Renewable and Sustainable Energy Reviews 158 (2022) 112097

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Towards a climate-neutral energy system in the Netherlands

Martin Scheepers [a,*], Silvana Gamboa Palacios [a], Elodie Jegu [a], Larissa P. Nogueira [a], Loes Rutten [a], Joost van Stralen [a], Koen Smekens [a], Kira West [a], Bob van der Zwaan [a,b,c,**]

[a] *TNO, Energy Transition Studies (ETS), Amsterdam, the Netherlands*
[b] *University of Amsterdam, Faculty of Science (HIMS and IAS), Amsterdam, the Netherlands*
[c] *Johns Hopkins University, School of Advanced International Studies (SAIS), Bologna, Italy*

ARTICLE INFO

Keywords:
The Netherlands
Energy scenarios
Emissions reduction
Renewable energy
Hydrogen
Energy system costs

ABSTRACT

This paper presents two different scenarios for the energy system of the Netherlands that achieve the Dutch government's national target of near net-zero greenhouse gas emissions in 2050. Using the system optimisation model OPERA, the authors have analysed the technology, sector and cost implications of the assumptions underlying these scenarios. While the roles of a number of key energy technology and emission mitigation options are strongly dependent on the scenario and cost assumptions, the analysis yields several common elements that appear in both scenarios and that consistently appear under differing cost assumptions. For example, one of the main options for the decarbonisation of the Dutch energy system is electrification of energy use in end-use sectors and for the production of renewable hydrogen with electrolysers. As a result the level of electricity generation in 2050 will be three to four times higher than present generation levels. Ultimately, renewable energy – particularly from wind turbines and solar panels – is projected to account for the vast majority of electricity generation, around 99% in 2050. Imbalances between supply and demand resulting from this variable renewable electricity production can be managed via flexibility options, including demand response and energy storage. Hydrogen also becomes an important energy carrier, notably for transportation and in industry. If import prices are lower than costs of domestic production from natural gas with CCS or through electrolysis from renewable electricity (2.4–2.7 €/kgH_2), the use of hydrogen increases, especially in the built environment.

1. Introduction

Nearly all countries have committed to substantial reductions in emissions of greenhouse gases (GHGs) in order to comply with the Paris Agreement target of limiting the global average anthropogenic temperature increase to 1.5–2.0 °C [1–3]. The European Union, in particular, aims to achieve full carbon-neutrality by the middle of the century [4]. In this context, the Netherlands has also set in motion an energy transition to fulfil its European and international obligations. According to the Dutch Climate Act [5], the Netherlands must have an energy system by 2050 with greenhouse gas emissions that are 95% lower than in 1990. How and with what technologies can that goal be achieved? What are the consequences of technology choices for the nature of the Dutch energy system? Can the Dutch targets be met by radically reforming the national economy, or can the current one be largely maintained complemented with means to avoid emitting CO_2 into the atmosphere? These are the types of questions that this article attempts to address.

It is impossible to predict what the future will look like. An energy system with drastically reduced or without CO_2 emissions is certainly conceivable from a technological point of view, but many differing opinions exist as to what such a system should look like. In recent years, various studies have been conducted describing decarbonisation pathways for the European Union [6–11], for multiple countries simultaneously [12] or individual European countries separately, e.g. Belgium [13], Denmark [14], France [15,16], Germany [17], Ireland [18] and the United Kingdom [19–21]. Meta-studies that compare different scenario studies have also been conducted, for the European Union [22], Denmark [23] and Germany [24], among others. In all these studies, the implications of far-reaching GHG emissions reduction (ranging from 75% to 100%) in the energy system are investigated with energy system models, which can determine the renewable energy share in the primary supply and the role of electricity. Several studies also map out economic

* Corresponding author.
** Corresponding author. TNO, Energy Transition Studies (ETS), Amsterdam, the Netherlands.
E-mail addresses: martin.scheepers@tno.nl (M. Scheepers), bob.vanderzwaan@tno.nl (B. van der Zwaan).

https://doi.org/10.1016/j.rser.2022.112097
Received 3 September 2021; Received in revised form 23 November 2021; Accepted 9 January 2022
Available online 21 January 2022
1364-0321/

List of abbreviations:

BECCS	Bio Energy with Carbon dioxide Capture and Storage
CCS	Carbon dioxide Capture and Storage
CCU	Carbon dioxide Capture and Utilisation
EV	Electric Vehicle
FCEV	Fuel Cell Electric Vehicle
GDP	Gross Domestic Product
GHG	Greenhouse Gas
PEM	Proton Exchange Membrane
PV	Photo Voltaic solar panels
SMR	Steam Methane Reforming
SOEC	Solid Oxide Electrolyser Cell

effects, varying from total investment costs and total system costs to the impacts these may have on GDP. Comparative studies provide insights into the similarities and differences in results that derive from different approaches to such energy scenarios. They can also show which energy system developments may be more likely than others, and which ones remain most uncertain.

Dutch scenario studies published in recent years indicate a wide variety of possible future energy systems for the Netherlands, but the determinants of these scenarios remain often unclear [25]. Multiple renewable energy options appear in most scenarios, while fewer options are available in others. The presence or absence of certain climate change mitigation options, as well as the abundance or limitation of specific low-carbon energy technologies, has a profound impact on the costs of the overall energy system. Parties involved in the Dutch energy transition, such as policy makers, energy companies, network operators, technology developers, non-governmental organizations, and energy users need insights into the availability and feasibility of options, and into the impacts that technology choices may have. The aim of this study is to meet these needs by calculating energy scenarios with a cost-optimised energy system model, and to show the impact of social developments and policy choices on the development of the energy system and on overall energy system costs. Although the energy system model used for this study has already been described in the scientific literature [26], a low-emissions scenario study with this model has not been presented to the scientific community before. This study differs from other national-level low-carbon scenario studies in the completeness of the energy system coverage (including the use of feedstocks for industrial production and energy supply to international aviation and maritime transport), the coverage of all domestic greenhouse gases, a wide range of technology options and a high time resolution. These features facilitate investigation of the optimal deployment of large capacities of intermittent renewable energy. Using this cost-optimised system model makes it possible to analyse in great detail the cross-sectoral consequences of changes in scenario assumptions (e.g. societal preferences, policy choices, technology developments) and their effects on system costs. The dataset used for this study contains the most up-to-date, publicly available techno-economic information for a large number of technologies. Modelling a near net-zero emission energy system in this way has never been done before for the Netherlands.

Country-specific characteristics play an important role in scenario studies for a particular country, such as the potential for sustainable energy production, the possibility to store CO_2 in depleted natural gas fields and the size and characteristics of different demand sectors. This also applies to political and social preferences and objections with regard to options such as nuclear energy, biomass and carbon dioxide capture and storage (CCS). This becomes more clear when the results of this scenario study are compared with those of comparable studies for some other EU countries. Today the Netherlands has a relatively large energy-intensive industry (in the top 5 in the EU [27]), and the demand for fuels for international aviation and shipping due to large seaports and a large airport is also relatively high (comparable to 1/5 of the domestic final energy consumption [28]). This influences the role of biomass and hydrogen in the future Dutch energy system and necessitates the import of biomass and possibly also hydrogen. Germany and Belgium also have relatively large industrial sectors. The North Sea offers the Netherlands, as well as the United Kingdom, Denmark, Germany, and Belgium, the possibility to generate wind energy offshore on a large scale and to store CO_2 in empty gas fields under the North Sea bed, but the societal support for the latter option is uncertain. Where Germany and Belgium phase out their nuclear capacity, the United Kingdom and France are building new nuclear power stations. The political and social support for this option in the Netherlands is not yet clear.

Section 2 of this paper explains the scenarios used for this study and also briefly introduces the cost optimisation model, called OPERA, that was employed to calculate these scenarios. The results of the model calculations are presented in Section 3: the changes in energy supply mix, the growth of electricity production, the application of CO_2 capture, storage and use, the role of biomass and hydrogen, and the changes in total system costs. The results of the scenario study show how the Dutch energy system could change under a stringent GHG reduction target. Section 4 discusses how likely these outcomes are and what they depend on. In this section the results will also be compared with those of scenario studies of several other EU countries. Based on this discussion, several overarching conclusions are drawn in section 5.

2. Methodology

For the analysis presented in this paper the energy system model OPERA is employed, a technology-rich energy system optimisation model for the Netherlands. OPERA is a Linear Programming (LP) optimisation model, which uses — like most modern optimisation models — the interior point method to solve the LP set-up. It computes the cost-optimal energy and GHG system configuration, under specific constraints, by minimizing an objective function that expresses the total system costs for a given future year. An extended model description with a detailed specification of OPERA's underlying set-up, assumptions, and methodology can be found in Ref. [26]. Two features that make OPERA especially useful for the purpose of the present study are: (1) it covers the complete energy system of the Netherlands and reflects all domestic emissions and types of greenhouse gases; (2) it simulates energy supply and demand on an hourly basis and allows for separately handling distinct sets of hours.

2.1. OPERA

In recent years, the OPERA model has been employed to give strategic policy advice to the Dutch government and other stakeholders in the Netherlands with regard to the national energy transition, and to undertake analyses on the roles of a broad variety of energy technologies needed to decarbonise the Dutch energy system (for example [29,30]). Using OPERA it is possible to examine the implications of technology diffusion and efficiency improvement as well as many kinds of policy interventions. For this study, OPERA was used to generate configurations of the Dutch energy system and the associated emissions, given specific goals and preconditions, at the lowest system costs for three specific years: 2030, 2040 and 2050. Although OPERA is not a dynamic model, it does consider existing assets by taking into account investments made in previous years and the technical lifetimes of technologies. In the year for which the optimisation is performed, new investments are added to the existing assets if needed. The model can choose from more than 600 technology options covering the whole technology chain from production to end-use demand services, including technologies that convert primary into final energy. The techno-economic data for these options are retrieved from a database containing current data and projections for parameter values in 2030 and 2050, derived from an extensive literature assessment. For a large number of technologies, detailed techno-economic fact sheets have been published including performance and cost parameters for 2030 and 2050 based on assumed learning rates.[1] For innovative technologies for which no learning rate is known, a cost reduction of 20% is assumed between 2030 and 2050.

The energy system solutions that OPERA computes must meet the demand for:

- energy services (heat and electricity) for the built environment, industry, services sector and agriculture,
- domestic transport of people and goods,
- fuels for international aviation and shipping (bunker fuels),
- production of industrial products (including steel, ammonia and high value chemicals).

OPERA calculates the optimal primary energy mix and final energy mix for each end-use sector. Several other assumptions and constraints are applied in the OPERA scenarios. Primary fossil fuels (oil, coal and natural gas) are assumed to be available at a given price (an exogenous assumption). For domestic renewable energy (solar, onshore and offshore wind, biomass, geothermal energy), a maximum potential applies. Captured CO_2 can either be stored, up to a maximum available capacity, or used in industrial processes. OPERA can import refined oil products, biomass, biofuels and electricity at a given (exogenous) price and maximum volume. Electricity import from and export to neighbouring countries have been determined using the European electricity market model COMPETES [31]. Import and export of hydrogen have been investigated in this study (see Section 3.5). In calculating system costs OPERA uses a national cost-benefit approach with a social discount rate of 3%. Taxes, levies (e.g. CO_2 price) and subsidies are not taken into account. Total system costs are the sum of the annualised investment costs, annual operation & maintenance costs, cost for energy transport and costs for imported energy minus revenues from exported energy.

2.2. Scenarios

For this study two scenarios were developed: ADAPT and TRANSFORM [32]. Both scenarios use the Dutch Climate Act objective: a reduction of GHG emissions in the Netherlands to a level that is 95% lower in 2050 than in 1990, supporting the goal outlined in the Paris Agreement to limit average global temperature rise to below 1.5°. The two scenarios also meet the objective of the Dutch Climate Agreement of a reduction of GHG emissions by 49% in 2030 [33]. The scenarios differ in the way these two goals are achieved, in particular the difference in intrinsic motivation and behaviour of citizens and companies. In the ADAPT scenario, the Dutch economy builds on existing infrastructure and strengths, while preserving the current lifestyle, but with a significant reduction in CO_2 emissions. In the TRANSFORM scenario, behavioural changes in Dutch society support a radical shift to a more sustainable economy, making the Netherlands a less energy intensive economy overall. While in the ADAPT scenario carbon capture and storage (CCS) can be applied, this technology is excluded from the TRANSFORM scenario as a result of increased resistance in society. Moreover, the TRANSFORM scenario further restricts biomass use compared to the ADAPT scenario. In accordance with Dutch government policy, no coal-fired power plants are used after 2024 in either scenario and the one existing nuclear power plant is decommissioned at the end of 2033. Construction of a new nuclear power plant is possible. Assumptions regarding GHG emissions reduction for the two scenarios are shown in Table 1. Other parameter assumptions are shown in the Appendix.

[1] The fact sheets are available on www.energy.nl.

Table 1
Assumptions for GHG emissions reduction for the ADAPT and TRANSFORM scenario. Values for 2040 are linearly interpolated.

	ADAPT		TRANSFORM	
	2030	2050	2030	2050
GHG reduction target for The Netherlands[a]	−49%	−95%	−49%	−95%
GHG reduction target for international aviation and shipping	0%	−50%	0%	−95%

[a] Applies to CO_2 and non-CO_2 GHGs for all domestic sectors, except GHG emissions from land use, land use change and forestry (LULUCF).

3. Results

3.1. Energy supply and system costs

Fig. 1 shows the total primary energy supply for the ADAPT and TRANFORM scenarios. The ADAPT scenario without a GHG emission target is also shown and, as a reference, the realised primary energy supply in 2018. The observed reduction in primary energy supply in the scenarios in 2030 compared to 2018 is the result of energy savings and reduced energy conversion losses in, among others, electricity production (e.g. wind and solar replace less efficient thermal power plants) and the transport sector (e.g. electric vehicles replace vehicles with internal combustion engines). Note that the primary energy supply in 2030 for both scenarios is the result of a cost-optimisation of the energy system, whereas the existing energy system is not cost-optimal, because economic actors behave rationally in their own interest and not necessarily have the optimal system solution in mind, have insufficient information and markets are imperfect. Furthermore, the calculated energy system in both scenarios only includes the energy use of oil refining for domestic use of oil products and bunker fuels and not for the export of oil products, whereas the 2018 figure does include exports.

After 2030, the total primary energy supply in ADAPT increases, due to an increase in energy demand caused by economic growth and higher energy conversion losses (for example, in hydrogen and synthetic fuels production). In TRANSFORM, by contrast, primary energy supply decreases after 2030 despite economic growth and increased hydrogen production, as a result of the assumed structural shifts away from industrial and agricultural activity towards services sector activities and changing demand and modal shifts in the transport sector.

The supply mix in the ADAPT and TRANSFORM scenarios show the shift from fossil primary energy to renewable energy. Both scenarios show a substantial increase of electricity production from wind and solar energy. More fossil fuels remain in the ADAPT scenario, particularly coal for steel production and natural gas for hydrogen production, both in combination with CCS. More biomass is used in the ADAPT scenario compared to the TRANSFORM scenario as a result of the scenario assumptions on biomass availability.

Fig. 1 also shows the total system costs relative to the system costs of the ADAPT scenario in 2030. After 2030, the total system costs for the ADAPT scenario increase, while total system costs for TRANSFORM decline. The change in total system costs is a combination of changing energy demand (growing in the ADAPT scenario and declining in the TRANSFORM scenario), decreasing technology costs and the application of new, more costly technologies (in both scenarios). In the ADAPT no-target scenario, investments continue to be made in fossil energy assets. In contrast to the two sustainable scenarios, fossil energy prices are assumed to be higher than in the ADAPT scenario and continues to rise after 2030 (see Table 2), because these energy sources will become scarce as it is assumed that other countries in the world also continue to use fossil fuels. Although renewable electricity and renewable fuel production technologies will at some point become competitive with fossil fuel options (e.g. in Fig. 1 the wind and solar energy share also increases in the no-target scenario), fossil production capacity only declines gradually and the depreciation costs of fossil assets continue to be

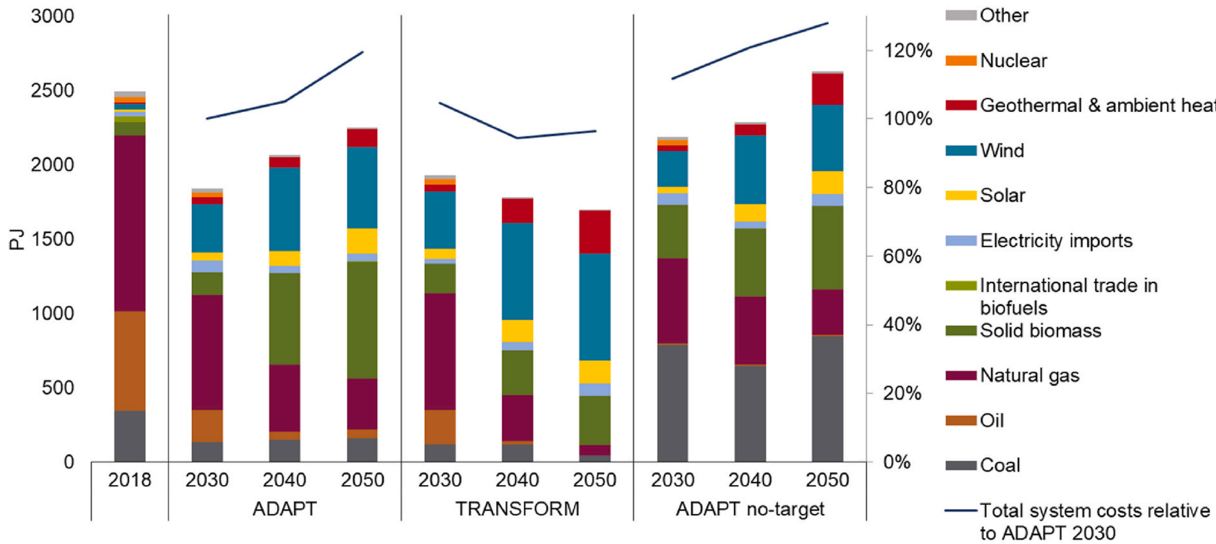

Fig. 1. Total energy supply in PJ (excluding energy for international aviation and shipping and non-energy use) and total relative system costs (ADAPT 2030 = 100%).

Table 2
Fossil energy prices in ADAPT, TRANSFORM and ADAPT no-target scenario. The fossil energy prices in the ADAPT no-target scenario are based on the IEA Current Policy scenario [34].

Prices in $€_{2017}$/GJ	2030	2040	2050
ADAPT and TRANSFORM			
oil	14,6	14,6	14,6
natural gas	7,5	7,5	7,5
coal	2,9	2,9	2,9
ADAPT no target			
oil	21,0	26,0	29,9
natural gas	10,4	11,5	12,7
coal	3,6	4,0	4,3

part of the total system costs. As a result, the total system costs in the ADAPT scenario without a GHG reduction target are higher than the ADAPT scenarios with a GHG reduction target.

3.2. Electricity production

In both scenarios fossil fuels for heat production are replaced by electrified heating in the built environment, agriculture and industry (for example, via electric boilers and electric heat pumps). In the transport sector, vehicles with internal combustion engines are replaced by electric vehicles, especially for passenger cars and light duty vehicles. Electricity is also used to produce hydrogen for industry and as a transport fuel. This leads to a substantial increase in the demand for electricity, in TRANSFORM more than ADAPT, because in TRANSFORM other emissions reduction options are unavailable (e.g. hydrogen production from natural gas with carbon capture and storage) or less available (e.g. biomass for heat production).

As a result, the share of electricity in the energy system (before conversion to other energy carriers, such as hydrogen) grows from 19% in 2018 to 43% and 71% in 2050 for the ADAPT and TRANSFORM scenarios respectively, see Fig. 2. In both scenarios in 2030,

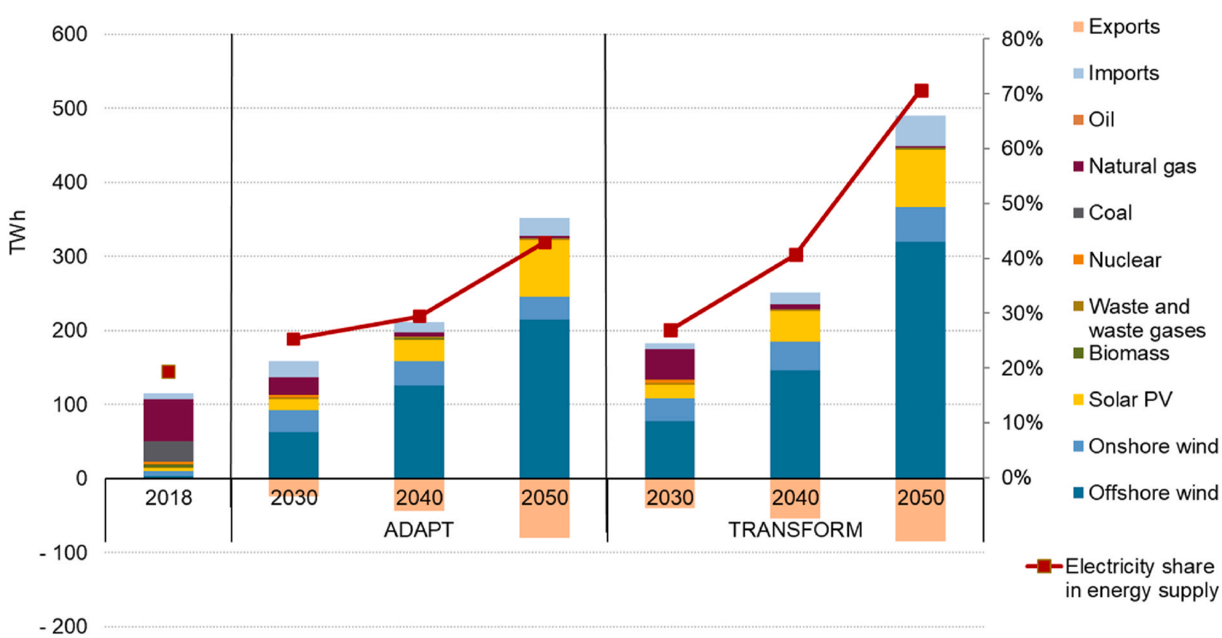

Fig. 2. Electricity supply (TWh) and electricity share in energy supply (%) for the Dutch energy system in 2018 and in the ADAPT and TRANSFORM scenarios.

approximately 68% of the electricity is generated from wind and solar energy. By expanding the generation capacity of wind and solar energy, electricity production comes almost exclusively from renewable energy sources by 2050. In addition to centralised electricity generation (e.g. offshore wind), electricity production also takes place in the end-use sectors, in particular in the built environment and agriculture sector with solar panels (PV).

Fig. 2 also shows trade of electricity with neighbouring countries. During a given year, there are periods when the Dutch electricity system imports or exports electricity. From 2030 onwards in the TRANSFORM scenario and from 2040 in the ADAPT scenario, the Netherlands becomes a net exporter of electricity over the year. More variable renewable energy in the electricity system increases the need for flexibility in order to keep electricity supply and demand in balance. In OPERA, this flexibility requirement is met with power trade with neighbouring countries, peak power generation (natural gas), demand response (EV's, electrolysers), curtailment of wind and solar energy, and with energy storage (batteries and compressed air and hydrogen storage in salt caverns). The required capacities for flexibility options were determined based on hourly demand and supply profiles. For energy storage options, electricity is stored in the event of surpluses and supplied to the system in the event of shortages.

3.3. CO_2 capture, storage and use

Carbon capture and storage (CCS) is only applied in the ADAPT scenario. Nevertheless, in the TRANSFORM scenario, carbon captured from biobased processes is used as feedstock for synthetic fuels production in 2050 (6.5 Mt of carbon capture and utilisation, CCU). In the ADAPT scenario in 2050, 15 Mt CO_2 (23% of the total captured CO_2) is utilised for the production of synthetic fuels.

In the ADAPT scenario, 86% of the available CO_2 storage capacity is used in 2030, and in 2040 and 2050 the full available capacity for CO_2 storage of is used (19 and 50 $MtCO_2$/year respectively). In OPERA, it is assumed that captured CO_2 is transported by pipeline to the processes that use CO_2. In both scenarios, carbon from CO_2 capture is used for the production of synthetic fuels. Because part of the captured CO_2 comes from biomass combustion, the synthetic fuels also contain biogenic carbon. CO_2 emissions from these fuels – synthetic fuels are used by airplanes and ships – end up in the atmosphere. In calculating the GHG reduction, OPERA takes the fossil part of CO_2 emissions into account as part of the residual GHG emissions.

Fig. 3 shows the total CO_2 captured in the ADAPT scenario and the processes from which it is captured. In 2030, CO_2 capture is applied to waste incineration plants and hydrogen production from natural gas ('blue hydrogen'). CO_2 capture from the steel and chemical industry is added in 2040. In 2050, CO_2 capture in hydrogen production and the steel industry increases, and it also takes place in other industries. The industry sector realises negative emissions (10 Mt in 2050) by applying CCS to biomass-based processes (bio-energy CO_2 capture and storage, BECCS) that compensate for remaining GHG emissions from other sectors.

3.4. Biomass

Fig. 4 shows the input-output flows for bioenergy. In addition to the biomass available in the Netherlands, woody biomass and biofuels are imported. The scenario assumption for available biomass is different in the ADAPT and the TRANSFORM scenario (see Appendix). In both scenarios biomass is used in industry for heat production and for the production of biofuels. The built environment and agriculture sectors also use biomass for heat production. Most of the biofuels are used by international aviation and shipping. It is assumed that half of the biofuels for international aviation and shipping are imported. Biogas is produced in industry and by the agriculture sector, and almost all biogas is used within these sectors.

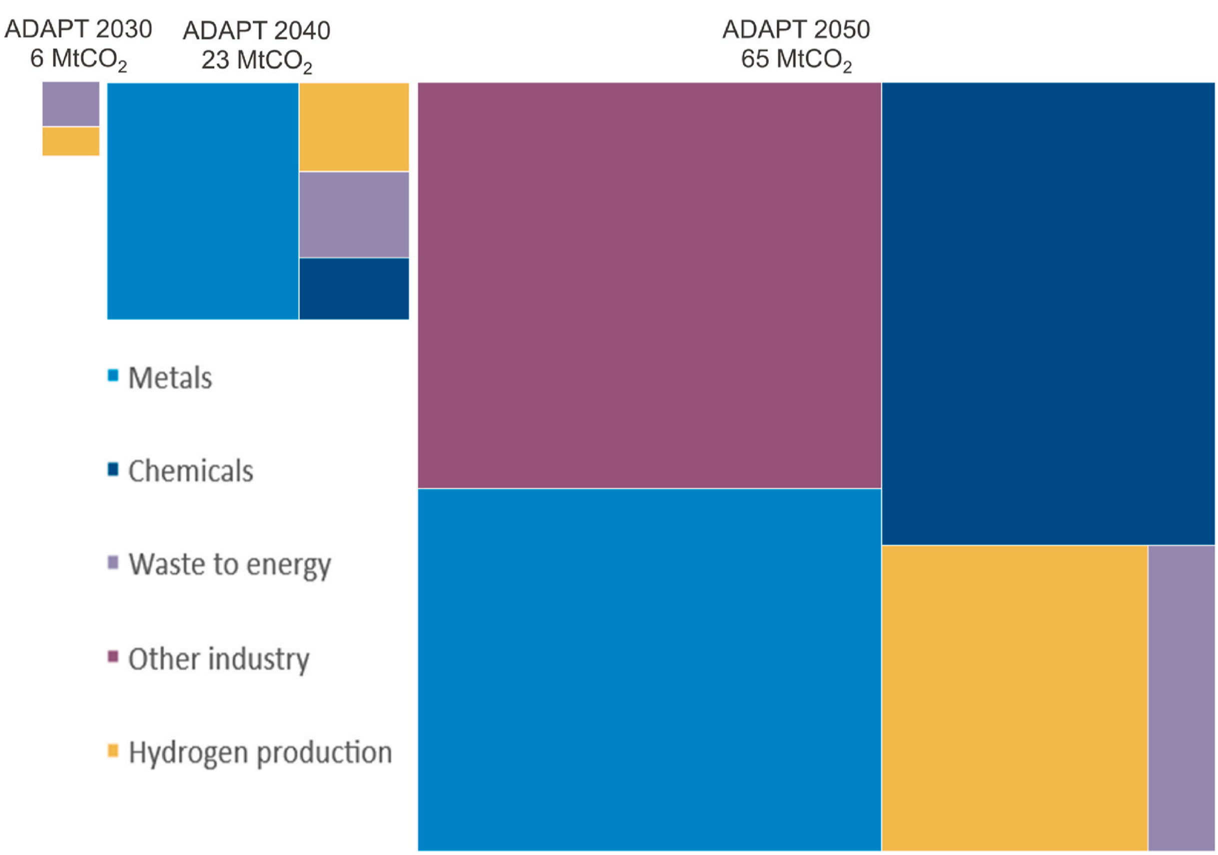

Fig. 3. Carbon captured for storage (CCS) and utilisation (CCU) in the ADAPT scenario by different industries.

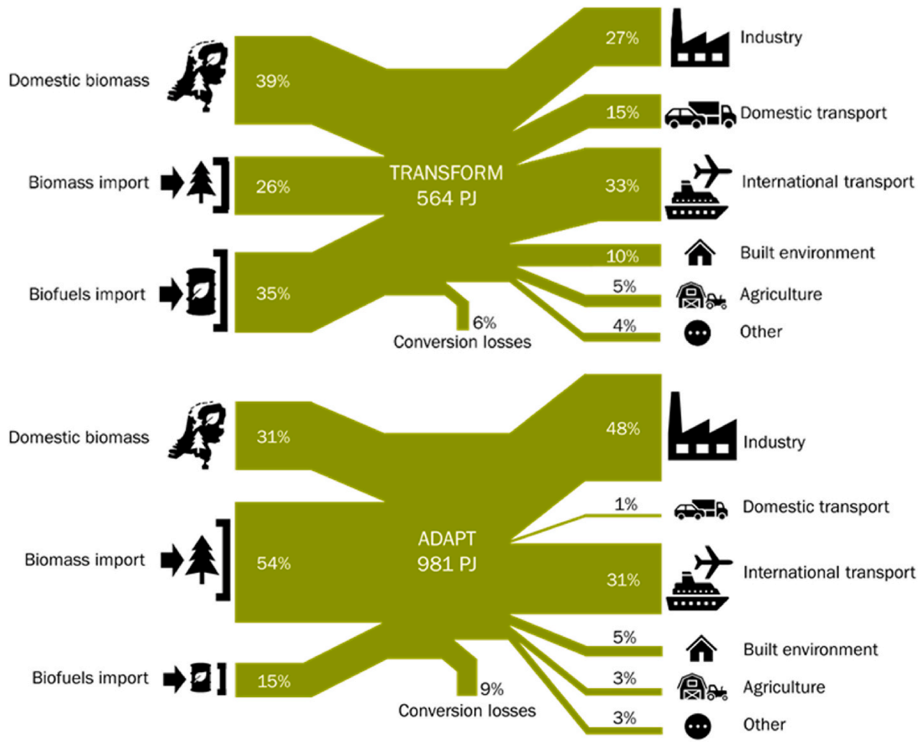

Fig. 4. Bioenergy flows in ADAPT and TRANSFORM scenarios in 2050.

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

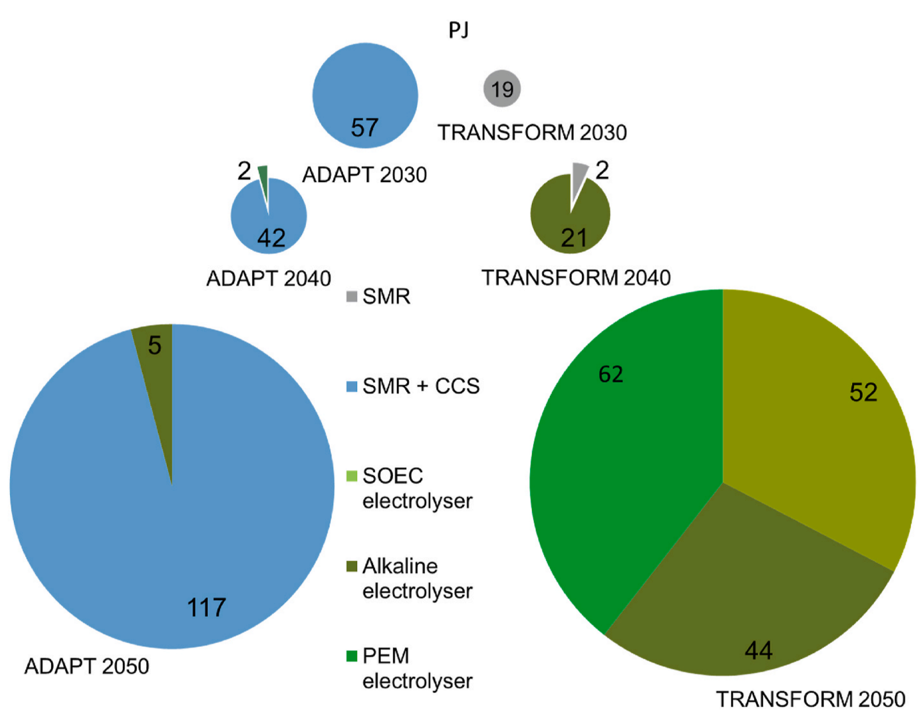

Fig. 5. Hydrogen production plants in ADAPT and TRANSFORM scenarios. SMR: steam methane reformer; SOEC: solid oxide electrolyser cell; PEM: proton exchange membrane.

3.5. Hydrogen production

A distinction is made between hydrogen from dedicated hydrogen plants and hydrogen produced within industrial processes. In 2018, hydrogen is only used in industry and produced from fossil fuels (estimated at 180 PJ, see Ref. [35]) and as by-product in electrolytic chlorine production. In the ADAPT and TRANSFORM scenarios the industrial hydrogen demand for production of chemicals and synthetic fuels increases to 341 and 402 PJ respectively. In addition to hydrogen that is produced in industrial processes (for example, in methanol and ammonia production), industry is also supplied with hydrogen (for energy and feedstock purposes) by hydrogen plants, which share is increasing in 2040 and 2050, see Fig. 5. These hydrogen plants also supply hydrogen for the transport sector (in 2050 112 and 109 PJ for ADAPT and TRANSFORM respectively) and to a limited extent for the built environment (in 2050 4 and 5 PJ for ADAPT and TRANSFORM respectively). In ADAPT, hydrogen is predominantly produced from natural gas (with CCS, i.e. blue hydrogen) and in TRANSFORM, from renewable electricity (i.e. green hydrogen).

Imports or exports of hydrogen were not taken into account in the base ADAPT and TRANSFORM scenarios. However, if trade is possible, it is assumed that hydrogen will be imported if the price in the international hydrogen market and the associated transport costs are lower than the production costs in the Netherlands. Hydrogen can be imported by pipeline from neighbouring European countries, but also by ship from countries outside Europe (see for example [36]). This is illustrated in Fig. 6 for the ADAPT scenario. In the base case there is no import or export of hydrogen, because the hydrogen price is approximately €2.4/kg at a natural gas price of €7.6/GJ (relevant for blue hydrogen production). At lower import prices (€1.5–1.8/kg), hydrogen production in the Netherlands decreases, but hydrogen use is more attractive, especially in the built environment. At low import prices, a small amount of domestic hydrogen production also continues to exist, to balance fluctuations in the electricity system with electrolysers. At high prices on the international hydrogen market (€2.7–3.3/kg), it becomes attractive for Dutch hydrogen producers to export. Production increases, with the majority of the hydrogen produced destined for export. The figure is similar in the TRANSFORM scenario, but with exclusively green hydrogen production. In this scenario, there is hardly any import or export of hydrogen at a price of approximately 2.7 € per kg hydrogen.

3.6. Changes in system costs

For all technologies, cost estimates were made for 2030 and 2050, with lower costs in 2050 where there is technological learning potential. However, the costs of some innovative technology options may fall faster than others. In a cost-optimised system, this leads to shifts in the energy mix, both in energy production and consumption. Accelerated cost reductions can be the result of (global) market developments, but targeted government policy can also accelerate the cost reductions of certain technologies, both with regard to technology development and implementation. In recent years, this effect has been observed in technologies such as solar panels, wind turbines and Li-ion batteries [37,38].

If for certain technologies, the cost reductions are stronger than assumed in the base scenarios, different technology investments may be made and the costs of the total energy system will be lower. Lower import prices will have a similar effect. Less cost reduction and higher import prices will have the opposite effect. The effect of costs reduction on the total system energy costs has been analysed with OPERA and is shown in Fig. 7. The larger the role of a technology option in the energy system, the greater the effect on the reduction in total system costs (e.g. electrification options). The effect of reducing costs on the use of a technology option will be less strong if the option is already close to its maximum potential (as is the case for energy-saving options). The effect of cost reductions of multiple options is also shown in Fig. 7. Since technology options compete with each other, such as EVs with FCEVs,

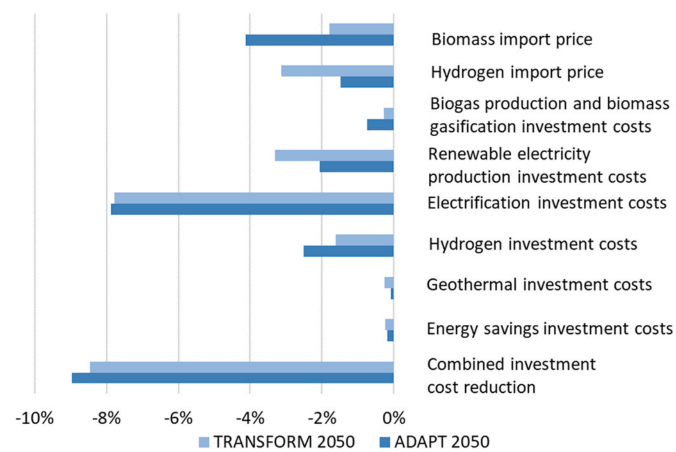

Fig. 7. Relative decrease in total system costs compared to the ADAPT and TRANSFORM scenarios in 2050 if import prices for biomass and hydrogen are reduced by 50% and 40% respectively and investment costs are reduced by 20%.

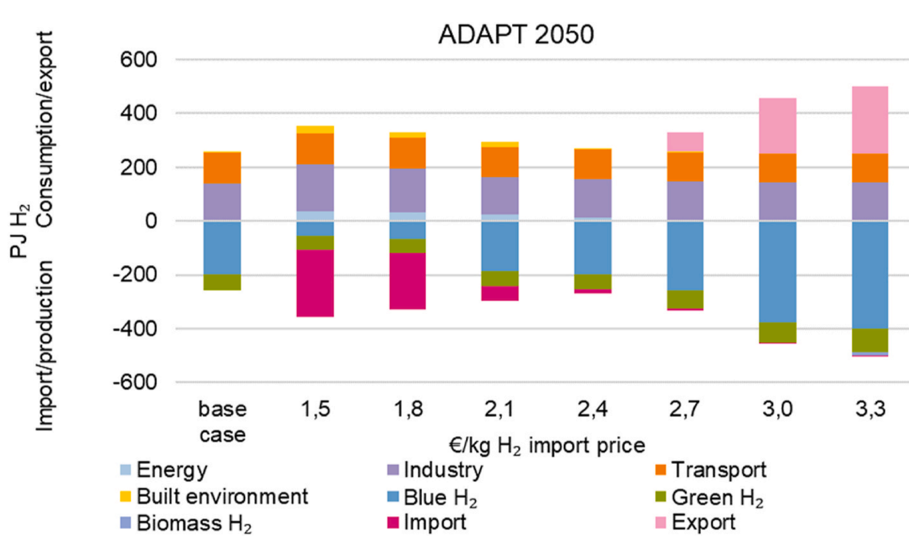

Fig. 6. Influence of international hydrogen price on the production, use, and trade of hydrogen in the Netherlands in the ADAPT scenario in 2050.

the effect of multiple cost reductions is generally smaller than the sum of the individual cost reductions.

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

If the use of one or more technology options is constrained, more expensive options will be used in order to be able to achieve the GHG reduction target, resulting in higher energy system costs, see Fig. 8. The cost-optimised system compensates for the limitation of one option by increasing the use of other options, or technologies with higher costs that have not yet been applied. However, if several options are limited at the same time, or even not allowed at all (such as no CO_2 storage in combination with a strong limitation of biomass imports and significant limitation of electricity production from offshore wind), OPERA shows that it is no longer possible to cover energy demand and meet the GHG reduction target, so there is no feasible solution.

4. Discussion

In the scenario calculations, the two scenarios yield a number of comparable results, which thus seem to be robust elements of a Dutch energy system in 2050, notably the increase in electricity use and the role of hydrogen and biomass. The extent to which different energy options are deployed differs per scenario, but under variations of the values of a large set of input parameters (such as technology costs), the changes in technology diffusion for each of the two scenarios remain relatively limited.

A predominant outcome of both ADAPT and TRANSFORM is that the use of electricity expands substantially. The share of electricity in primary energy supply triples in 2050 in the ADAPT scenario, and in the TRANSFORM scenario the electricity production in 2050 is more than four times that of 2018. By then, more than 99% of electricity will be generated by wind turbines and solar panels. New nuclear power plants are not selected by the model. This is because the costs of renewable electricity production are decreasing faster than those of nuclear power plants, so that, despite higher costs for system balancing due to a larger amount of variable electricity production from wind and solar energy, electricity prices are generally lower in a system without a nuclear power plant than without one. In this scenario study, the use of nuclear energy for electricity production is determined endogenously based on the results of the optimisation, while in many other studies this is done exogenously as an input parameter. This exogenous assumption is often in line with the energy policy of the country in question, for example in scenario studies with nuclear energy in the electricity production mix for France [15,16] and the UK [19,20] and without nuclear for Belgium [13] and Germany [17,24]. Another difference between the outcomes of the ADAPT and TRANSFORM scenarios is that no biomass is used for electricity production, while this is the case in scenarios for other EU countries, such as Denmark [14], Germany [17,24] and the UK [19,20]. On the electricity supply side, costs for electricity generation from biomass are higher than those of solar and wind, and on the demand side, biomass is preferably used in industry for heat supply and the production of biofuels because alternatives are limited.

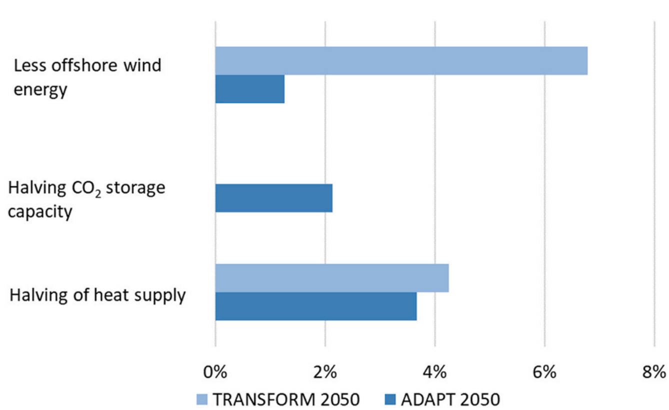

Fig. 8. Relative increase in total system costs compared with the ADAPT and TRANSFORM scenarios when options are limited. Offshore wind potential reduced from 40 to 30 GW in the ADAPT scenario and from 60 to 40 GW in the TRANSFORM scenario.

The increase in electricity use in the Dutch energy system is driven by the electrification of energy services in all sectors: electric vehicles in the transport sector, electric boilers and heat pumps in industry as well as the residential and agricultural sectors, electrolysers for the production of renewable hydrogen, and electrified processes in industry. In international aviation and shipping, electricity is not used directly but applied indirectly via the production of synthetic fuels. The electrification of energy use in end-use sectors is also reported in other scenario studies and presented as an absolute increase in electricity demand or growth in the share of final energy demand (for example [7,17,18,39]). With regard to the electricity share in final energy consumption, it remains unclear whether the authors of other studies have also included the electricity that is converted into other energy carriers, i.e. power-to-X or indirect electricity [24]. For that reason, in this study the growth of electricity is presented in relation to the primary energy supply. This, however, also includes conversion and distribution losses.

As a result of the increase in the amount of electricity from wind and solar energy, there can be instantaneous shortages and surpluses of electricity, which lead to an imbalance between supply and demand. These are accommodated with flexibility options. In the model calculation, the most important flexibility options are taken into account: power trade with neighbouring countries, peak power generation from natural gas, demand response (EVs, electrolysers), curtailment of wind and solar energy, and energy storage (batteries, compressed air, hydrogen storage). Other flexibility options mentioned in the literature (for example [30,40–42]), such as vehicle-to-grid (V2G), could also be included and could potentially lead to lower electricity costs. Export of renewable electricity is also notable in the ADAPT and TRANSFORM scenarios, despite the strong increase in Dutch electricity demand. The available potential for wind and solar energy enables the Netherlands to supply electricity to adjacent electricity markets. In both scenarios, the potential for onshore and offshore wind is fully used, but the potential for solar power is not fully exploited.

The use of each energy option depends significantly on the cost or availability of key technologies. For example, domestically produced hydrogen competes on the international market. If trading prices are lower than the costs of domestic hydrogen production, domestic production will be low, and hydrogen will be mostly imported. The reverse also applies: at high hydrogen import prices, hydrogen is not only produced for the domestic market, but also serves for export purposes. In some energy scenarios for other European countries, imports of hydrogen are also included, such as for Belgium [13], Ireland [18] and the UK [19,20], but other energy scenario studies for EU countries do not consider hydrogen imports. If CO_2 storage is allowed in the Netherlands (ADAPT scenario), the production of blue hydrogen from natural gas with CCS is the most commonly applied technology. If CO_2 storage is not permitted (TRANSFORM scenario), however, green hydrogen is produced through electrolysis. Hydrogen production from natural gas with CCS is also mentioned in scenario studies for the UK [19,21], but in energy scenario studies for some EU countries, hydrogen is only produced with electrolysers (for example [13–15,17]). In the ADAPT and TRANSFORM scenarios, hydrogen is mainly used in industry and as a transport fuel and, at low hydrogen prices, also in the built environment. In most scenario studies for other European countries with which this study is compared, hydrogen is also used as fuel for domestic transport, and sometimes for heating in the built environment (Belgium [13], France [15] and the UK [21]). In scenario studies for countries that, like the Netherlands, have a relatively large industrial sector, hydrogen is also used in industry, such as for Belgium [13] and Germany [17]. Hydrogen can also be converted into ammonia and thus transported and stored as a liquid. However, this route is not yet available in the OPERA model and has therefore not been investigated in the scenario study. Ammonia is not used as an energy carrier in the other scenario studies examined for EU countries either.

CCS, if socially acceptable, may play an important role in reducing emissions in industry, possibly in combination with the use of biomass (BECCS) to deliver negative emissions. Other scenario studies where the role of CCS has been investigated come to similar conclusions (see for example [6,11]). In scenario studies for Belgium [13], Germany [17,24] and the UK [20,21], CCS is also used in industrial processes, as in the ADAPT scenario. In many of the considered scenario studies for other European countries, CCS is not applied for electricity production, because by 2050 virtually no fossil power plants will be used. However, in scenario studies for the UK [19–21], CCS is used in 2050 in power plants that produce electricity from natural gas, coal and biomass. In the ADAPT scenario, by 2050 power generation with CCS does not play a role. Coal-fired power plants cannot be used after 2030, and gas-fired power generation with CCS is too expensive compared to electricity from wind and solar energy.

Biomass plays a large role in the future Dutch energy system. In 2050 in TRANSFORM, bioenergy covers 25% of the final energy use in industry (mainly for heat generation) and 39% in ADAPT. In the built environment, the bioenergy share in final energy use is 10% for ADAPT and 11% for TRANSFORM and in the agriculture sector these shares are 33% and 44% respectively. In these sectors, heat generation from bioenergy is competing with electricity, residual heat from industry and, to some extent, with hydrogen and geothermal energy. The scenarios show that the use of biomass to produce biofuels for domestic transport and international aviation and shipping is particularly attractive. Biofuels compete with electricity and hydrogen for domestic transport and with synthetic fuels for international aviation and shipping. In all considered scenario studies for other European countries, biomass is also used for the production of biofuels, while in some countries biomass is also used for heating in the built environment (for example Denmark [14]), for heating and processes in industry (for example Belgium [13] and Germany [17]) and for power generation [for example Germany [43] and UK [19–21]). In order to meet the demand for biomass and biofuels, 69% of the biomass and biofuels are imported in ADAPT in 2050 and 61% in TRANSFORM. In scenario studies for Belgium [13], Denmark [14], the UK [18,20,21] imports are also considered, while in scenario studies for Germany biomass imports do not take place or are very limited [17,24].

Another remarkable result is that the available biomass is almost entirely used for energy generation and the production of fuels, but hardly used as feedstock. The model analysis shows that fossil fuels, notably natural gas and oil, remain the preferred feedstock for producing chemicals, because bio-based materials production does not lead to direct GHG emissions. A scenario study for the UK [21] also reports that in a low-CO_2 scenario fossil fuels will continue to be used as feedstock for industry. This can be explained by the fact that OPERA only takes into account CO_2 emissions from plastics that end up in waste incineration plants. This model result is consistent with the current policy: there is no direct incentive to replace the use of fossil fuel as feedstock with biomass and recycled plastics. If such an incentive is put in place, this will lead to a further reduction in fossil fuel use and potentially different use of the available biomass. For example, in the TRANSFORM scenario, if 30% of the fossil oil is replaced by biomass in 2050, then 85% of the available woody biomass is needed for production of chemicals [44]. The lower biomass availability for energy use will be compensated by a further electrification of heat supply (i.e. more heat pumps) and more synthetic fuels to meet the demand for sustainable transport fuels. The extra electricity demand will be met by extra solar energy and less exported electricity. Few integrated energy scenario studies consider the use of biomass as a feedstock for the production of chemicals. Instead, dedicated models are used, and analyses performed to study the non-energy use of fossil fuels and biomass (for example [45, 46]).

5. Conclusions

This scenario study yields important insights into the range of possibilities for a sustainable energy system for the Netherlands in 2050. With the energy system optimisation model OPERA the technology, sector and cost implications of two scenarios were determined for future energy systems of the Netherlands that would achieve the Dutch government's national target of near net-zero greenhouse gas emissions in 2050. While the role of a number of key energy technologies and emission mitigation options is strongly dependent on the scenario, or on their assumed costs, the analysis yields several elements that the two scenarios clearly have in common. Electrification is one of main options to decarbonise the Dutch energy system: its contribution to total primary energy supply increases from 19% today to 41–71% in 2050, depending on the scenario. By then electricity production will come almost completely from renewable energy sources, particularly wind turbines and solar panels. Hydrogen becomes another important energy carrier, notably for transportation and in industry. Domestic hydrogen production, either from natural gas with CCS or through electrolysis from renewable electricity, will compete with hydrogen available in the international market, with imports at prices below €2.4 to 2.7/kgH_2 (depending on the scenario) and exports if international market prices exceed these levels. Biomass is mainly used in industry and for the production of fuels for international aviation and shipping; these are applications where alternative decarbonisation options are limited or very costly. The application of CCS makes it possible to continue to use limited amounts of fossil fuels and simultaneously achieve the GHG reduction objective.

If certain adjustments to the energy system are more difficult to realise, or if certain technology solutions are less socially desirable, the goal of a climate-neutral energy system will remain achievable in most cases. However, limitations on sustainable energy options do lead to higher system costs. If several options are limited at the same time, or even not allowed at all, it may no longer be possible to cover energy demand in a sustainable manner. Faster technology development through innovation and supporting policies enhancing implementation can accelerate the decrease in technology costs, which can in turn lower future costs for the energy system. Further research and development is of course necessary, not only for technology development, but also to facilitate further implementation and behavioural change. This scenario study helps to demonstrate how the energy transition can be influenced to make the future Dutch energy system more affordable and sustainable.

Authors statement

Martin Scheepers Conceptualisation, Methodology, Investigation, Writing – original draft. Silvana Gamboa Palacios Investigation, Validation. Elodie Jegu, Methodology. Larissa P. Nogueira Software, Investigation. Loes Rutten, Visualization. Joost van Stralen Methodology, Software, Investigation, Writing – review & editing. Koen Smekens Methodology, Investigation. Kira West Investigation, Writing – review & editing. Bob van der Zwaan Supervision.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Martin Scheepers reports financial support was provided by Ministry of Economic Affairs and Climate Policy.

Acknowledgements

The authors would like to thank the Ministry of Economic Affairs and Climate Policy of the Netherlands for its financial support of the research underlying the results presented in this article. Any views expressed in this paper, or possible errors, are exclusively those of the authors.

Appendix

Assumptions for the ADAPT and TRANSFORM scenario are listed in the table below. Values for heat and electricity demand relate to conventional technologies. Energy consumption values change if OPERA opts for alternative technologies.

	ADAPT[a]		TRANSFORM[a]	
	2030	2050	2030	2050
Fuel prices				
Natural gas (€$_{2017}$/GJ)	7.6	7.6	7.6	7.6
Oil (€$_{2017}$/GJ)	14.8	14.8	14.8	14.8
Coal (€$_{2017}$/GJ)	2.9	2.9	2.9	2.9
Biomass (woody) (€$_{2017}$/GJ)	8.1	8.1	8.1	8.1
Biofuel (€$_{2017}$/GJ)[b]	24.1	70.6	24.1	70.6
Industry				
Electricity demand (PJ)[c]	202	204	461	252
Heat demand (PJ)[c]	669	697	622	548
Production volume				
Steel (Mton)	8.50	9.00	7.65	6.80
Ammonia (Mton)	3.43	3.81	2.88	1.60
High value chemicals (Mton)[d]	4.15	4.65	3.86	3.00
Service sector				
Electricity demand (PJ)	128	133	141	160
Heat demand (PJ)	119	95	125	105
Agriculture sector				
Electricity demand (PJ)	29	31	38	47
Heat demand (PJ)	94	83	75	50
Households				
Electricity demand (PJ)	74	82	74	82
Heat demand (PJ)	278	242	278	242
Domestic mobility				
Passenger road traffic (bill. vehicle km)	125.2	149.9	101.6	84.7
Light freight road traffic (bill. vehicle km)	19.5	22.0	19.5	22.0
Heavy freight road traffic (bill. vehicle km)	7.7	8.3	7.7	8.3
International mobility (fuel use)				
Aviation (PJ)	198	213	188	149
Navigation (PJ)	572	649	486	286
Biomass and waste availability				
Domestic biomass (PJ)	220	220	147	147
Imports biomass (PJ)	187	515	70	129
Waste incineration (PJ)	48	28	48	14
Maximum CO_2 storage capacity (Mton)[e]	7.5	50	0	0

a 2040 values are interpolated.
b Biofuel price in 2040 is 46,5 €/GJ for both scenarios.
c Figures for heat and electricity demand also relates to additional heat and electricity demand for producing steel, ammonia and high value chemicals.
d High value chemicals mean ethylene, acetylene, propylene, butadiene, benzene.
e CO_2 storage capacity in 2040 is 19 Mton.

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