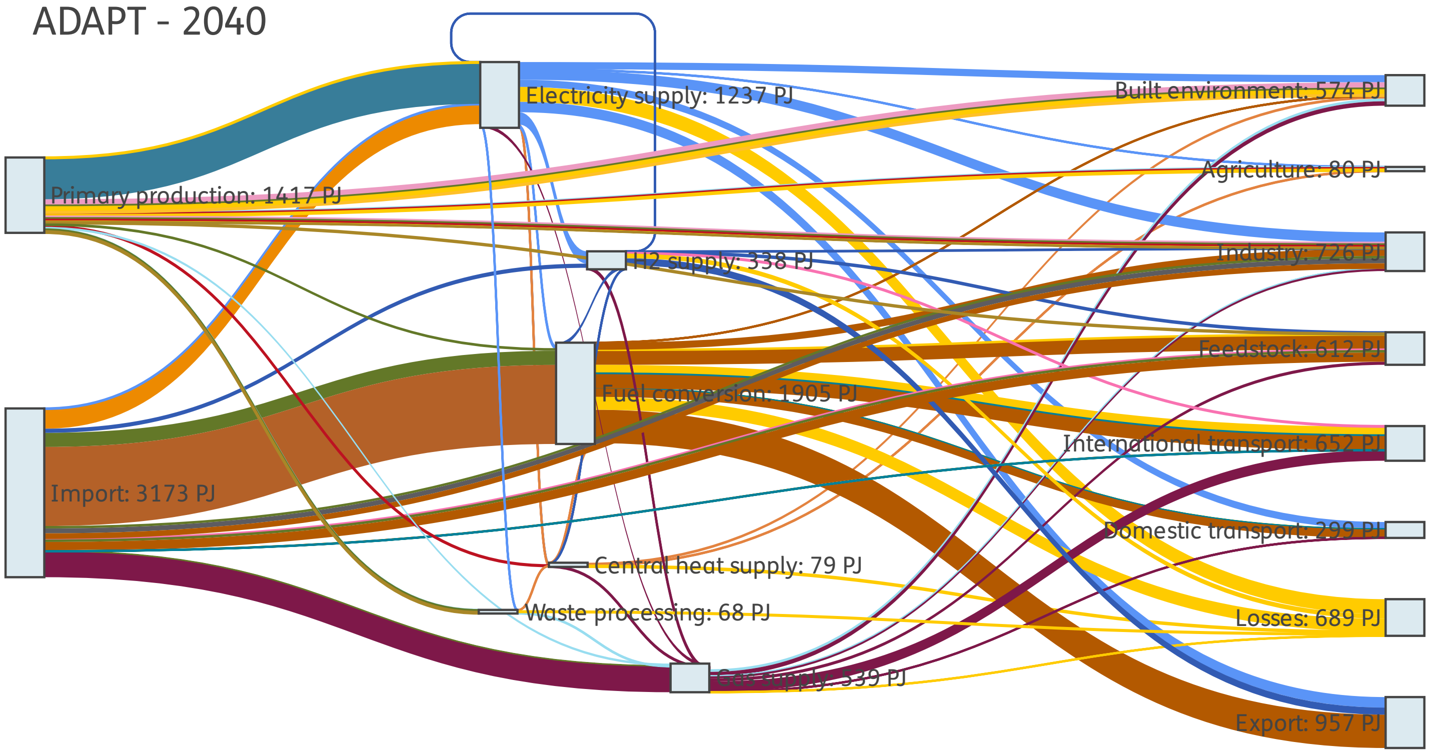
Appendix F

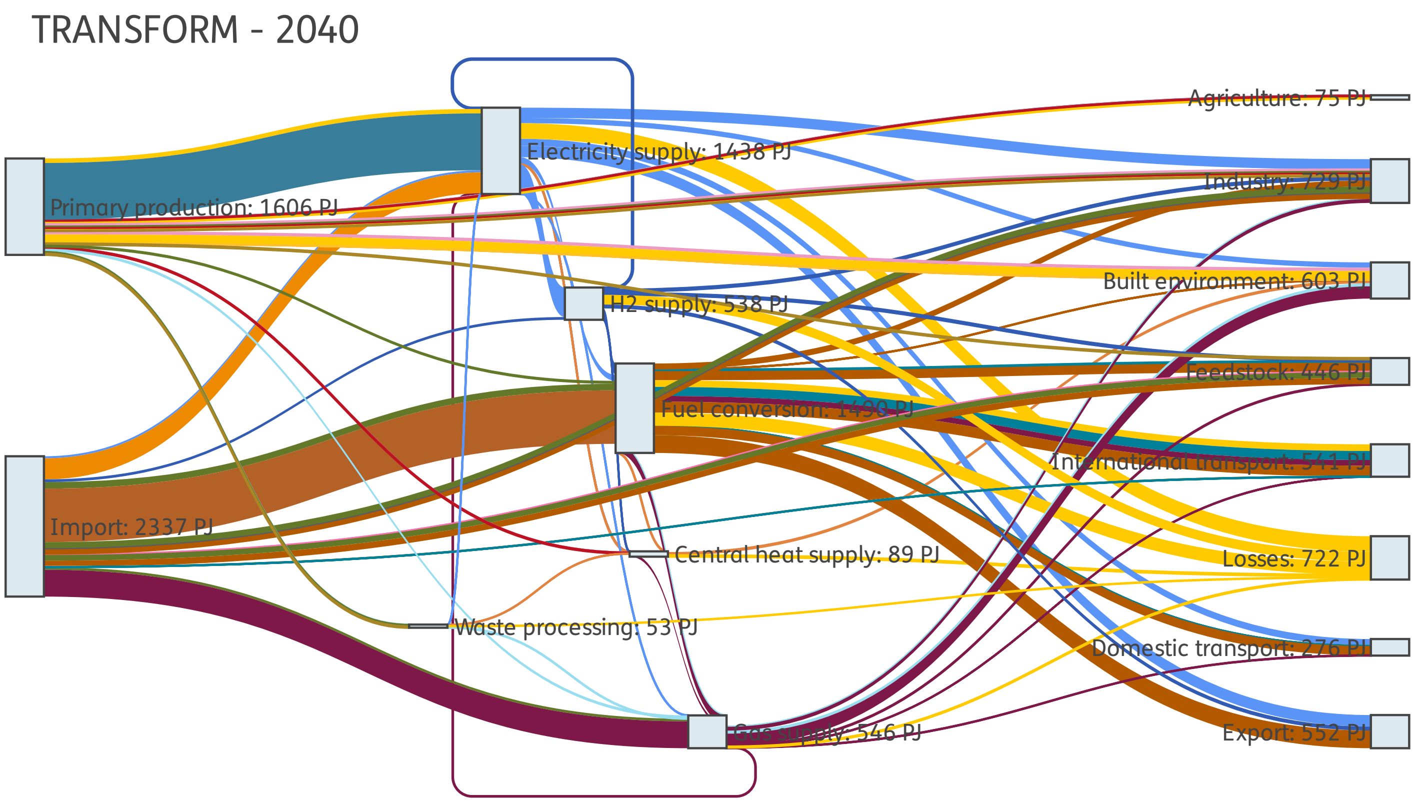
Sankey diagrams of the total energy system

Below are Sankey diagrams of the Dutch energy system in 2030, 2040 and 2050 for ADAPT and TRANSFORM. To read each individual energy flow from the Sankey diagrams, please go to the interactive website that can be found at www.energy.nl

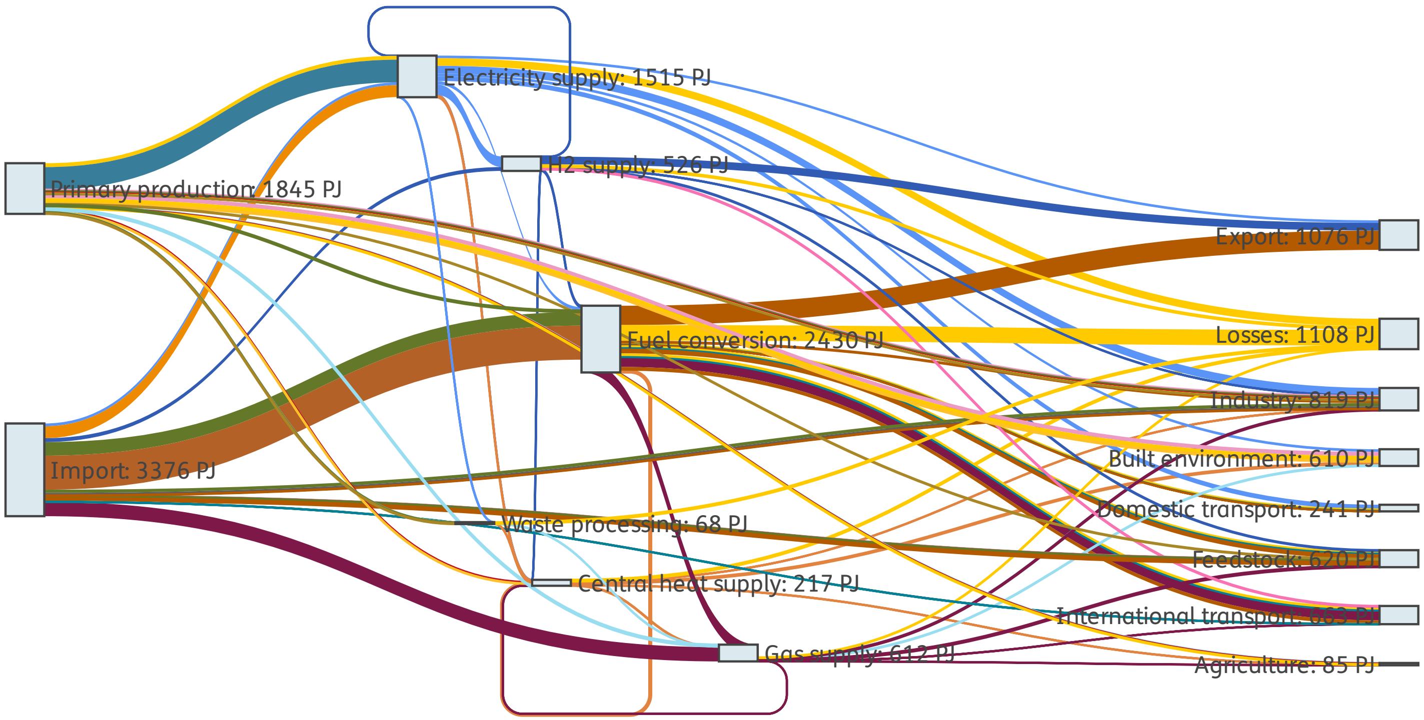

ADAPT - 2030
Agriculture: 78 PJ
Industry: 591 PJ
Electricity supply: 858 PJ
Primary production: 783 PJ
Built environment: 548 PJ
H2 supply: 176 PJ
Feedstock: 566 PJ
Fuel conversion: 2027 PJ
Export: 763 PJ
International transport: 632 PJ
Import: 3238 PJ
Central heat supply: 97 PJ
Waste processing: 68 PJ
Losses: 462 PJ
Gas supply: 777 PJ
Domestic transport: 415 PJ


TRANSFORM - 2030
Agriculture: 85 PJ
Industry: 611 PJ
Electricity supply: 718 PJ
Built environment: 566 PJ
Primary production: 796 PJ
H2 supply: 201 PJ
Feedstock: 504 PJ
Fuel conversion: 1654 PJ
Export: 632 PJ
International transport: 567 PJ
Central heat supply: 78 PJ
Import: 2871 PJ
Waste processing: 68 PJ
Losses: 383 PJ
Gas supply: 775 PJ
Domestic transport: 412 PJ

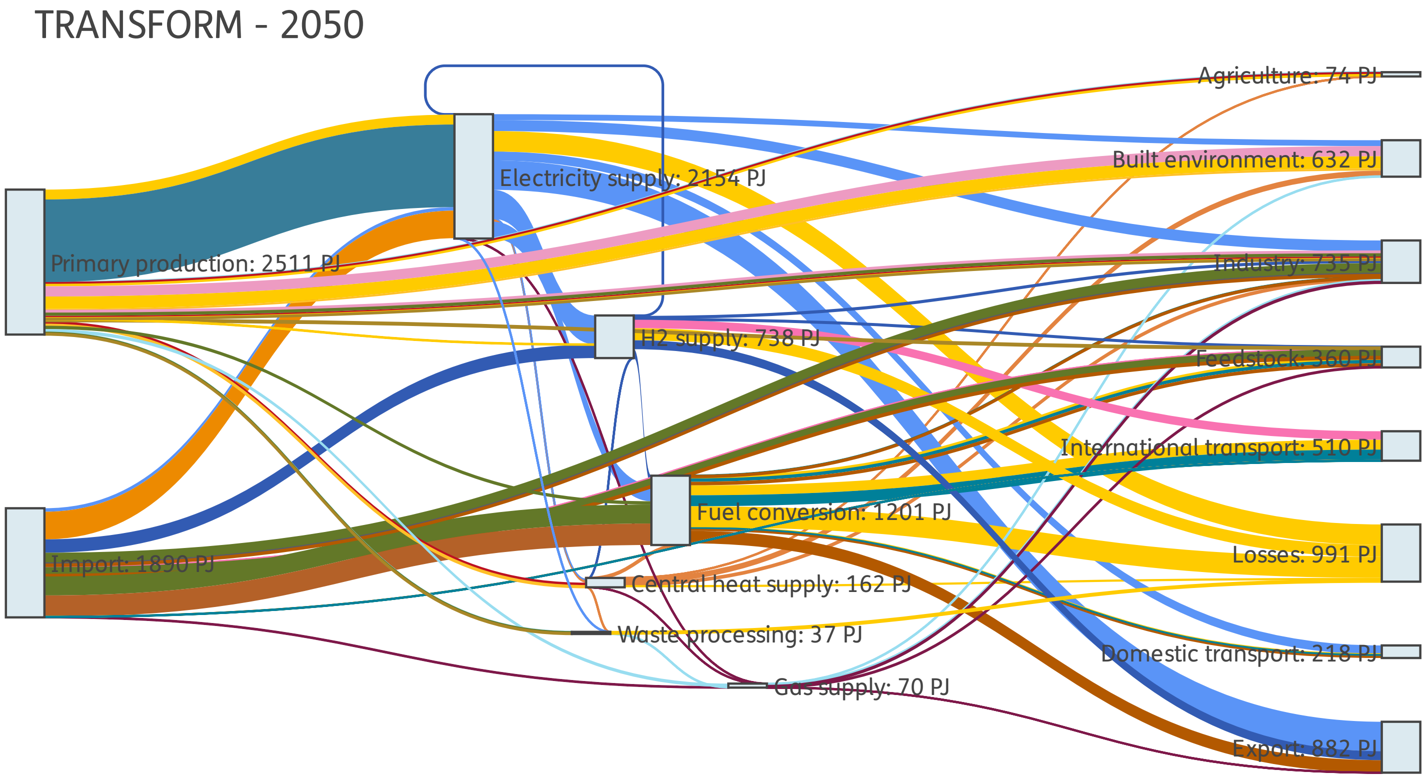

ADAPT - 2040
Electricity supply: 1237 PJ
Primary production: 1417 PJ
H2 supply: 338 PJ
Fuel conversion: 1905 PJ
Import: 3173 PJ
Central heat supply: 79 PJ
Waste processing: 68 PJ
Gas supply: 539 PJ
Built environment: 574 PJ
Agriculture: 80 PJ
Industry: 726 PJ
Feedstock: 612 PJ
International transport: 652 PJ
Domestic transport: 299 PJ
Losses: 689 PJ
Export: 957 PJ


TRANSFORM - 2040
Primary production: 1606 PJ
Import: 2337 PJ
Electricity supply: 1438 PJ
H2 supply: 538 PJ
Fuel conversion: 1490 PJ
Central heat supply: 89 PJ
Waste processing: 53 PJ
Gas supply: 546 PJ
Agriculture: 75 PJ
Industry: 729 PJ
Built environment: 603 PJ
Feedstock: 446 PJ
International transport: 541 PJ
Losses: 722 PJ
Domestic transport: 276 PJ
Export: 552 PJ

ADAPT - 2050



Electricity supply: 1515 PJ
H2 supply: 526 PJ
Primary production: 1845 PJ
Export: 1076 PJ
Fuel conversion: 2430 PJ
Losses: 1108 PJ
Industry: 819 PJ
Import: 3376 PJ
Built environment: 610 PJ
Domestic transport: 241 PJ
Waste processing: 68 PJ
Feedstock: 620 PJ
Central heat supply: 217 PJ
International transport: 663 PJ
Gas supply: 612 PJ
Agriculture: 85 PJ


TRANSFORM - 2050
Agriculture: 74 PJ
Built environment: 632 PJ
Electricity supply: 2154 PJ
Primary production: 2511 PJ
Industry: 735 PJ
H2 supply: 738 PJ
Feedstock: 360 PJ
International transport: 510 PJ
Fuel conversion: 1201 PJ
Losses: 991 PJ
Import: 1890 PJ
Central heat supply: 162 PJ
Waste processing: 37 PJ
Domestic transport: 218 PJ
Gas supply: 70 PJ
Export: 882 PJ

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