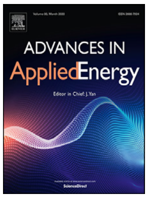
Advances in Applied Energy 7 (2022) 100105

Contents lists available at ScienceDirect

Advances in Applied Energy

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



High technical and temporal resolution integrated energy system modelling of industrial decarbonisation

Sánchez Diéguez Manuel[a,*], Taminau Floris[b], West Kira[b,c], Sijm Jos[b], Faaij André[a,b,c]

[a] Groningen University Faculty of Science and Engineering, the Netherlands
[b] TNO Energy Transition, the Netherlands
[c] Utrecht University, the Netherlands

ARTICLE INFO

Keywords:
Industrial decarbonisation
Integrated energy system
Clean conversion technologies
Pathways for industry transition
Green molecules

ABSTRACT

Owing to the complexity of the sector, industrial activities are often represented with limited technological resolution in integrated energy system models. In this study, we enriched the technological description of industrial activities in the integrated energy system analysis optimisation (IESA-Opt) model, a peer-reviewed energy system optimisation model that can simultaneously provide optimal capacity planning for the hourly operation of all integrated sectors. We used this enriched model to analyse the industrial decarbonisation of the Netherlands for four key activities: high-value chemicals, hydrocarbons, ammonia, and steel production. The analyses performed comprised 1) exploring optimality in a reference scenario; 2) exploring the feasibility and implications of four extreme industrial cases with different technological archetypes, namely a bio-based industry, a hydrogen-based industry, a fully electrified industry, and retrofitting of current assets into carbon capture utilisation and storage; and 3) performing sensitivity analyses on key topics such as imported biomass, hydrogen, and natural gas prices, carbon storage potentials, technological learning, and the demand for olefins. The results of this study show that it is feasible for the energy system to have a fully bio-based, hydrogen-based, fully electrified, and retrofitted industry to achieve full decarbonisation while allowing for an optimal technological mix to yield at least a 10% cheaper transition. We also show that owing to the high predominance of the fuel component in the levelled cost of industrial products, substantial reductions in overnight investment costs of green technologies have a limited effect on their adoption. Finally, we reveal that based on the current (2022) energy prices, the energy transition is cost-effective, and fossil fuels can be fully displaced from industry and the national mix by 2050.

1. Introduction

Since the Paris Agreement in 2015, 195 countries have agreed to reduce greenhouse gas (GHG) emissions from fossil fuels to prevent a global temperature increase of more than 1.5°C compared to pre-industrial times [1]. To achieve this, every country needs to adopt an accelerated response to curtail carbon emissions; hence, the government of the Netherlands aims to adopt a more ambitious climate policy[1]. However, to achieve the targets set in national climate policy, it is paramount to understand where emissions originate. In the Netherlands, emissions in 2019 amounted to over 180 Mt of CO_2 equivalents (excluding land use, land use change, and forestry (LULUCF)) [2], of which 20% can be directly attributed to industrial activities. Because of this, the industrial sector has received considerable attention from policymakers,

---

Abbreviations: BECCS, Agent-Based Model; BFO, Blast furnace oxidation; BIO, Name of the scenario implementing the bio-based options in industry; BP, Bio-Plastics; CCS, Name of the scenario implementing the carbon capture and storage options in industry; CCUS, Carbon Capture Utilization and Storage; CHP, Cogeneration of Heat and Power; CO_2, Carbon Dioxide; DAC, Direct Air Capture; ENTSO-E, European Network of Transmission System Operators for Electricity; ELE, Name of the scenario implementing the electrification options in industry; ESOM, Energy System Optimization Model; ETS, Emissions Trading Scheme; EU, European Union; EUA, European Union Allowance; Ey, Ethylene; FT, Fischer Tropsch; GHG, Greenhouse Gas; HTWIN, High Temperature Electro-winning; HYD, Name of the scenario implementing the hydrogen based options in industry.; KEV, Climate and Energy Outlook of the Netherlands; LTWIN, Low Temperature Electro-winning; LULUCF, Land Use, Land-Use Change, and Forestry; MIDDEN, Manufacturing Industry Decarbonization Data Exchange Network; MTO, Methanol to Olefins; ONIC, Overnight Investment Costs; OPN, Name of the scenario with open implementation of decarbonization measures in industry; PBL, Netherlands Environmental Assessment Agency; Py, Propylene; RWGS, Reverse Water Gas Shifting; SMR, Steam Methane Reforming; TGR, Top-Gas Recirculation; TNO, Netherlands Organization for Applied Scientific Research; TRL, Technology Readiness Level; TTF, Title Transfer Facility for Natural Gas, name of the Natural Gas market in the Netherlands; TYNDP, Ten Year Network Development Plan; VRES, Variable Renewable Energy Supply.

* Corresponding author.

E-mail address: m.sanchez.dieguez@rug.nl (S.D. Manuel).

[1] Increase the 2030 and 2050 emission reduction targets from 49% to 55% and 95% to full carbon neutrality, respectively [45].

https://doi.org/10.1016/j.adapen.2022.100105
Received 5 May 2022; Received in revised form 3 August 2022; Accepted 4 August 2022

particularly from two axes, namely carbon pricing and technology support [3]. On the first axis, an example of carbon pricing is the emissions trading scheme (ETS), which was created in Europe with the intention of imposing an economic value on GHG emissions. The ETS includes crucial energy and industrial activities, such as electricity and heat generation, refineries, and the production of iron, steel, aluminium, zinc, construction materials, glass, ceramics, paper and cardboard, fertilisers, and organic chemicals [4]. In addition, from January 2021, the Dutch Emissions Authority imposed a CO_2 tax on direct emissions resulting from all industrial activities [5]. On the second axis, the Dutch government provides technology support in the form of subsidies focused on research, development, piloting, and adoption of green technologies that contribute to the abatement of industry GHG emissions [6].

In addition to policy packages designed to reduce emissions, a broad spectrum of investment signals that provide guidance are needed. The purpose would be to decrease the uncertainty risks for stakeholders adopting green technologies before it becomes fully evident that they are more cost-effective than current practices. A delay cannot be afforded due to the urgency of actions required to reach the 1.5°C target. These investment signals must be focused on two main areas: 1) presenting a portfolio of decarbonisation technologies for each industrial activity and 2) evaluating the economic performance of such technologies when integrated into the energy system. Adequate mapping of resource efficiency for a broad range of technological possibilities would prove valuable for policy and decision-makers [7] and would make current climate policy measures more agile and effective.

However, it is challenging to define optimal technological choices in a complex landscape, in which technologies can influence all other parts of the system. First, it is necessary to understand the operation and cost of the technologies with sufficient detail to holistically capture the economic and environmental performance of the portfolio of options. Second, it is necessary to consider all adjacent system elements that influence the economic performance of the technologies. Examples include the price of energy carriers, the hourly profile at which different price events occur if the technology has flexibility enhancements, competition with other technologies and other sectors for scarce green resources, and the total cumulative impact on system emissions and targets. The simultaneous presence of both elements in a single analysis for the entire industrial sector, while accounting for the most substantial feedback between the system and technologies, requires a substantial methodology framework in terms of data and quantification tools. Thus, there is a knowledge gap in both the academic literature and consultancy reports.

We encountered three types of materials when searching for available information on industrial decarbonisation: 1) consultancy reports presenting pathways and roadmaps for industrial decarbonisation, 2) academic publications focusing on the cleaning of specific industrial activities and their compatibility with a system with highly variable renewable energy sources (VRES), and 3) academic publications focusing on the integration of industry into the energy system.

The first group includes a report by the Netherlands Organization for Applied Scientific Research (TNO) presenting an overview of opportunities for electrification within the chemical industry and addressing crucial topics such as heat, hydrogen, and feedstock [8]. This report presents a potential impact on the demand for energy carriers for the sector and mentions the possibility of lowering capital and operational costs; however, this is not quantified. Similarly, the Dutch consultancy bureau Berenschot explores transition pathways for electrification in the Dutch process industry, focusing on the quantification of electrification potential based on an extensive list of options and on their respective drivers and barriers [9]. However, a system perspective is not presented, and neither the cost nor the impact of emissions on the system is included. McKinsey also provides two extensive reports focusing on industrial decarbonisation at both the national (Dutch) [10] and global [11] scales. These reports touch on the emission impact and the required costs of the industrial sectors, but do not provide detail on the process technology portfolio, nor do they explain the flexible operation of technologies and the repercussions on the variable costs of technologies and energy system prices. Finally, the Dutch Climate and Energy Outlook (KEV) is carried out annually by The Netherlands Environmental Assessment Agency (PBL). The KEV uses ‘SAVE Production’ (a bottom-up industry model) in combination with a larger system of linked models, such as the COMPETES power system model, to account for energy system integration [12]. However, detailed results for the industry are not reported publicly in the KEV, and the scenarios presented simulate current trajectories towards decarbonisation based on planned policy rather than optimisation.

In the second group, academic publications focusing on specific industrial activities are found in many publications on steel decarbonisation focusing on national energy systems, such as Germany [11] and Sweden [13]. Studies also exist for different sectors such as electrification of fuels and feedstock production [14], paper-and-board focusing on decarbonisation in the UK [15] and its economic potential for demand response [16], operation strategies of aluminium smelters to provide demand-side management [17], and analysing the potential for recirculation of waste heat in the general heat sector [18]. These studies provide detailed sectoral insights but lack a systemic perspective.

The third group includes industrial decarbonisation analyses that use bottom-up integrated energy system optimisation models[2] (ESOMs), where the interaction between economic activities and energy sectors is considered. However, they lack details in the description of individual industrial sectors or present simplified temporal resolutions to adjust for future high-VRES systems [19]. Some models have addressed this separately. For example, PyPSA-Eur-Sec-30 has been used to explore European sectoral interactions with high amounts of renewable energy while considering the energy demand of the entire energy system and many power-to-X alternatives at an hourly level [20]. However, because of the extensive mathematical challenges, the study excludes detailed descriptions of different industrial demand sources and their processes. In a more focused study, the UK TIMES model was used to explore the role of the industrial sector in reaching energy transition targets for the United Kingdom [21]. Such a study provides a rich industrial framework for its purpose, but it lacks a high temporal resolution to capture the dynamics of VRES and the advantages that could be presented for flexible technologies. Finally, the integrated energy system analysis optimisation (IESA-Opt) model was recently used to explore the energy transition in the Netherlands, while adopting hourly resolution and a wide description of cross-sectoral flexibility [22]. Although the IESA-Opt model presents a comprehensive approach to analyse industrial decarbonisation, it lacks a detailed description of the industrial activities and technologies contained within it.

Perhaps the two most notable reasons for the lack of such integrative studies are 1) the lack of available industrial-activity level data and 2) the lack of a modelling tool capable of using such an extensive database and feasibly solving the large optimisation problem. Both are crucial for providing guidance in the form of optimal system configurations for the industrial technological stock to continue the transition. Recently, two research efforts have been conducted, in which they are separately provided.

The first is the Manufacturing Industry Decarbonisation Data Exchange Network (MIDDEN) initiative, which was carried out by the TNO and PBL. Here, data were collected from industrial sites and alternative processes to create an extensive plant-level database for the Netherlands [23]. Most of the required materials are in the rich portfolio of sector-oriented reports and in the resulting database held by MIDDEN. The database includes currently used technologies and their green alternatives. Descriptions of the energy and material flows are provided, together with the expected cost profiles. This provides a complete

---

[2] Some examples of ESOMs are: TIMES, PyPSA, OSeMOSYS, OPERA, and PRIMES.

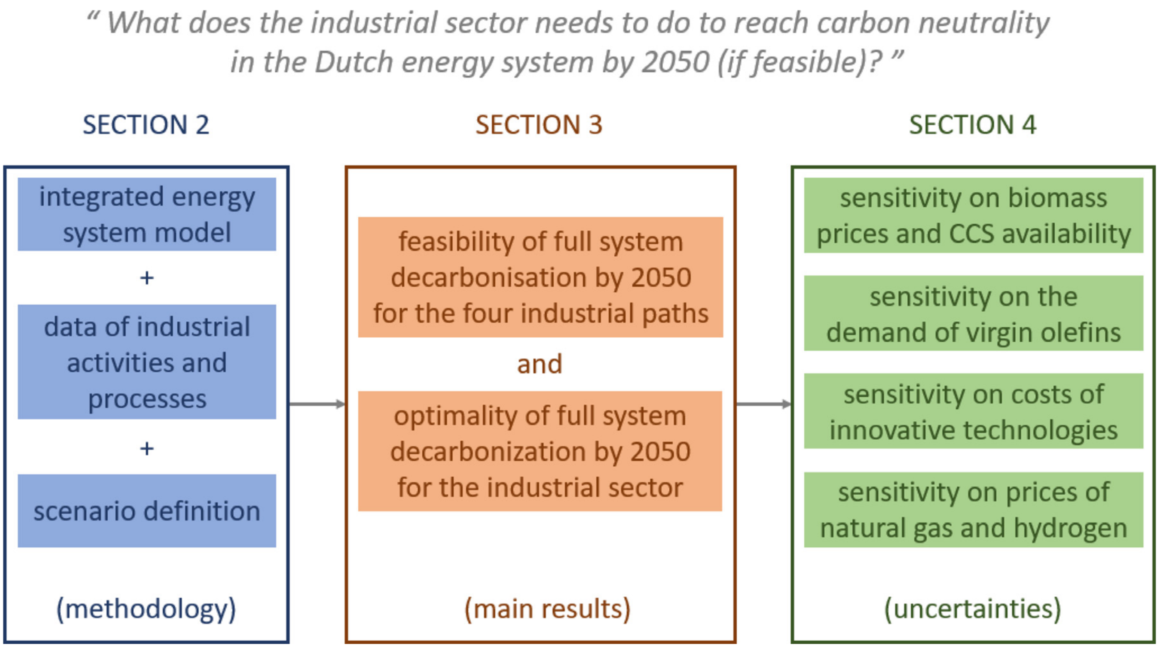


Fig. 1. Structure of the research steps presented in this study.

techno-economical representation of decarbonisation technologies and processes for the most important industrial sectors in the Netherlands.

Second, the recently developed IESA-Opt model explores the energy transition under high levels of VRES, with temporally and technologically rich descriptions of the energy system. The IESA-Opt model determines the optimal path to invest in the available portfolio of technologies for each activity of the energy system. Furthermore, IESA-Opt allows for the simultaneous connection of optimal emission reduction efforts in different sectors while accounting for operational feedback between different technologies. This model was specifically built to address the economic impact of cross-sectoral flexibility (demand response and storage options) [24], which is a requisite to explore the transformation of an energy system with a high presence of VRES. The resulting extensive mathematical challenge can be solved because of the flexible integrative framework adopted by IESA-Opt [19] and has already been used to explore the decarbonisation of the Dutch energy system [22], the impact of different modelling capabilities for integrational energy system analyses [25], and the decarbonisation of an integrated North Sea region considering detailed energy system descriptions for eight countries [26].

In this study, we used the resources presented in the MIDDEN project to improve the modelling of the industrial sector. The IESA-Opt model was used to solve the optimisation problem for capacity planning, intra-year dispatch, and operation, while including the impact of hourly flexible demand. This aims to close the knowledge gap in two main areas: 1) the role of the industrial sector in decarbonising the Netherlands energy system, and 2) the ability of the flexible industry to operate cost-effectively in a system with high levels of VRES. Bridging such a gap would help understand path dependency, provide investment signals resulting from comprehensive system reviews, and guide policy and decision-makers. The contributions of this study are as follows.

1. We provide a modelling framework with an extensive representation of industrial activities and of the portfolio of decarbonisation technologies that can be used for both sectoral and system analyses.
2. We analysed the transition for Dutch industrial sectors up to 2050, in which both sectoral and system effects are highlighted.
3. We explain how the modelling framework can explore different decarbonisation paths for industry.
4. We demonstrate the impact of crucial uncertainties on the transition via sensitivity analyses on the following aspects:
    a. Biomass,
    b. BECCS,
    c. Natural gas prices,
    d. Technological leaning on key technologies,
    e. Import hydrogen prices,
    f. European availability of VRES,
    g. Material efficiency (as exogenous recycling volumes).

The above contributions are presented to clarify the actions needed within the industrial sectors to achieve carbon neutrality in the energy system of the Netherlands by 2050, for which this article is structured (Fig. 1). Section 2 presents an overview of the activities and technologies extracted from the MIDDEN database which are used in the study. In addition, section 2 provides an overview of the scenario definitions and uncertainty parameters that will be used for the sensitivity analyses. Section 3 provides the results and analysis of the main scenario and compares it to four alternative decarbonisation paths. Section 4 presents the results of the sensitivity analyses included above.

2. Methodology

An energy system optimisation model (ESOM) is necessary to explore cost-optimal paths for industrial decarbonisation while considering the most important feedback mechanisms within the surrounding market dynamics. The IESA-Opt was selected for this purpose because it is a peer-reviewed ESOM with a published methodology [27] and has been widely used in academic research to explore the energy transition in the Netherlands and the North Sea, and has considerable modelling capabilities, including high technological and temporal resolution. For this study, the latest version of the model (housed by TNO and Groningen University) was complemented with an enriched representation of the industrial sectors and used to evaluate a reference scenario and its corresponding sensitivity cases around key uncertainty parameters.

The updated tool represents a substantial improvement to the methodology used to date in academic research. Industrial representations have been embedded in ESOMs before, but typically, the adopted models lacked details on 1) the temporal resolution used to describe power supply, 2) the representation of industrial processes and activ-

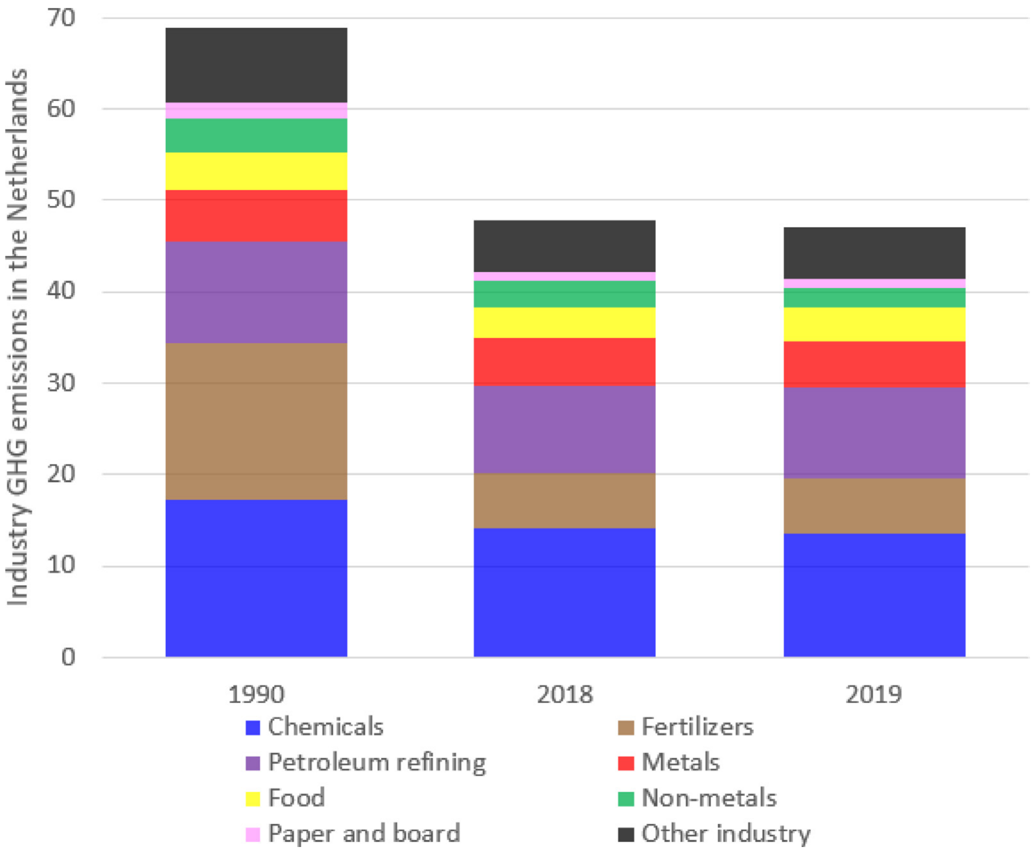


Fig. 2. Industry related emissions in the Netherlands per sector extracted from the National Inventory Report 2021 [2].

ities, or 3) the description of flexible operation and dispatch of industrial assets. Compared with the available models, the methodology presented here is a substantial step forward in terms of technological detail and feedback accounting between industry and the energy system. Furthermore, this methodology allows us to include key transition concepts, such as material efficiency and recycling (exogenous), path dependency, cost-effectiveness, and complete accounting of carbon neutrality[3].

2.1. Modelling a highly decarbonised industrial landscape in the Netherlands

2.1.1. Energy and carbon inventory in the industrial sector in the Netherlands

Despite the modest land area of the country, the Netherlands has one of the most active industrial sectors in north-western Europe. The Netherlands has several energy-intensive industries that produce goods for local and foreign markets. In the Netherlands, oil refining[4] represents the largest energy-consuming sector owing to the high volumes of exported oil-based products, and the chemical industry has the largest emission volumes owing to the CO_2 emitted during naphtha steam cracking. Fertiliser production also represents an important portion because of the CO_2 emitted during the steam methane reforming phase in ammonia production. Furthermore, TATA Steel produces approximately seven megatonnes of primary steel, making it energy- and emission-intensive. There are also many industrial areas in the Netherlands that produce food and manufacture glass, ceramics, paper and board, and other goods. Fig. 2 displays the contribution of these industrial sectors to the national GHG emissions inventory[5].

The emission Fig.s displayed in Fig. 2 correspond to both energy-use emissions (i.e., CO_2 emitted from fossil fuel combustion) and emissions from industrial processing. The last group (i.e., other industry) comprises emissions released inherently as part of the industrial process unrelated to fuel combustion, such as the CO_2 resulting from the reforming of methane to produce hydrogen, the CO_2 embedded in clay carbonates which is released when processing ceramics, and leakages of refrigeration gases. However, for most of the industrial activities in the Netherlands, the most important source of emissions corresponds to energy use. In the Netherlands, most of the energy consumed, both as fuel and feedstock, can be allocated to four processes: oil refining, high-value chemical production, steel manufacturing, and ammonia (fertiliser) synthesis. Most of the remaining activities consume energy either as heat or electricity. Hence, it is crucial to properly describe these four activities and the heat supply in an energy model to provide an accurate and explicit description of more than 95% of the industrial sector energy use and emissions in the country.

However, other processes are also important in terms of the flexibility they can provide to the system or because they have specific process emissions or can connect to the carbon capture, utilisation, and storage (CCUS) network. However, for each new process included in

---

[3] The model accounts for all emissions within the national inventory, as well as international transport emissions and emissions from feedstock at the end of their lifetime. Reference to carbon neutrality in this paper therefore also includes international transport and feedstock.

[4] Oil refining is an energy conversion sector, and listed as such in the Dutch central bureau of statistics (CBS). However, for the purposes of this study it has been included within the analysed industries owing to its importance to the country and its crucial relationship with the decarbonisation of olefins production.

[5] Note that emissions from most industrial activities have not yet decreased substantially, and most of the achieved emission reductions are within the fertiliser sector. These are mostly a result of N_2O capture from ammonia and nitric acid production (5.9 Mt).

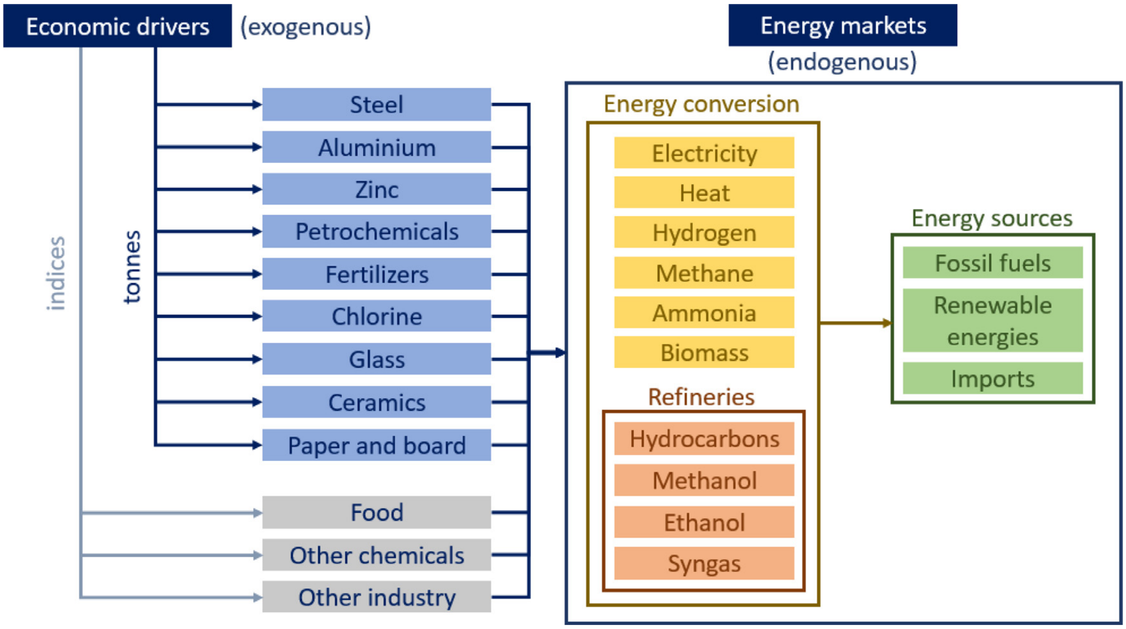


Fig. 3. Modelling framework of the industrial sector in IESA-Opt.

the model representation, there are large research challenges: first, the techno-economic data of currently operating processes and their alternative decarbonisation options for each sector and activity, and second, representing the particularities of each activity within the energy model.

2.1.2. Representation of industrial activities in the model

The industrial sector in the IESA-Opt is enriched based on a complete representation of industrial processes and their promising decarbonisation options in the Netherlands provided by PBL and TNO in the MIDDEN database [20]. The modelling of the different industrial activities designed for this study is primarily based on the MIDDEN reports and was devised in consultation with the experts involved. The resulting framework and associated activities are presented in Fig. 3. This framework provides the conceptual flow of demand, which begins with the exogenous volumes of produce based on economic drivers, follows through the interlinked energy markets which are needed to satisfy the energy requirements of the industrial processes, and culminates with the primary and imported energy which is used to fuel the entire system. The conceptual flow in IESA-Opt is determined simultaneously under the same problem formulation, assuming perfect rationality and foresight to determine the social optimum for the transition.

Furthermore, it is important to highlight the distinction between industrial activities, which are driven by physical flows and described by their explicit production processes and grouped activities which are driven by indexed production volumes and described by their sectoral energy balance. The first group (i.e., physical flow industrial activities) provides valuable information to determine which industrial processes are considered cost-effective under a certain scenario but requires the evaluation of more information, including cost profiles and energy and feedstock balances. Another advantage of the first group is that flexible technologies can be modelled and their feedback with the power sector can be included in the decision-making process. These flexible technologies can be: 1) electrified processes which can limit operations during expensive electricity hours (at the expense of required overinvestments to satisfy demand), such as aluminium or zinc smelters, electrolytic steel production, and chlorine electrolysers; and 2) flexible processes which can reschedule their operations, such as paper and board mills.

2.1.3. Decarbonisation paths for high-value chemicals production

The current volumes of high-value chemicals produced by naphtha steam cracking are mostly a consequence of the national and global demand for monomers in the manufacturing of plastic. For this reason, there are many uncertainties regarding the extent of the challenge for decarbonising this sector in the future. The size of the market of each country depends on the global supply chain and the demand for virgin monomers. This means that material substitution, recycling, and better circular economy practices could change the size of this sector considerably. In addition, asymmetric policies in different regions could result in decisions by countries to externally source these materials, potentially reducing the future role of green technologies in this sector. However, this does not mean that monomer production cannot be cleaned in this sector. On the contrary, local production can be maintained by finding alternatives to fossil fuels, adopting circular carbon practices, and profiting from the sectoral benefits provided by the European Union ETS allowance scheme. The options comprising the retrofitting of current crackers, synthetic and bio-based fuel sources, direct synthesis of monomers, and recycling are presented in Fig. 4.

It is important to note that recycling is exogenous to the model. This means that the potential of the total waste that can be recycled is exogenously determined based on plastic waste proportion projections. The technology representing the recycling options, namely refurbishment, mechanical recycling, and dissolution, satisfies part of the required waste-processing demand and lowers the demand for virgin olefins. In addition, the material components are not within the scope of this study, which means that this analysis does not assess the material composition, which is a crucial component of the relationship between waste and plastics.

2.1.4. Decarbonisation paths for refineries and hydrocarbon production

Analogous to the high-value chemicals sector, the production of hydrocarbons in the future will be predominantly influenced by the international market. Motor vehicles are being electrified rapidly which will reduce the demand for road transport fuels, and the aviation sector has been growing worldwide over the past few decades, which will boost the demand for kerosene and sustainable aviation fuels. Similarly, maritime transport is exploring cleaner energy options such as natural gas, bio-based and synthetic fuels, and ammonia. However, the likely decrease in oil demand does not necessarily mean that the oil refining industry and production of hydrocarbons will come to an end by 2050. It is likely that regions such as Latin America and Africa will lag in the transition and will still require traditional hydrocarbons to power motor

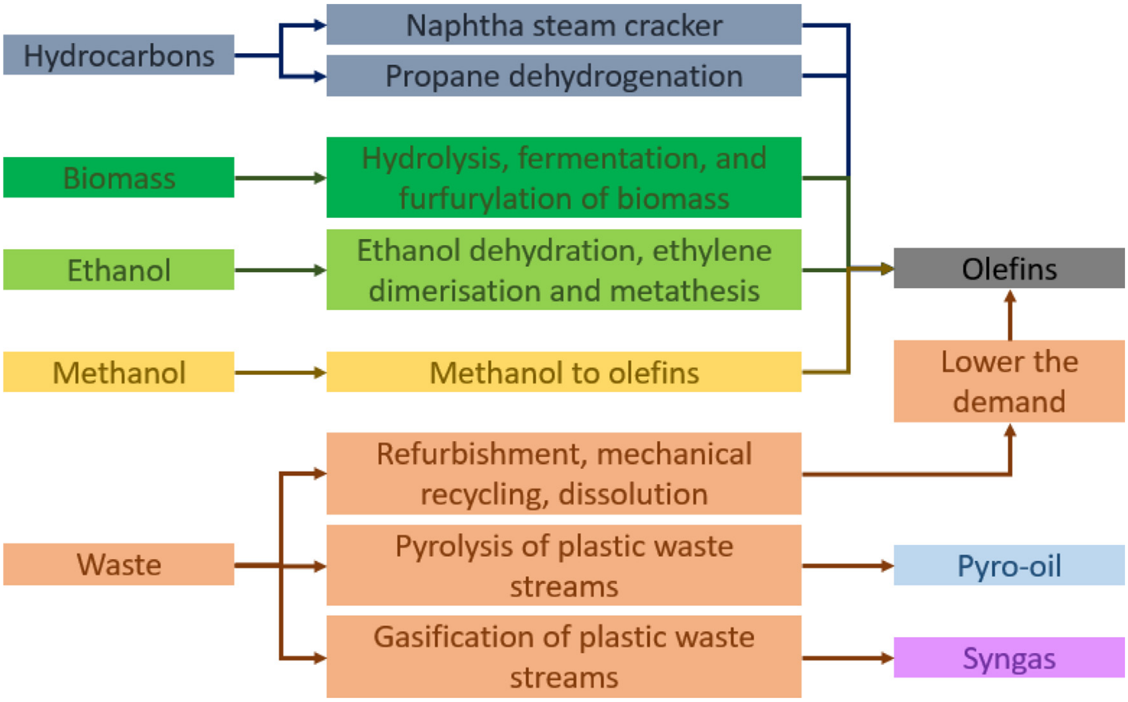


Fig. 4. Technological options in the basic organic chemicals sector.

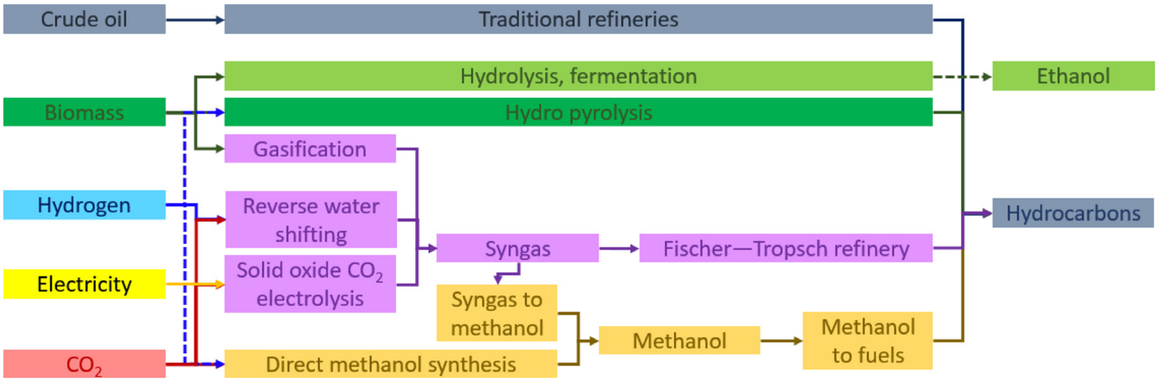


Fig. 5. Technological options in the hydrocarbons sector.

vehicles and transport fleets, as well as industry. On the one hand, these regions could become more competitive in hydrocarbon production, especially if they continue to extract oil. On the other hand, developed regions could exploit their privileged position to become producers of sustainable synthetic fuels and help to accelerate the transition in regions where hydrocarbons are still needed.

The modelling framework adopted in IESA-Opt for this industrial sector considers three general conversion paths: 1) the traditional path, which converts crude oil into the hydrocarbons that are in current energy markets; 2) the bio-based path in which biomass can be fermented into ethanol, gasified to produce syngas, or directly converted into hydrocarbons via the upgrading of bio-pyro-oil with hydrogen; and 3) the synthetic path either via methanol or syngas, in which captured CO_2 can be recirculated into the system with the aid of hydrogen or electricity. The modelling framework is illustrated in Fig. 5.

2.1.5. Decarbonisation alternatives in steel production

Although steel can be recycled using electric arc furnaces (secondary steel), the vast majority of steel manufacturing uses virgin iron ores (primary steel). Primary steel manufacturing is a carbon-intensive process which is traditionally reliant on coal-fuelled blast furnaces and therefore requires a complete production transformation to be decarbonised. Fig. 6 displays four technological alternatives for the steel industry. First, the blast furnace can be adapted, by retrofitting, to recirculate the top gases to reduce coal consumption, or end-of-pipe carbon capture can be adopted or both. Second, to reduce fuel consumption, a HIsarna reactor could be installed to directly smelt the iron ore and eliminate the pre-processing steps. A HIsarna reactor (not yet commercially available) can operate off coal or biomass, and either option could be implemented with carbon capture. Third, to eliminate CO_2 emissions, direct-reduced iron can be produced in a shaft furnace using natural gas or hydrogen. Finally, electrochemical reduction of iron ore is also an alternative to reduce emissions, and a moderate production rate can be achieved with a low-temperature electro-winning process (LTWIN), and a high production rate can be achieved with a high-temperature electro-winning (HTWIN) process [28].

2.1.6. Decarbonisation alternatives in ammonia production

Currently, ammonia is the second-most produced chemical by volume globally, with the fertiliser industry using over 85%. The projected demand for ammonia in the fertiliser industry is uncertain. The demand could increase owing to the increasing demand for food products and

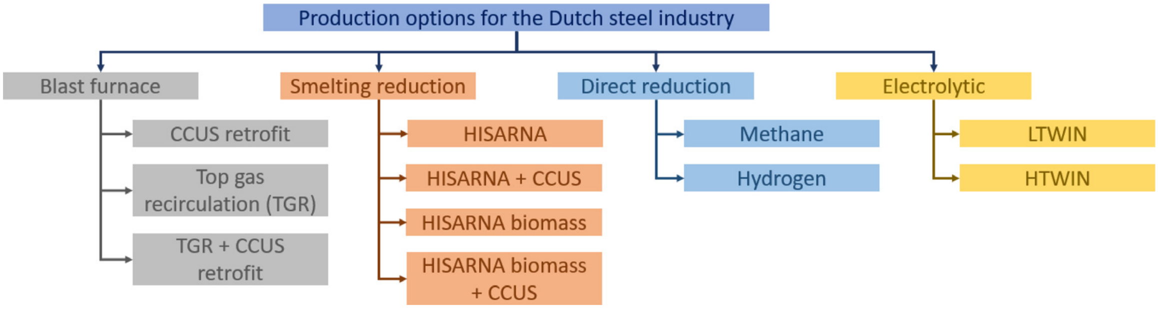


Fig. 6. Technological options for the steel production industry.

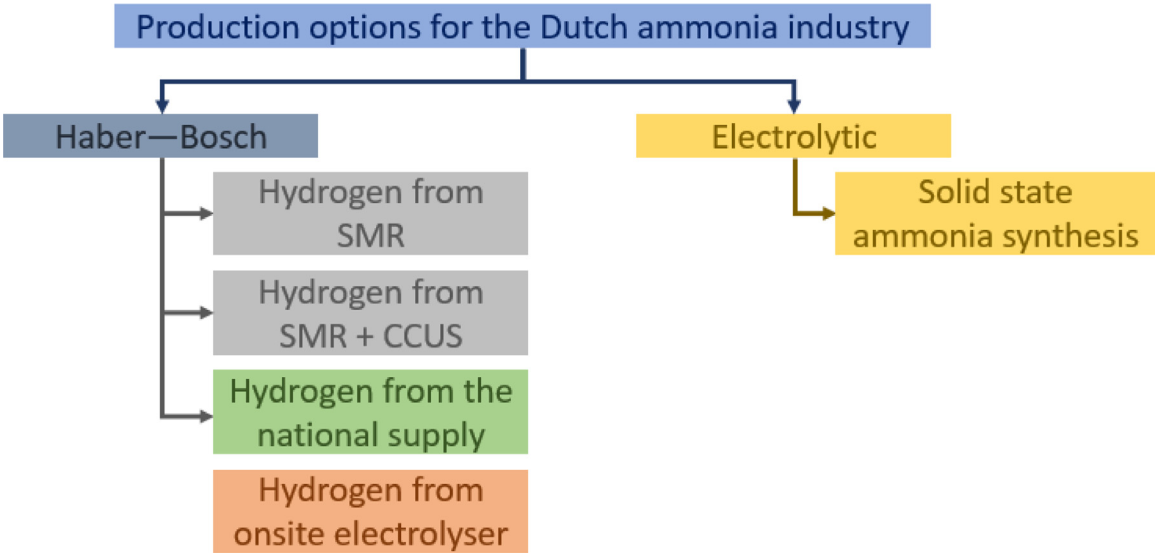


Fig. 7. Technological options in the ammonia production industry.

degradation of industrialised agricultural soils, which is typically overcome by applying an increasing amount of fertilisers. In contrast, the demand could decrease owing to the adoption of soil-health-oriented sustainable agricultural practices [29] and changes in diet and food consumption. However, the most abrupt change that the industry could face is the adoption of ammonia as fuel for ships, which could increase the by up to two orders of magnitude.

The most used process for producing ammonia is the traditional Haber–Bosch process, where hydrogen from steam methane reforming (SMR) is mixed with nitrogen at a high pressure and temperature. During this process, while producing hydrogen, all the carbon contained in the methane is emitted as CO_2.As shown in Fig. 7, the IESA-Opt model considers five ways of producing ammonia: 1) the Haber–Bosh process with hydrogen obtained from onsite SMR; 2) retrofitting with carbon capture traps to prevent the emissions of CO_2 during methane reforming; 3) the Haber–Bosch process with hydrogen from the national supply; 4) an onsite electrolyser to feed hydrogen into the Haber–Bosch process; and 5) solid-state ammonia synthesis, which is a direct electrolytic path from air and water to ammonia. The technology readiness level (TRL) of solid-state ammonia synthesis (SASS) is low and may only become available late in the energy transition; however, it has the potential to transform the industry and assist with the integration of VRES into the grid.

2.1.7. Overview of technologies in other sectors

The remaining industrial sectors represented by the explicit processes in the model are aluminium, urea, chlorine, glass, ceramics, and paper and board production, and were included because each has a characteristic that is important for the integrated energy systems. First, aluminium and chlorine production is heavily electrified, and curtailing demand could assist the power sector by overinvesting in installed capacity. Similarly, paper and board mills can schedule operation times to align with electricity price signals, thus lowering operational costs. Urea requires CO_2 as an input stream, and once CCUS networks are deployed in the country, carbon requirements could be met from captured CO_2 in other processes. Finally, ceramic production emits CO_2 initially stored as carbonates in the input materials.

Furthermore, all the processes use heat in some form. We differentiated between two main groups, namely steam/hot water and furnaces. Steam and hot water are used in many processes at different operational temperatures and pressures. In this study, we have adopted the term hot water for technologies with a low-temperature output stream, and therefore can only be used for limited purposes. Among these are heat pumps, geothermal, and biomass codigesters. Steam technologies can be used indistinctly in all the processes that require utility heat. Within this group, we include boilers, hybrid boilers, cogeneration of heat and power (CHP), and direct electric heating. Combustion includes fuel options for coal, natural gas, biomass, and hydrogen, with special consideration given to CHPs using blast furnace gas (BFG) from steel blast furnaces and coke ovens. Similarly, these furnaces can be fuelled by natural gas, biomass, hydrogen, or electricity, and all CO_2 emitting technologies can be retrofitted together to capture emissions. An overview of the heat-supplying technologies is presented in Fig. 8.

In general, with this updated representation of the industrial sector, we are improving the evaluation tools as more detailed technical resolutions are made available. The improvements can be summarised as follows: 1) the production processes of the four most energy-intensive sectors of Dutch industry are included with an extensive portfolio of de-

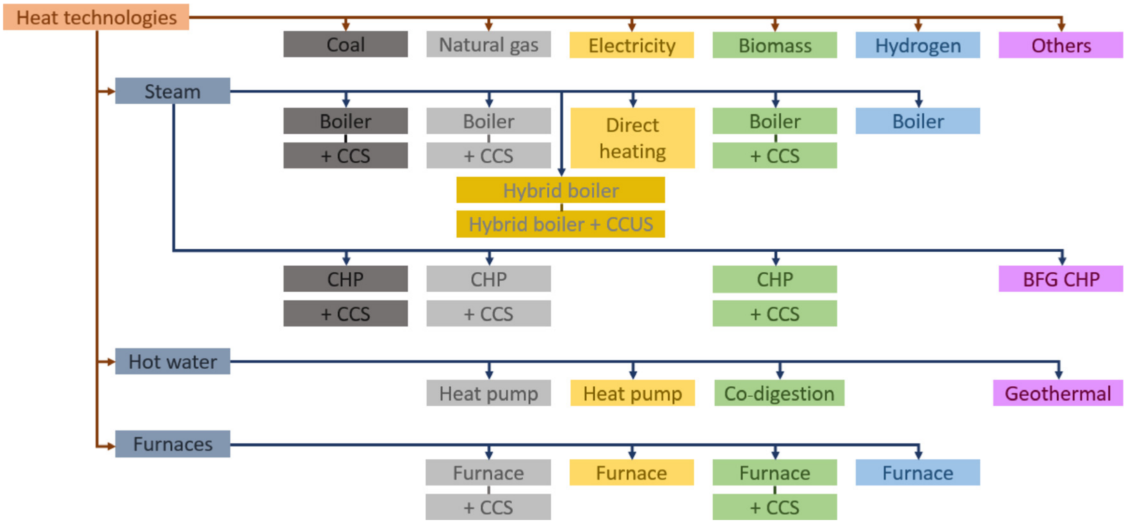


Fig. 8. Technological options for heat supply in industry.

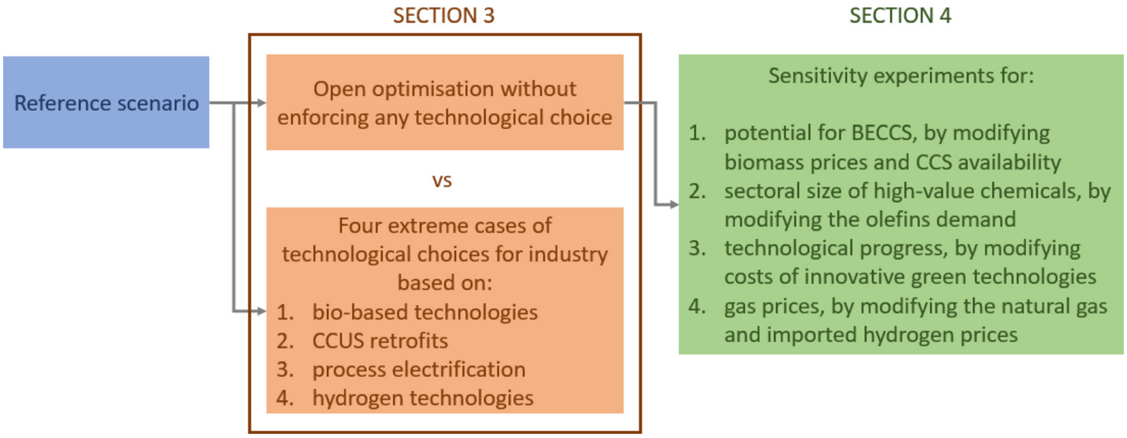


Fig. 9. Experiments in this study.

carbonisation options; 2) these options allow comparison on the same level for electrification, CCUS retrofitting, biomass, and hydrogen-based processes within an integrated energy system where respective energy markets are modelled in detail; 3) industrial heat supply is included for the three most important applications (steam, hot water, and furnaces), allowing for an extensive range of technologies and fuel options; and 4) the operation of all industrial processes is presented while considering their flexibility capabilities, which are crucial for energy systems where VRES are present.

Appendix A reports the cost parameterisation of the technologies included in the sectors and activities presented above. The complete list of technology options used for this study and their parametric representations in the model can be found in the scenario database on the publication website (https://energy.nl/tools/iesa).

2.2. Experiment definition

The experiments in this study are based on two main axes, as shown in Fig. 9. The first evaluates whether it is feasible to achieve full decarbonisation of the energy system by 2050 in four different extreme decarbonisation paths in which industrial sectors exclusively adopt: 1) bio-based technologies, 2) CCUS retrofits, 3) electrified processes, and 4) hydrogen-based technologies. Here, we contrast the outcome of these scenarios with an open optimisation scenario in which no technological choice was enforced in the industrial sectors. The second measures the impact of diverse levels of 1) bio-energy with carbon capture and storage (BECCS), 2) olefin demands, 3) technological progress, and 4) gas prices in the transition by performing sensitivity analyses for these four crucial parameters.

2.2.1. Reference scenario and sensitivity topics

A description of the scenario assumed for the entire energy system described in the IESA-Opt is necessary to explore the decarbonisation transition in industry using the framework presented previously. The assumed scenario can be defined as follows: 1) projections for the economic production volumes of; 2) prices of the raw commodities used to fuel the energy system; 3) potential and availability of technologies and resources in the energy system; 4) evolution of the surrounding European power system configuration; and 5) policy landscape. This scenario is mostly based on the national description in the 2021 climate energy outlook of the Netherlands [12] (with trend extrapolations for the year 2050) and on the surrounding EU power landscape on the national trends scenario of the ten-year network development plans (TYNDP) (ENTSOE 2020). The scenario approach for the adopted activity drivers is for the Dutch energy system to continue as normal during the transition while analysing a carbon neutrality policy package for national and international transport and feedstock emissions. A complete scenario description is reported in the parameter tables presented in Appendix B.

There are many elements of energy transition that are still uncertain, which could influence the decarbonisation process. Unknowns such as the prices of energy carriers, size and nature of economic activities, the capacity of the system to adopt solutions, and the evolution of techno-

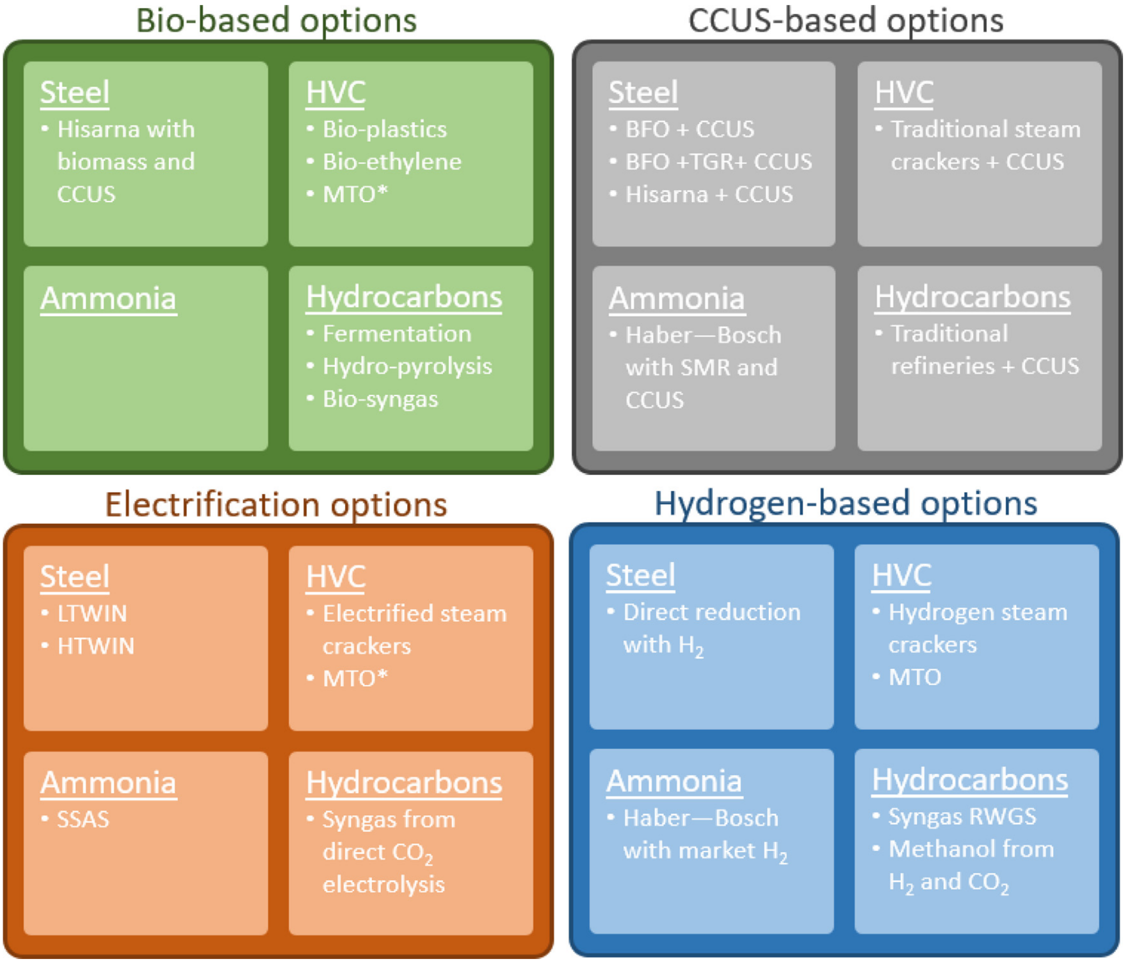


Fig. 10. Technologies within the four options for industrial decarbonisation.

logical development are some examples of what could drive the transition and technological choices that will shape the final picture of the system in the target years. It is important to consider different possible variations of these uncertain elements when developing conclusions and to quantitatively compare these to the reference scenario by means of sensitivity analyses. For this study, we identified and selected four crucial aspects of the transition and performed sensitivity analyses based on each. These include the: 1) capacity of the system to provide negative emission accounts by means of BECCS, 2) demand for virgin olefins for the high-value chemical sector, 3) expected advancement of key green technologies, and 4) possible changes to natural gas and import hydrogen prices. A complete justification and description of the sensitivity analyses are provided in Appendix C.

2.2.2. Decarbonisation paths for industry

As previously mentioned, the vast majority of decarbonisation options for industry are based on four main archetypes, including the: 1) adoption of bio-based fuels and feedstock (bio-based economy); 2) retrofitting traditional facilities with CCUS; 3) process electrification; and 4) hydrogen-based processes (hydrogen economy). By means of bans and subsidies, policymakers could attempt to influence industry decisions to lead the transition towards a desired outcome. The purpose of this analysis is to understand the consequences (and feasibility) complete the industrial energy transition based on any of these four archetypes. The aim is first to determine whether it is possible to attain these extreme scenarios and second to understand their implications for the energy system. Fig. 10 illustrates the technology choices under each decarbonisation group for the key industrial sectors selected for this study. However, it is noted that industrial heat can also be produced by biomass, traditional fuels with CCUS, electrified technologies, and hydrogen.

The CCUS-based options for steel include two possible retrofits of the current blast furnace oxidation process (BFO) and top-gas recirculation for higher efficiencies (TGR) and the adoption of the HIsarna process. Furthermore, traditional steam crackers can be retrofitted with end-of-pipe CCUS for the HVC sector, ammonia can be produced using the traditional Haber–Bosch process with integrated steam methane reforming (SMR) and CCUS, and traditional refineries can also be modified to capture CO_2.

For electrification technologies in the primary steel sector, LTWIN and HTWIN can be considered. High-value chemicals can be produced with electrified steam crackers or methanol to olefins (MTO) from methanol produced by syngas from electrolysis. Similarly, SSAS can produce ammonia directly from electricity, water, and air. Finally, hydrocarbons can be produced from syngas produced directly by solid oxide electrolysis of CO_2.

Hydrogen-based technologies include the hydrogen direct reduction of iron ore to manufacture steel. The HVC sector could use hydrogen-fuelled steam crackers or MTO processes with syngas produced from reverse water-gas shifting (RWGS) and methanol from hydrogen and CO_2 to provide the required hydrocarbons. Finally, ammonia can be produced using hydrogen from the market to feed the Haber–Bosch process.

Therefore, in this study, we define four components in which the energy transition can take place for industry. We explored four extreme scenarios, presented in Table 1, in which only exclusive technology choices can be made in industry: 1) the BIO scenario only allows for bio-based technologies and a biogenic source of CO_2, which may be mixed with hydrogen; 2) The CCS scenario includes CCUS retrofitting

Table 1
Description of the four decarbonisation paths for industry adopted in this study.

	Name of the decarbonisation path for industry			
	BIO	CCS	ELE	HYD
Steel manufacturing	Only HIsarna processes are available in the transition, and only the bio-based option is permitted in 2050.	All the BF and HIsarna processes are available for the transition, but only the CCUS is permitted in 2050.	Only electro-winning processes are available for the transition and permitted in 2050.	Only direct reduction processes are available in the transition, and only the hydrogen-fuelled option is permitted in 2050.
HVC production	All options are enabled.	Only the naphtha steam cracker CCUS retrofit and the methanol-to-olefins technologies are permitted.	Only the electrified naphtha steam crackers and the methanol-to-olefins are permitted decarbonisation technologies.	Only the hydrogen-based naphtha steam crackers and the methanol-to-olefins are permitted decarbonisation technologies.
Ammonia production	All processes are permitted in 2050.	Only the Haber–Bosch process with steam methane reforming and CCUS is available in 2050.	Only SASS is permitted in 2050.	Only the Haber–Bosch process with hydrogen purchases from the network is permitted in 2050.
Hydrocarbons production	All processes are permitted.	None of the bio-based processes are permitted.	None of the bio-based processes are permitted.	None of the bio-based processes are permitted.
Industrial heat	The installed capacities are permitted to remain at a maximum until 2040, but only investments in biomass boilers and CHPs are permitted, both with and without CCUS. Geothermal heat is permitted.	The installed capacities are permitted to remain at maximum until 2040. The biomass-based supply can be retrofitted to CCUS and can remain in the system by 2050. Only new investments in gas and hybrid boilers and gas CHPs are permitted, both with and without CCUS. Geothermal heat is also permitted.	The installed capacities are permitted to remain at maximum until 2040, but only investments in direct electric heating and heat pumps are permitted. Geothermal heat is also permitted.	The installed capacities are permitted to stay at maximum until 2040, but only investments in hydrogen boilers are permitted. Geothermal heat is also permitted.
Furnaces	The currently installed furnaces may remain until 2040. Only investments in biomass furnaces with and without CCUS are permitted.	The currently installed furnaces may remain until 2040. Only investments in gas furnaces with CCUS are permitted.	The currently installed furnaces may remain until 2040. Only investments in electric furnaces are permitted.	The currently installed furnaces may remain until 2040. Only investment hydrogen furnaces are permitted.
Extra modifications	Ships running on ammonia are disabled[1].	None.	None.	None.

[1] With ammonia, ships can operate indirectly on natural gas (where SMR and CCUS are used to produce ammonia), hydrogen (where Haber–Bosch based ammonia is used with hydrogen from the network), and electricity (where electrolytic ammonia is produced). Bio-based options for ammonia production do not exist; however, ships may run on biofuels.

of currently applied technologies where the source of CO_2 can be fossil fuels, biogenic from current biomass using technologies, and direct air capture (DAC), but bio-based options are not permitted in the hydrocarbons or HVC sectors; 3) The electrification (ELE) scenario allows only direct electrification technologies to be used in industry, CO_2 is only sourced by DAC, and bio-based technology is not permitted; and 4) the HYD scenario takes the hydrogen-economy to the extreme, where DAC is the only source of CO_2, bio-based options are not permitted, and only syngas from RWGS and methanol are permitted in hydrocarbons. These scenarios are then contrasted against an open optimisation scenario (OPN) in which all the technology choices are available.

3. Results

The open scenario is compared in this section with the four scenarios that each follow a separate decarbonisation path. The results are presented from two perspectives: 1) energy system versus industrial sector impacts and 2) impacts on the energy mix, emissions, and costs. Based on this, the results are divided into Section 3.1 presenting the energy system impacts, and Section 3.2, presenting industrial sector impacts.

3.1. Energy system impacts

3.1.1. National energy mix

The energy mix is the most direct indicator of the different industrial decarbonisation path impacts on the energy system. Fig. 11 displays the evolution of the net primary energy mix in the Netherlands for the open optimisation scenario; owing to the carbon neutrality target, imported crude oil, oil fuels, and coal are phased out and replaced by renewable energies such as wind, solar, biomass, and hydrogen in some scenarios. In addition, Fig. 11 provides a comparison of the primary energy mix in 2050 for the four decarbonisation paths and the open optimisation scenario. The differences mainly in the use of natural gas, biomass, biofuels, hydrogen, and imported electricity are indicated in the graph. As expected, the CCS scenario used the most natural gas, the BIO scenario used the most biomass, the ELE scenario imported the most electricity, and the HYD scenario imported the most hydrogen. Both the HYD and ELE scenarios relied heavily on nuclear energy to meet the electricity deficit. In addition, more wind energy is deployed in the ELE scenario because of the more flexible demand, thus enabling improved integration of VRES into the system. Natural gas maintains a steady volume of use in the OPN scenario, with projected prices lower than in the current market, but is rarely used in the BIO, ELE, and HYD scenarios. Even the CCS scenario does not use a large amount of natural gas because offsetting of fossil fuel CO_2 with negative emissions, which can come from BECCS or DAC) is required.

3.1.2. System costs

The energy system costs during the transition increase from €100 billion to €130 billion from 2020 to 2050, as shown in Fig. 12, which is driven mostly by an increase in capital costs owing to the adoption of greener technologies. This switch from fuel to capital costs is partially countered by the projected increase in energy carrier prices. When comparing the system costs of the OPN with the other scenarios, it is evident that there are no major changes in the capital components, and larger differences are evident in the variable components of the scenarios that require biomass, electricity, and hydrogen imports. The OPN scenario provides the most cost-effective 2050 system configuration, whereas the other scenarios will cost at least 10% more in 2050. The key uncertain parameters are biomass and hydrogen import prices. Interestingly, when

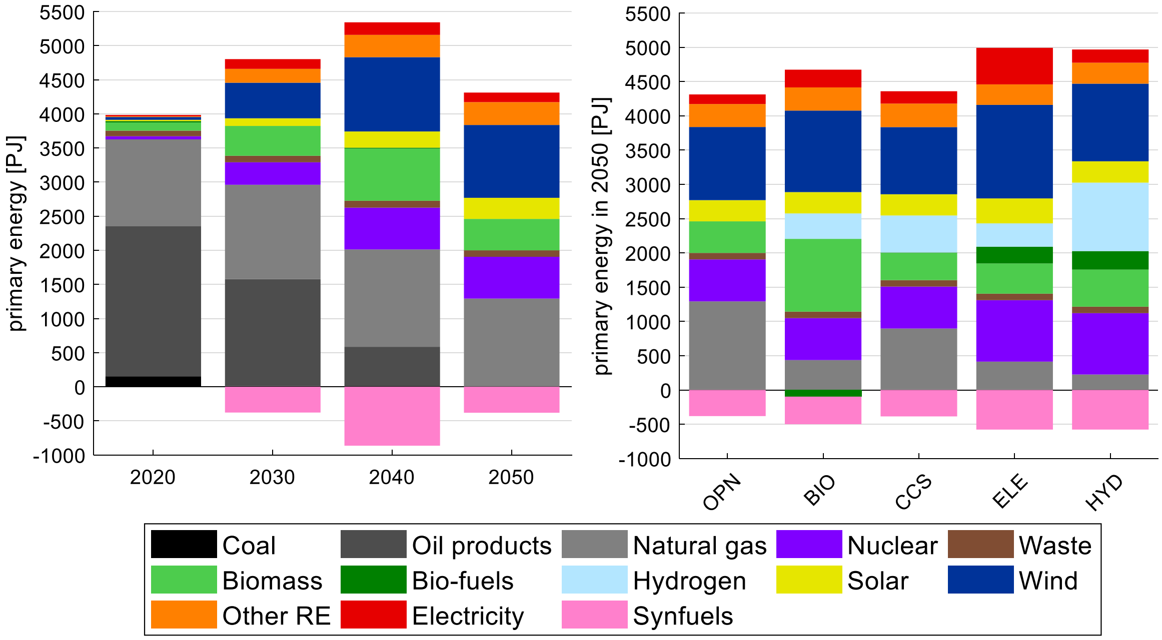


Fig. 11. Left: Evolution of net primary energy in the open optimisation scenario (OPN) transition. Right: Primary energy mix in 2050 for the five different scenarios The negative Fig.s in the primary mix correspond to net energy exports..

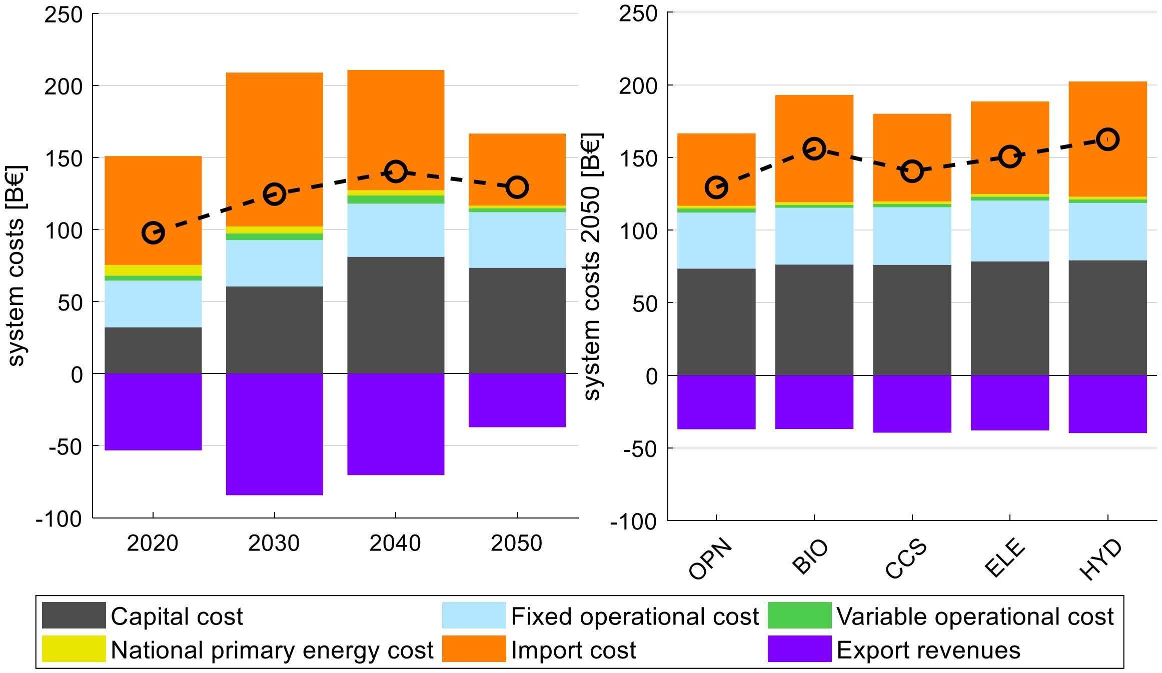


Fig. 12. System costs for the five scenarios in 2050, presented with their capital, fixed-operational, variable-operational, and revenues (from exports) components. Left: transition in the OPN scenario. Right: the five scenarios in 2050.
Annual costs of the energy system. The capital component corresponds to the annualized cost of the technological stock in the country, the variable costs exclude fuel, and the fuel components are incorporated in the national primary energy cost and import cost categories depending on their source.

testing the scenarios at lower temporal resolutions, we observed that the costs of the ELE scenario decreased but increased in absolute terms when a higher temporal resolution was applied.

3.2. Industrial sector impacts

3.2.1. Technology choice for key industrial sectors

When analysing industrial results, the primary aspect is to understand which technologies are used for which processes; as such, the energy balances, emissions, and production costs within each of the analysed industrial activities are then possible to understand. Fig. 13 illustrates these sectoral choices, demonstrating that direct hydrogen reduction for steel and ammonia from onsite blue hydrogen is the optimal choice in the OPN scenario. The low ammonia production in the BIO scenario is because of the exclusion of ammonia ships.

Naphtha steam crackers will remain valuable to the Netherlands in 2050 because they appear to be the predominant energy source that meets the olefin demand. The HYD and ELE scenarios only permit hydro-

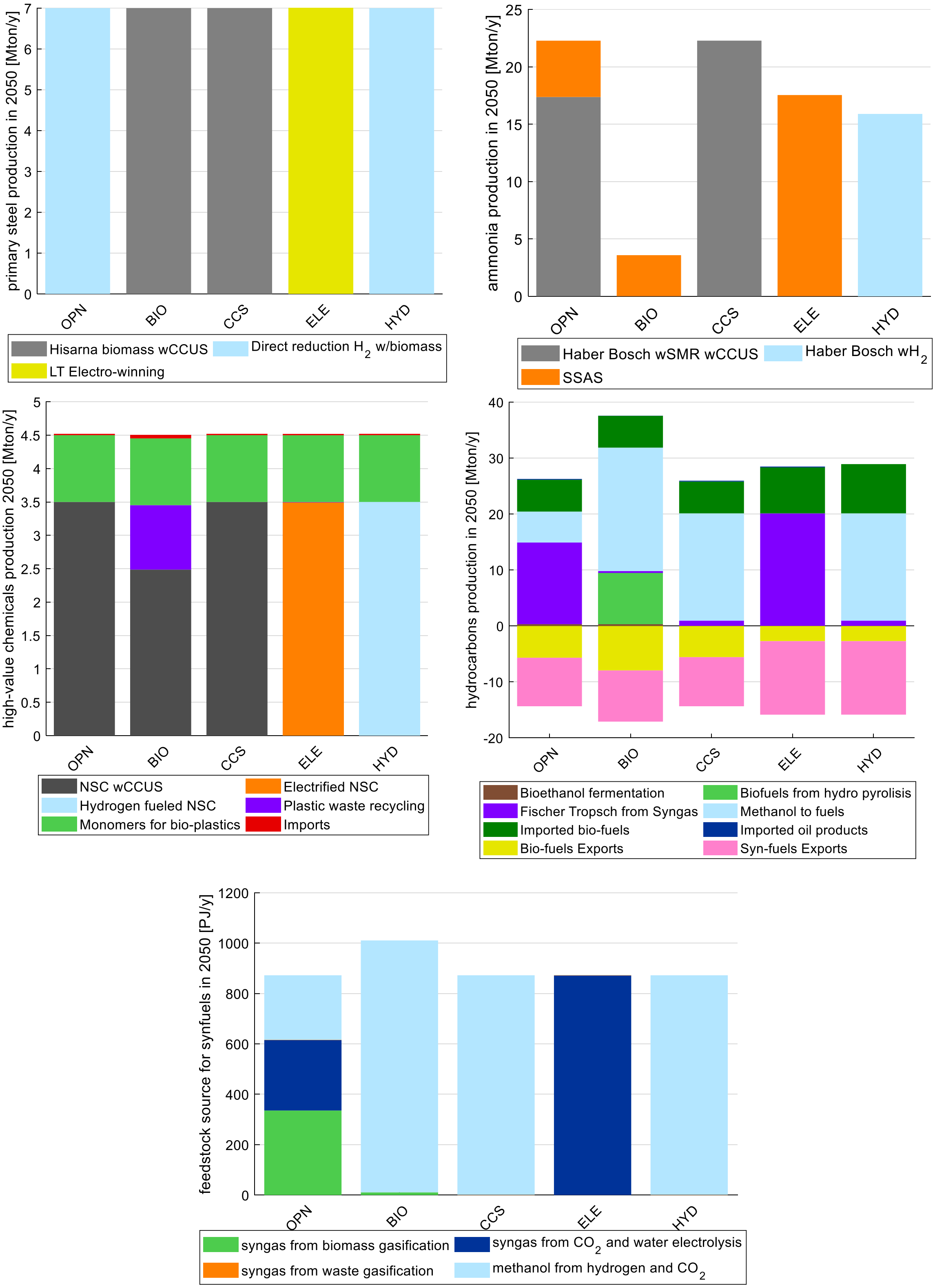


Fig. 13. Technology choices to satisfy the key industrial activities in 2050 for the five scenarios. Top left: steel. Top right: ammonia. Centre left: high-value chemicals. Centre right: hydrocarbons. Bottom: feedstock for hydrocarbons.

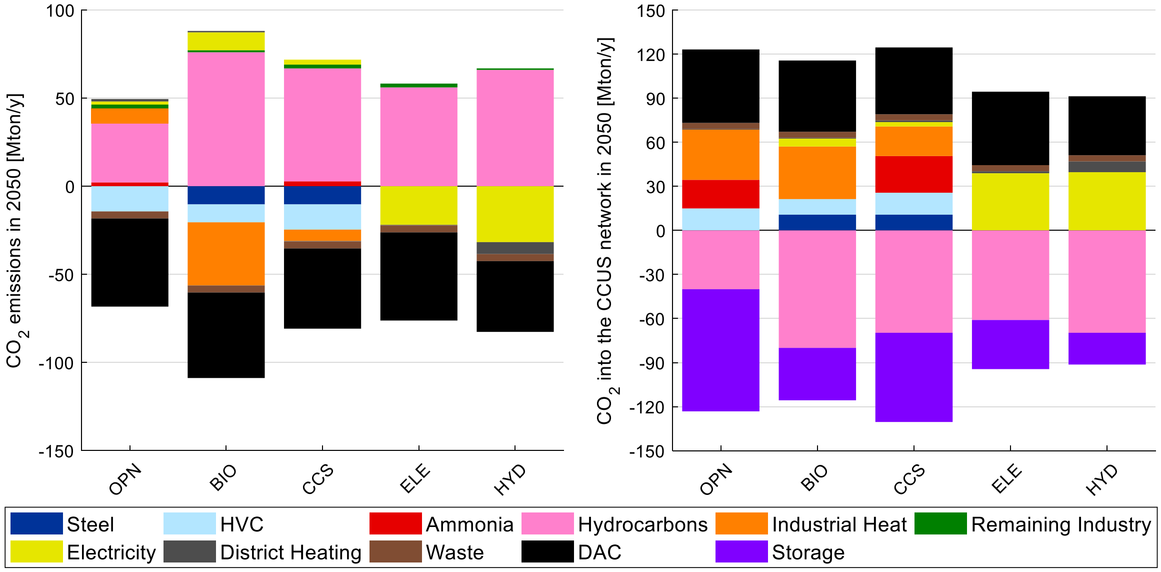


Fig. 14. ETS emissions in 2050 for the five scenarios. Left: Net CO2 eq. emissions released into the air. Right: Net CO2 injected into the CCUS network.

gen and electrified crackers to compete with methanol-to-olefins, and both crackers proved superior in their respective scenarios. Another notable difference in the BIO scenario is that plastic waste recycling and refurbishing is a superior solution to plastic waste pyrolysis, which is the preferred option in the other scenarios. In addition, the BIO scenario is the only scenario where BIO naphtha, which originates from bio-hydro-pyrolysis, is used in the crackers, whereas synthetic naphtha is used in all the other scenarios.

The hydrocarbon sector is the most interesting because biofuels and synthetic fuels are mixed to satisfy the demand for export products, whereby biofuel imports are mixed with synthetic fuels using methanol to fuels (MTF) and Fischer–Tropsch (FT) processes. The OPN and ELE scenarios are those with more synthetic fuels from the FT, as they both use electricity and CO_2 to produce the required syngas. In addition to electricity and CO_2, the OPN scenario also uses biomass. The remaining scenarios rely mostly on MTF to produce synthetic fuels, whereas the BIO scenario is the only scenario in which biofuels from bio-hydro-pyrolysis are produced. The BIO scenario produces noticeably more hydrocarbons than the other scenarios because ammonia ships have been disabled.

3.2.2. Emissions in key industrial sectors

The volume of CO_2 in industry falls into two categories: 1) CO_2 emitted to the atmosphere and 2) CO_2 flow in and out of the CCUS network. Fig. 14 presents the net emissions and use of the CCUS network of selected industries and energy activities. Hydrocarbon production is the largest emitter in all the scenarios, which is a direct consequence of categorising synthetic fuels as carbon neutral. These emissions correspond to the CO_2 taken from the CCUS network that will be released during synthetic fuel combustion or at the feedstock end-of-life, and their use will not be accounted for because they are considered carbon-neutral fuels in the assumed policy landscape. Similarly, it is notable that DAC plays a role in all of the scenarios, with the HYD scenario requiring less DAC to synthesise CO_2-based fuels and uses less fossil fuels because there is less CO_2 stored underground. The natural gas used, as shown in Fig. 11 is proportional to the storage volumes reported in Fig. 14 (right).

Both steel and HVC industries become sources of negative emissions in selected scenarios (BIO and CCS for steel and OPN, BIO and CCS for HVC) because of the CO_2 sequestration of carbon-neutral fuels in the HIsarna biomass and steam crackers. Industrial heat also provides negative emissions due to BECCS in scenarios where biomass for heating is used (BIO and CCS), as well as power generation in the ELE and HYD scenarios. An interesting observation is that although there is a relative scarcity of carbon dioxide molecules in the ELE and HYD scenarios, the demand for synthetic fuels is still met because biomass with CCUS is used in the power system to meet both the CO_2 demand and the increased electricity.

3.2.3. Levelised production costs for key industrial sectors

Levelised costs of production (LCOPs) are one of the most important indicators of the decarbonisation transition because they provide an understanding of the evolution of commodity prices. The international energy agency (IEA) regularly updates the LCOP key commodity production figures., which are occasionally reported per technology, commodity, or region. The typical LCOP of steel via blast furnace production can oscillate between 330 and 480 €/t, whereas direct reduction of hydrogen (DR-H_2) can escalate up to 870 €/t [40]. The indicators reported in Fig. 15 illustrate the positive case for steel, where the evolution of the hydrogen price facilitates an LCOP of slightly above 400 €/t in 2050 in the open optimisation scenario. It is notable that from the perspective of system optimisation, a lower LCOP is not always selected as part of the solution. This occurs either because an emission shadow cost is attached to the process or because the process uses a scarce resource which is more important in other sectors.

The ammonia sector also has a positive LCOP. Currently, the IEA reports that ammonia can be produced for between 280 and 580 €/t with the Haber–Bosch process and SMR from natural gas. Capturing CO_2 in the process could raise production costs up to almost 700 €/t, and manufacturing ammonia via electrolysis could raise the cost up to 1,200 €/t [41]. In this study, the OPN scenario produces ten times more ammonia than that currently produced in the Netherlands (to satisfy the fuel demand for shipping), mostly by using onsite blue hydrogen (Haber–Bosch with carbon capture in the SMR process). Here, the LCOP of ammonia remains under 500 €/t and reaches 1,200 €/t in the HYD scenario, where hydrogen is purchased from the market at high prices. In the ELE scenario, SSAS (direct electrolysis) reaches 1,500 €/t because there is no production alternative, which forces the sector to use electricity during higher-cost hours. In other scenarios, such as BIO, where SSAS is used at a smaller scale in combination with other technologies, the LCOP of the technology remains at approximately 500 €/t and has a much higher capital cost.

However, olefins and hydrocarbons are impacted substantially during the transition. The IEA reports that high-value chemicals in Europe are currently produced for under 1,200 €/t [42], and fossil-based hy-

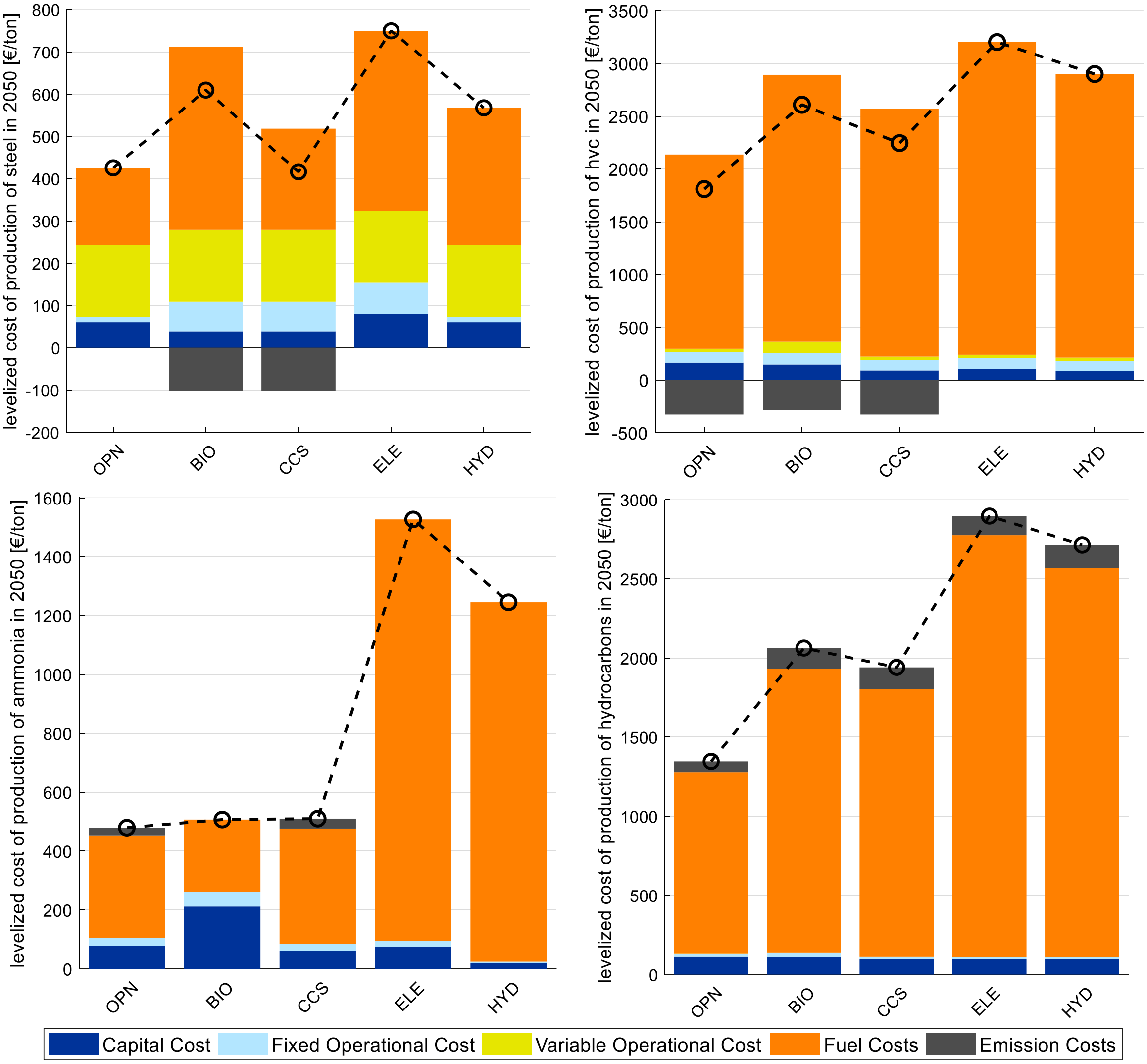


Fig. 15. Levelised cost of production of key activities in 2050 for the five scenarios. Top left: steel. Top right: high-value chemicals. Bottom left: ammonia. Bottom right: hydrocarbons.

drocarbons for under 700 €/t [43]. In the OPN scenario, these values reach 1,800 and 1,400 €/t for HVC and hydrocarbons, respectively, and 3,100 and 2,900 €/t, respectively, in the ELE scenario. These increases in the LCOP may appear to be high; however, both commodities have traditionally been manufactured from crude oil, which is costly. Quite an unfair comparison if we consider that fossil fuels break the ‘circularity wheel,’ and part of the cost of the process is subsidised by nature in a non-renewable way. In addition, typical price projections assume that crude oil maintains a relatively low value; however, if we use current oil prices for the projection, synthetic hydrocarbons become cheaper than fossil-based hydrocarbons.

Note that the CO_2 price of the CCUS network was neglected in the reported LCOPs. The price of CO_2 in the network is a sensitive topic because it is difficult to determine which value to use. It is unclear whether those providing CO_2 to the network should pay penalties for the emissions or if they should receive revenue. The same question applies to the manufacturing of feedstock from CO_2. From a market point of view, it would be reasonable to conclude that CO_2 from the network becomes more cost-effective than underground storage. However, if the underground storage capacity is limited, then the grid users could request payment to dispose of the captured CO_2. Similarly, if the system becomes too dependent on CO_2 to manufacture feedstock, then the CO_2 producers could request a purchasing price capped by the DAC cost. Thus, the CO_2 price from the network will be capped at the low end by the negative DAC cost, which will decrease the cost of underground storage, and will be capped at the high end by the difference in marginal abatement cost between deploying CCUS technology and other decarbonisation technologies for diverse industrial activities. Shadow prices can address this; however, the rigidity of the network operation and limited market accessibility requires a costlier network infrastructure and an increased in storage buffers per unit of activity, resulting in excessive CCUS shadow prices. To avoid this, the solution can be modelled again with a sufficiently high assumed network capacity installed, and consequently, only the variable component of the CCUS CO_2 network price is considered in the shadow exercise. A situation like this is possible if governments subsidise the infrastructure required to enable CO_2 markets. When remodelling the OPN scenario, the value obtained was 20 €/t of CO_2 for those injecting CO_2 into the CCUS network.

3.3. Sensitivity analyses

The sensitivity analyses discussed in this section were performed according to the descriptions of the four key uncertain parameter groups presented in Section 2.2, including: 1) imported biomass prices and CO_2 storage capacity, 2) virgin olefin demand, 3) evolution of overnight in-

Table 2

Synthesized results from the sensitivity analyses of this study.

Experiment	Variables affected	Impact on system costs	Impact on energy use	Other observations
BECCS availability	- Biomass import price: between 5 and 60 €/GJ - CO_2 storage capacity: between 10 and 200 Mt/y	Higher imported biomass costs and lower CO_2 storage capacities result in higher system costs. Imported biomass prices play a more important role than CO_2 storage availability to keep the energy transition affordable.	Biomass: There is no decrease in the use of imported biomass below 20€/GJ Natural gas: Higher response to the CO_2 storage capacity than to biomass price. Imported hydrogen: Over 1000 PJ for low CO_2 storage availability and high biomass price.	The results are important in combination, biomass prices above 40 €/GJ are not taken by the system, below that there is not much of a need for extra CO_2 storage capacity.
Olefins demand	- Evolution of the olefins demand for HVC: between 0 and 10 Mt/y in 2050	Progressive increase in system costs up to a demand of 7 Mt/y, above where it becomes increasingly difficult to reach targets and the system costs increase more steeply.	Biomass: Noticeable increase for over 7 Mt/y where biofuels begin to be produced and exported. Natural gas: not significant effects. Hydrogen: No imports. Local hydrogen increases until 7 Mt/y.	There is a threshold point at around 7Mt/y, where the driver of synthetic fuels productions swifts from kerosene to naphtha.
TRL of green technologies	- Evolution of the overnight investment costs of novel green technologies: high and reference TRL.	Practically not different between the two scenarios.	Biomass: Not different. Natural gas: Not different. Imported hydrogen: Not different.	Technology choice is mainly driven by energy prices, so TRL of industrial technologies has very limited effect on technology choices. Only syngas from CO_2 electrolysis and SSAS receive an slight extra boost from the lower investment costs.
Gas prices	- Imported natural gas and imported hydrogen prices: between 10 and 50 €/GJ	Natural gas price affects system costs more than imported hydrogen price. Imported hydrogen price affect system costs only when it costs 10 €/GJ.	Biomass: Always very present, but it is affected by low hydrogen prices. Natural gas: Its adoption is only affected by the natural gas price, imported hydrogen price has no effect on it. Imported hydrogen: Noticeable import flows when cheaper than 20 €/GJ.	The impact of natural gas prices has a significant impact on technological choices and the outcome of the transition. The transition becomes cost effective at current gas (and oil) prices, as the emission constraint becomes not binding in 2050, so fossil fuels are displaced out of the mix by their own merit.

vestment costs of novel green technologies, and 4) impact of imported hydrogen and natural gas prices. Different sensitivity techniques were used for the assessment of each groups. For the first and fourth groups, we modified the values of imported biomass prices and available CO_2 storage capacity and the values of imported hydrogen and natural gas prices, resulting in a mix of combinations. For the second group, we modified the values for virgin olefin demand. Finally, for the third group, we contrasted two scenarios with lower and higher overnight investment costs for key green technologies. All the values used for the sensitivity analyses are presented in Appendix C, the detailed results of the sensitivity analyses are presented in Appendix G, and the synthesized results reflecting the impact on system costs, energy use and main observations are reported in Table 2.

From the experiments above we identified that biomass is needed for the energy transition, as its presence in the mix remains unaffected up to a value of 20 €/GJ. This is a crucial result as most of biomass available in Europe is well below that range. Biomass is crucial to deliver biogenic CO_2 to the CCUS network, where it can be used to manufacture circular molecules or to be stored underground to achieve negative emissions. These negative emissions are crucial as it allows for carbon neutrality in the system while allowing for limited amounts of fossil fuels (mostly natural gas) to be used to decarbonized challenging activities, or to offset non-energy related emissions such as enteric fermentation from agriculture. Because of this, we can observe that an availability of at least 50 Mt/y to store CO_2 underground could help to make the energy transition more affordable. Above this limit, there are not significant gains and the system only gets the capacity to keep using more fossil fuels.

The variation in the demand for olefins show that the ratio in the demand of kerosene and naphtha is important to avoid transition costs. We see that when naphtha is the secondary product of the synthetic fuels manufacturing, system cost increase less severely than when naphtha becomes the driver of the activity and kerosene the secondary product. This experiment shows that manufacturing olefins can be accommodated cost effectively in the system as long as the demand does not exceed the naphtha manufactured as a bi-product of kerosene production processes such as bio-pyro oil, methanol-to-fuels, and Fischer Tropsch.

We noticed that the investment costs of green novel industrial processes such as electrified steel, ammonia, and syngas are not detrimental to trigger technological choice. We have discussed in the previous section how the energy component is the predominant share of the LCOPs of industrial processes, which explains why for electrified processes is not sufficient to lower the capex component by 30% to compensate for the higher energy costs. For these processes, efficiency improvements could be key to unlock them as solutions for the energy transition.

Finally, the last sensitivity experiment shows that current natural gas prices (above 50 €/GJ) could displace it completely out of the mix for the transition (the emission constraint becoming non-binding), and even at lower levels natural gas could have a very limited share as even at 10 €/GJ it hardly keeps half of its current volume. Imported hydrogen, on the other hand, responds strongly to variations in both imported hydrogen and natural gas prices. The national energy system has a significant production capacity, which requires prices of 10 €/GJ for imported hydrogen to take a large share of the mix, or up to 20 €/GJ if natural gas is more expensive than that.

4. Discussion

This study represents a significant step in developing a model for industrial decarbonisation analyses in terms of sectoral representation and integration with the energy system. However, there are several conceptual and methodological aspects that for transparency are outlined and areas where this line of research could be strengthened are highlighted.

The IESA-Opt model was adopted for the analyses undertaken in this study. As presented in the original IESA-Opt publication [22], the model describes simultaneous activities in all sectors of the energy system, namely residential, services, agriculture, transport, industry, and energy sectors, to account for all GHG emissions under diverse national targets. The resulting challenge when using this model with high technological and temporal resolutions for the entire decarbonisation transition with perfect foresight necessitates the use of linear programming (LP). Therefore, some capabilities have not been included in the model because they require mixed-integer programming, such as the accounting of individual plants or unit commitment in the power sector. Accounting for cost savings arising from economies of scale is the most important capability sacrificed when using linear programming to analyse industrial decarbonisation.

An additional weakness of this study is that the adopted representation of the energy system is described in a single node, which does not consider geographical elements of the system. This is important for two reasons. First, there are national resources such as geothermal heat and electricity generation from wind which are strongly dependent on location. Neglecting these gives rise to unfeasible solutions and cost underestimations of infrastructure needs. Second, it is impossible to account for industrial clusters. Industrial clusters could lead to more efficient use of utilities, such as steam recirculation and on-site hydrogen production. The IESA-Opt model is suitable for working with nodes and adopting a subnational representation of the energy system. However, efforts are required to collect adequate data and design an input architecture which will incorporate a description the most crucial geographical constraints in a computationally efficient manner.

In this study, a large amount of data could be processed owing to the availability of the MIDDEN database. Nevertheless, substantial efforts are still required to fill the data gaps to describe the processes in all industrial sectors and activities that are and will be available during the transition. For example, finding data for the expected future costs of industrial processes is challenging, and when available, these are usually within large uncertainty ranges. Another example is the wide range of techno-economic parameters for which heat technologies are described. These technologies are often subject to capacity factors, scale, heat-exchanger configuration, and many other elements which hinder the provision of definitive figures to describe them. In addition, available data sometimes do not allow further disaggregation of industrial activities, which, in the case of the remaining chemical activities and the food sector, could assist in accounting for possible cost reductions and material efficiencies. This topic is particularly important for the plastic and waste sectors, which can benefit considerably from more explicit material representations to endogenously account for the value of a circular economy.

From an analytical perspective, there are many uncertainties in the transition. Some of the parameters representing uncertainties of the transition were explored here; however, many others were not. Examples include the availability of renewable energy in the Netherlands and Europe, power generation technologies in Europe, evolution of the ETS price, potential future developments in the North Sea which could greatly affect the industrial landscape in the Netherlands, and macroeconomic links or demand volumes which could substantially change the scenario outcomes. Similarly, it is important to mention that the development of technologies in all sectors is parameterised in terms of cost profiles and energy balances, which contain implicit and highly uncertain technological advancement capabilities. It is not feasible to cover this in a single analysis for more than 800 technologies. For this reason, it is recommended that the topic with specific analyses that focus on certain sectors or issues be explored.

To finalise the discussion, it is important to note that the goal of the study was to carry out a technical optimisation analysis for the transition towards a clean decarbonised industrial sector in the Netherlands. Thus, many analytical elements were excluded from the study, such as the development of novel markets and market dynamics, the role of policy subsidies, and the impact of social behaviour agents and their perceptions. These all have the potential to steer the transition in different directions; hence, are worthy of further exploration.

5. Conclusion

Exploring industrial decarbonisation in an integrated analysis will assist in reducing one of the most crucial knowledge gaps in the energy transition. Typically, energy system models tend to represent industrial processes and neglect their interactions with the energy sector. In this study, using IESA-Opt, a state-of-the-art energy system optimisation model, we have represented the most important industrial activities in the Netherlands. This approach allows us to better account for the feedback between the industrial demand of an energy carrier and the energy market. In addition, by using a high temporal resolution, we can account for the impact of industrial flexibility in the market and, therefore, provide a superior account of the cost-effectiveness of each decarbonisation option. By disaggregating industrial sectors and focusing on technologies and processes, we were able to include aspects such as technology readiness levels, material efficiency, and fuel substitution.

In this study, we analysed four extreme decarbonisation paths for industries where the predominant technological choices are based on biomass, carbon capture retrofits, electrification, and hydrogen. Full decarbonisation could be successfully reached via all paths; however, energy system configurations and costs differed. An open optimisation scenario was used to contrast each of these extreme scenarios with a flexible scenario where the different options could be combined and applied without any imposed constraints. The flexible scenario provides the best results for the transition, as both system costs and CO_2 shadow prices are considerably lower than in the other scenarios. This study demonstrates that a mixture of technologies helps to facilitate cost effectiveness in the decarbonisation transition and, more importantly, helps to lower the average costs of energy carriers, which is crucial for the energy poverty issue.

These observations are strengthened when looking into the future, for example, higher fossil fuel prices relative to the current 2022 prices. In this scenario, the emission reduction target is no longer limiting, which reduces the CO_2 shadow price to zero, meaning that the energy transition can be carried out cost-effectively and that a fully decarbonised system would be a direct consequence of cost performance. This conclusion alone underlines the importance of being able to create a future in which renewable energies are skilfully integrated with novel industrial processes, and it strengthens when we focus on import dependency. In the resulting decarbonised system, natural gas, oil, and coal imports are substituted by imported electricity, hydrogen, and biomass, all of which are sourced or produced within the EU. We can conclude that the resulting decarbonised energy system would not only be less expensive than using fossil fuels at current prices, but would also incentivise energy independence and strengthen energy markets and collaboration within Europe.

This study reveals the importance of the interaction between energy systems and the industrial sector. For example, the impact of the industrial technology mix on energy carrier prices or, vice versa, the role of fuels and raw materials influences technology choices. In Section 4.2, we illustrate the importance of the demand for high-value chemicals for the outcome of the transition of the entire system. Higher olefin demand requires more biomass, resulting in higher system costs. This is a good example where a baseline change results in a different approach toward reaching the targets is taken by the system. Similarly, with foreign demand for hydrocarbon exports, different scales of deployment for technologies of methanol to fuels or Fischer—Tropsch (FT) would be required. These changes can trigger different resource allocations and facilitate or complicate targets, not only for national emissions, but also for international transport and Scope 3 emissions. In the Netherlands, ammonia and synthetic fuels have become the preferred technologies for bunker fuels and aviation, and synthetic naphtha has become the preferred feedstock for high-value chemicals. Therefore, it is valid to weigh the stress in the system of decarbonising larger production volumes against the desire to provide clean carriers to other parts of the world, especially if the Netherlands is able to perform better and produce cleaner molecules than other countries.

The results obtained at the sectoral level are also a substantial contribution not only because they show which technologies are the preferred choices for the transition, but also because they help to understand the drivers behind them. For example, the capital and fixed operational cost components of the Levelised costs of production (LCOP) are significantly lower than the fuel (or raw materials) components for the four industrial sectors. Based on this observation, it is evident that hydrogen direct reduction is the preferred choice for fully decarbonised steel production. However, this can change towards biomass-based HIsarna if hydrogen becomes relatively more expensive than biomass. Similarly, steam methane reforming with CCUS is the preferred choice for ammonia production. However, solid-state ammonia synthesis, SASS, can take a small share of the production mix, up to 5 Mt, by using electricity during the most cost-effective times. This share cannot increase because the fuel component of the LCOP increases considerably if more expensive electricity is used.

For a similar reason, naphtha steam crackers remain the preferred choice for high-value chemicals in all scenarios because synthetic naphtha is derived from a significantly lower fuel component for the LCOP. For this to change, the methanol and ethanol synthesis processes would need to become significantly cheaper. It is important to note that because of the model structure of bio-plastics (e.g. polylactic acid and polyethylene furanoate), they do not compete with traditional olefins, and each of them has a fixed demand volume. A similar analysis should be performed, in which traditional olefins and bio-plastics compete for the same market. However, a better representation of plastic materials and functionalities in the model would be required.

Heat technologies in the industrial sector interact closely with power systems. For example, in the OPN scenario presented in this study, most of the industrial heat was sourced either by gas boilers or by gas cogeneration of heat and power (CHP), both with CCUS. As CHPs in IESA-Opt are provided with a certain degree of flexibility, both by changing the fuel input and the heat-to-power output ratio, the industry assists in the generation of electricity at times when it is limited. Biomass is also a viable alternative for heat generation in industry; however, its adoption depends on the availability of cheap imported biomass. Hydrogen and electricity seem less likely to be extensively adopted for heat generation because in these scenarios, the price of heat in the industrial sectors is considerably higher than that in the others.

Furthermore, it is important to mention that we selected the assumed overnight investment costs, ONICs, of novel green industrial technologies as a crucial parameter. Surprisingly, when we reduced the investment costs required in 2050 by 30% in a sensitivity analysis of 18 of these technologies, we observed that the outcomes did not differ. The reason is that the criterion behind technology adoption is linked to their LCOPs and that fuel is the predominant component of most industrial LCOPs. As most of the technologies modified in this exercise directly or indirectly consume electricity, the price and availability of electricity is the driving force behind the adoption of these technologies. Hence, we assume that their adoption could be more strongly influenced by the ONICs of electricity generation and storage technologies, the assumed availability profiles and potentials of renewable electricity, and the development of the European power system in general.

Biomass has also been identified as a fundamental carrier of decarbonisation. As demonstrated in the sensitivity analysis performed on the imported biomass price, all biomass available below 20 €/GJ will be used by the system. Biomass is valuable for decarbonisation because of its net zero fuel attribute and because it can enable negative emissions when coupled with carbon capture and storage. These negative emissions make provision for emissions in sectors and activities which are very difficult or impossible to decarbonise (e.g., agricultural emissions from enteric fermentation). When the potential for the underground storage of captured CO_2 is limited, hydrogen enters the mix as a carbon-neutral fuel to compensate for the lack of negative emissions. However, as we are including international transport and Scope 3 emissions in the carbon neutrality definition, there is always a bare minimum storage requirement for the system to reach full decarbonisation (approximately 10 Mt of CO_2 eq./y). From this minimum, the amount of stored underground CO_2 is a consequence of fossil fuel usage in the scenario. Therefore, only the OPN and CCS scenarios used these resources extensively (80 and 60 Mt/y, respectively).

It is also important to mention that many other countries and regions in the world have higher GHG emissions and more challenging energy transitions. With adequate data on their current energy balances, economic activities, and energy assets, it is possible to describe their energy systems using the IESA-Opt model [44]. The model code and database are open source and available for any research group to use or modify.

In this study, we demonstrate that a systemic analysis with high technological and temporal resolution is crucial for understanding the energy decarbonisation transition in the industrial sector. However, there are still many areas to improve where future work is recommended. The most important aspect is the need for an improved representation of the plastic streams to better account for material efficiency, circularity, recycling, and the endogenous demand for bio-plastics. We also recognise that our conclusions could benefit considerably from an improved geographical resolution focused on industrial clusters and their ability to use local resources and share utilities and waste streams. In addition, potential developments in the North Sea, such as offshore hydrogen production or the offshore relocation of some processes to reduce the need for inland transmission infrastructure [33], could greatly affect our conclusions and the industrial landscape of the Netherlands. Other topics, such as macroeconomic linkages, subsidies, or other policy directives, could strongly affect industrial decarbonisation and hence are worthy of further exploration. Finally, the framework presented in this study is flexible enough to analyse these important issues, and consequently, we recommend that the IESA-Opt model be suited and expanded for the purpose, and used further to compare results and conclusions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors wish to acknowledge the support provided by the Integrated Energy System Analysis (ESTRAC) project, financed by the New Energy Coalition (finance code: 656039). The views expressed here are those of the authors alone and do not necessarily reflect the views of the project partners or policies of the funding partners.

Appendix A. Cost parameters used to describe the technologies in the model

Steel manufacturing

The technologies mentioned in Fig. 6 are described in IESA-Opt accordingly with the cost profiles presented in Table 3.

High-value chemicals production

The framework presented in Fig. 4 visualize the connections between the feedstock sources and the technological options which are able to convert them into the olefins required by the exogenous demand of the high-value chemical sector. The list of technologies as well as their corresponding cost profile is reported in Table 4.

Table 3
Economic characterization in the model of the steel manufacturing technologies. *Note that the electro-winning processes are not always available in 2030 for the scenarios due to their assumed low TRL.

		Overnight investment costs [€]			Fixed Costs	Lifetime
Technologies	Units	2020	2030	2050	[€/ton-y]	[y]
Blast furnace BOF	ton/y	551	551	551	34.6	20
Blast furnace BOF wCCUS (end-of-pipe)	ton/y	795	795	795	60.9	20
Blast furnace BOF with top gas recycling wCCUS (end-of-pipe)	ton/y	815	815	815	67.8	20
HIsarna	ton/y	575	370	320	42.2	20
HIsarna wCCUS (cryogenic)	ton/y	840	545	545	68.3	20
HIsarna biomass wCCUS (cryogenic)	ton/y	900	600	600	70.0	20
Direct reduction	ton/y	435	435	435	13.0	20
LTWIN	ton/y	NA	900*	640	45.0	20
HTWIN	ton/y	NA	950*	710	58.0	20

Table 4
Economic characterization in the model of the basic organic chemical technologies.

		Overnight investment costs [€]			Fixed Costs	Lifetime
Technology	Units	2020	2030	2050	[€/ton-y]	[y]
Existing naphtha steam cracker	ton_Ey/y	725	725	725	36	25
Existing naphtha steam cracker wCCUS (MEA post-combustion)	ton_Ey/y	1,000	1,000	1,000	48	25
Electrified naphtha steam cracker	ton_Ey/y	1,100	1,100	1,100	51	25
Hydrogen fueled naphtha steam cracker	ton_Ey/y	1,060	1,060	1,060	38	25
Ethylene from bioethanol dehydration	ton_Ey/y	1,200	850	650	28	25
Methanol to olefins	ton_Ey/y	2,500	2,200	1,600	90	25
Propane dehydrogenation	ton_Py/y	1,100	1,100	1,100	52	25
Propylene from ethanol dehydration, ethylene dimerization and metathesis	ton_Py/y	1,500	1,100	850	34	25
Bioplastics from hydrolysis, fermentation and furfularization of cellulosic biomass	ton_BP/y	2,000	1,700	1,200	200	25

Table 5
Economic characterization in the model of the ammonia producing technologies.

		Overnight investment costs [€]			Fixed Costs	Lifetime
Technologies	Units	2020	2030	2050	[€/GJ-y]	[y]
Haber-Bosch with H2 from SMR	GJ/y	41	41	41	1.2	20
Haber-Bosch with H2 from SMR wCCUS	GJ/y	50	50	50	1.3	20
Haber-Bosch with external H2	GJ/y	8	8	8	0.3	20
Haber-Bosch with electrolyzer	GJ/y	42	32	32	1.1	20
Solid State Ammonia Synthesis	GJ/y	NA	NA	35	0.7	20

Ammonia production

The economic parameters used to describe the technologies shown in Fig. 7 in the model are presented in Table 5. Other technologies based on biochemical paths or electrolysis of plasma states of oxidized nitrogen were not included due to the extremely low TRLs.

Hydrocarbons production

The technologies used in IESA-Opt to represent the technologies shown in Fig. 5 vary depending on the specific type of feedstock, process or output configuration, and is more complex than the conceptualization presented in the framework. The complete list of technologies as well as their cost-profiled are reported in Table 6.

Remaining sectors

The list of efficiency measures and decarbonization alternatives for the remaining sectors as shown in Fig. 3 is reported in Table 7 alongside with the cost profiles fed to the model.

Diagram

Table 6
Economic characterization in the model of the refineries technologies.

Technologies	Units	Overnight investment costs [€]			Fixed Costs
		2020	2030	2050	[€/GJ-y]
Deep cracking refinery	GJ/y	14.5	14.5	14.5	0.8
Deep cracking refinery wCCUS	GJ/y	15.5	15.5	15.5	0.9
Basic cracking refinery	GJ/y	16.5	16.5	16.5	0.8
Basic cracking refinery wCCUS	GJ/y	17.8	17.8	17.8	1.0
Koch refinery	GJ/y	2.5	2.5	2.5	0.6
Koch refinery wCCUS	GJ/y	3.5	3.5	3.5	0.6
Bioethanol from sugar fermentation	GJ/y	32.0	32.0	32.0	3.9
Bioethanol from starch fermentation	GJ/y	45.0	45.0	45.0	4.5
Bioethanol from cellulosic biomass trough hydrolysis and fermentation	GJ/y	75.0	75.0	75.0	11.2
Biodiesel from FAME	GJ/y	6.0	6.0	6.0	1.5
Biodiesel oriented hydro pyrolysis	GJ/y	7.0	6.5	5.0	0.3
Bio-kerosene oriented hydro pyrolysis	GJ/y	7.0	6.5	5.0	0.3
Syn-diesel oriented Fischer Tropsch	GJ/y	60.0	25.0	20.0	0.8
Syn-diesel oriented methanol to fuels	GJ/y	45.0	30.0	15.0	0.8
Syn-kerosene oriented Fischer Tropsch	GJ/y	60.0	25.0	20.0	0.8
Syn-kerosene oriented methanol to fuels	GJ/y	45.0	30.0	15.0	0.8
Syngas from biomass gasification	GJ/y	9.5	7.0	4.0	0.2
Syngas from CO2 and H2 RWGS	GJ/y	2.0	1.6	1.2	0.1
Syngas from SOEC electrolysis	GJ/y	8.0	5.0	1.0	0.0
Methanol from syngas	GJ/y	6.0	6.0	6.0	0.2
Methanol direct synthesis from CO2 and H2	GJ/y	11.0	8.0	7.0	0.2

Table 7
Economic characterization in the model of the remaining industrial sectors.

Activity	Technology	Units	Overnight investment costs[1] [€]	Fixed Costs [€/ton-y]	Lifetime [y]
Aluminium	Hall Héroult + oil anodes + casting	ton/y	450	135	20
	Hall Héroult + biomass anodes + casting	ton/y	455	138	20
	Hall Héroult + inert anodes + casting	ton/y	460	140	20
	Hall Héroult + oil anodes w/wet cathodes + casting	ton/y	490	145	20
	Hall Héroult + biomass anodes w/wet cathodes + casting	ton/y	495	148	20
	Hall Héroult + inert anodes w/wet cathodes + casting	ton/y	500	150	20
Urea	Urea production from Ammonia	ton/y	185	6	20
	Urea production from Ammonia and CCUS	ton/y	185	6	20
Chlorine	Chlor - alkali electrolysis	ton/y	1,250	90	20
Glass	Conventional furnaces + post-melting	ton/y	181	6	20
	Efficient furnaces + post-melting	ton/y	211	6	20
	Electric cold-top furnaces + post-melting	ton/y	389	12	20
Ceramics	Conventional kilns + preparation, drying, treatment	ton/y	150	8	20
	Electric kilns + preparation, drying, treatment	ton/y	275	14	20
Paper and board	Conventional paper and board milling	ton/y	1,250	100	20
	Compressed refining of paper and board	ton/y	1,380	120	20
	Compressed refining of paper and board with air-laid forming	ton/y	1,550	150	20

[1] Some of the technologies listed above are considered to have lower TRLs so the model is not enabling them until later in the transition.

Appendix B. Reference scenario definition

The demand for products from the industrial sector is in general assumed to increase, with two notable exceptions. First, steel production is assumed to stay constant with current production levels up to 2050 as there is only one site in the Netherlands producing steel and there are no announced plans of capacity expansion. Second, the demand for monomers in the high value chemicals sector is assumed to decrease after 2030 due to an increased role of recycling (exogenous in the model) not only in the Netherlands but in the surrounding EU landscape, which will drive down the need of virgin ethylene and propylene for plastic manufacturing. In a similar fashion, due to an assumed structural change giving an increased role to reuse and refurbishment in the economy, the amount of waste generated in the country is expected to decrease after 2040. The complete demand volumes for all the industrial sectors are reported in Table 8.

The production of oil-based products and hydrocarbons is driven both by the energy demand of national economic activities such as naphtha steam cracking or transport, and by the external demand for exported fuels. As shown in Table 9, in this scenario it is assumed a steady decrease in the exports of oil-based products after 2030 down to a fully halt of the exports by 2050. This, as it is assumed that in the international arena, especially in the EU, road transport will be almost absolutely electrified, and ships will run on more sustainable fuels. As an exception to this, foreign kerosene demand is expected to increase as the aviation sector is expected to continue growing, and innovative airplanes running on hydrogen have a very low TRL. It is important to mention that many of the oil products satisfying the demand in this table are imported and then re-exported, rather than produced internally in the Netherlands.

Finally, the policy directives assumed for this scenario assume a full zero emission target for 2050 for national and international transport emissions, as well as for the fossil CO_2 embedded in feedstock that will be emitted at the end of its life time. The scenario assumes open optimization and there is not a specific technological path enforced other than the ban on burning coal to produce heat or electricity after 2030. Also important to mention, the scenario considers that synthetic fuels are carbon neutral. This means that

Table 8
Demand for industrial produces in the reference scenario. *Note: For waste processing activities the units refer to Mton of waste processed.

Demand	Units	2020	2030	2040	2050	Source
Steel production	Mton	7.00	7.00	7.00	7.00	[30]
Aluminum production	Mton	0.28	0.30	0.31	0.33	[12],[31]
Zinc production	Mton	0.25	0.27	0.28	0.30	[12],[32]
Nitric acid production	Mton	2.40	2.60	2.80	3.00	[12],[33]
Urea production	Mton	1.80	1.94	2.08	2.22	[12],[33]
Other ammonia based fertilizers production	Mton	1.20	1.30	1.40	1.50	[12],[33]
Ethylene production	Mton	4.00	4.00	3.30	2.00	[12],[34]
Propylene production	Mton	2.50	2.50	1.90	1.00	[12],[34]
Other HVC production	Mton	0.60	0.60	0.48	0.30	[12],[34]
Bioplastics (PLA and PEF)	Mton	0.00	0.10	0.50	1.00	[35]
Chlorine production	Mton	1.00	1.05	1.10	1.15	[12],[36]
Glass production	Mton	0.92	0.98	1.04	1.10	[12]
Ceramics production	Mton	2.80	2.90	3.00	3.10	[12]
Paper and board production	Mton	2.90	3.05	3.20	3.35	[12],[37]
Food & beverage production growth projection	Index 2020	1.00	1.12	1.24	1.36	[12]
Other ETS chemicals growth projection	Index 2020	1.00	1.06	1.12	1.18	[12]
Other ETS industry growth projection	Index 2020	1.00	1.08	1.16	1.24	[12]
Other non-ETS growth projection	Index 2020	1.00	1.08	1.16	1.24	[12]
Fuel demand for machinery	PJ	25.40	26.00	26.60	27.20	[12]
Waste management	Mton*	7.60	9.10	9.50	8.20	[1]
Waste gasification (syngas)	Mton*	0.00	0.50	1.90	1.90	[35]
Plastic waste recycling, refurbishment, and dissolution	Mton*	0.10	0.20	0.50	0.80	[35]

Table 9
Foreign demand of hydrocarbons in the reference scenario [27].

Netherlands' fossil products demand for export	Units	2020	2030	2040	2050
Natural gas	PJ	2000	2200	1500	1000
Natural Gas LNG	PJ	150	300	100	100
Naphtha	PJ	700	700	350	0
Road Fuel	PJ	1100	1100	550	0
Kerosene	PJ	350	350	450	550
Fuel Oil	PJ	400	400	200	0
Other Oil Products	PJ	700	700	350	0
Crude Oil	PJ	1700	1700	850	0

Table 10
Policy directives assumed for the reference scenario.

Policy directive	Units	2020	2030	2040	2050
National CO2 emissions cap	Mton CO_2/y	NA	99	44	0
International transport emissions cap (NL)	Mton CO_2/y	NA	24	12	0
CO_2 embedded in feedstocks	Mton CO_2/y	NA	120	40	0
Synthetic fuels considered CO2 neutral	[yes/no]	yes			

using captured CO_2 to produce synthetic fuels cannot be accounted as negative emissions, as the emissions resulting from burning the synthetic fuel is not generating accountable CO_2 emissions, hence the sector manufacturing these fuels "emit" the CO_2 that will be emitted when combusted. An alternative to this would be that synthetic fuels are not considered carbon neutral, hence the industries using trapped CO_2 to form hydrocarbons could report negative emissions and receive profits from selling EUAs. These are the only two alternatives, as the total cycle of capturing CO_2 and releasing CO_2 is neutral, so assuming neutral synthetic fuels and negative emissions in the production would result in a regulatory loophole where a misleading negative account of emissions is created, which is especially critical in the case of a country with such a large amount of exports. These assumptions are reported in Table 10.

Furthermore, the following parameters are also used within the reference scenario definition Tables 11–20 Tables 21, 23 Figs 16–19.

Table 11
Demand volumes for the remaining sectors in the reference scenario.

Demand source	Units	2020	2030	2040	2050
Electricity demand residential	PJ	84.00	88.00	92.00	96.00
Number of flats	x1000 houses	3000	3220	3390	3540
Number of terraced houses	x1000 houses	3440	3690	3880	4060
Number of dwellings	x1000 houses	1730	1850	1950	2040
Electricity demand services	PJ	122.20	126.00	130.00	134.00
Space area services	Mm2	515	540	555	560
Electricity demand agriculture	PJ	36.00	38.00	40.00	42.00
Heat demand for horticulture	PJ	88.00	92.00	96.00	100.00
Heat demand for other purposes	PJ	8.40	8.80	9.20	9.60
Fuel demand for machinery in agriculture	PJ	23.00	25.00	27.00	29.00
Waste management	Mton	7.60	9.10	9.50	8.20
Sewage management	PJ	3.70	4.30	5.00	5.60
Waste landfill	PJ	0.40	0.05	0.00	0.00
Motorcycles	Gvkm	5.10	5.90	6.50	7.20
Passenger cars	Gvkm	105.00	120.00	135.00	150.00
Light-duty vehicles	Gvkm	19.00	21.00	23.00	25.00
Heavy-duty vehicles	Gvkm	7.70	8.10	8.50	8.90
Buses	Mvkm	620.00	630.00	640.00	650.00
Rail	Mvkm	170.00	200.00	215.00	230.00
Intra-EU aviation	Mvkm	210.00	260.00	260.00	260.00
Extra-EU aviation	Mvkm	670.00	740.00	740.00	740.00
Inland-domestic navigation	Mvkm	55.00	70.00	80.00	90.00
International navigation	Mvkm	110.00	125.00	125.00	125.00
Fuel demand for other transport	PJ	30.00	30.00	30.00	30.00

Table 12
Projected other GHG emissions in the reference scenario.

Other non-energy related GHG emissions	Units	2020	2030	2040	2050
CH4 emissions from enteric fermentation	Mton CO2 eq.	8.70	7.94	7.35	6.88
CH4 emissions from manure management	Mton CO2 eq.	3.90	3.62	3.40	3.22
N2O emissions from manure management	Mton CO2 eq.	0.80	0.74	0.69	0.65
N2O emissions from fertilizer	Mton CO2 eq.	3.10	2.97	2.83	2.70
HFC emissions from leaked refrigeration fluids	Mton CO2 eq.	1.50	1.50	1.50	1.50
CO2 emissions from other sources	Mton CO2 eq.	2.67	2.51	2.36	2.20
CH4 emissions from other sources	Mton CO2 eq.	2.60	1.82	1.03	0.25
N2O emissions from other sources	Mton CO2 eq.	2.90	2.60	2.30	2.00
F-gas emissions from other sources	Mton CO2 eq.	0.40	0.33	0.27	0.20

Table 13
Electricity demand assumed for the interconnected EU nodes in the reference scenario.

Electricity demand in the EU power system	Units	2020	2030	2040	2050
non-EU Balkan countries	PJ	273	311	349	389
EU Balkan countries	PJ	820	936	1052	1167
Baltic countries	PJ	102	122	142	162
Finland	PJ	307	321	335	351
Italy	PJ	1160	1374	1588	1800
Portugal	PJ	180	202	224	248
Spain	PJ	967	1065	1163	1262
Slovakia	PJ	104	118	132	146
Czech Republic	PJ	242	272	302	333
Poland	PJ	587	699	811	925
Austria	PJ	258	298	338	378
Switzerland	PJ	216	262	308	355
France	PJ	1697	1935	2173	2413
Sweden	PJ	502	532	562	593
Ireland	PJ	141	157	173	188
Belgium	PJ	308	348	388	428
Germany	PJ	2052	2296	2540	2784
Denmark	PJ	140	154	168	180
Norway	PJ	490	502	514	525
Great Britain	PJ	1164	1302	1440	1580

Table 14

Cost of the primary energy sources in the reference scenario.

Primary energy	Units	2020	2030	2040	2050
Imported coal	€/GJ	2.00	2.67	3.33	4.00
Imported crude oil	€/GJ	7.00	11.00	15.00	19.00
National natural gas	€/GJ	4.00	5.20	6.40	7.60
Imported uranium	€/GJ	0.81	0.81	0.81	0.81
Waste	€/GJ	7.00	7.00	7.00	7.00
Wood (crops, and others)	€/GJ	10.00	14.00	18.00	22.00
Imported Wood	€/GJ	12.50	17.50	22.50	27.50
Grass-crops	€/GJ	9.50	8.70	8.40	8.20
Dry organic matter	€/GJ	4.50	4.50	4.50	4.50
Wet organic matter	€/GJ	0.10	0.10	0.10	0.10
Manure	€/GJ	0.10	0.10	0.10	0.10
Sugars	€/GJ	4.29	4.57	4.60	4.63
Starch	€/GJ	16.00	21.00	21.50	22.00
Vegetable Oil	€/GJ	26.00	38.00	38.00	38.00
Imported Vegetable Oil	€/GJ	30.00	45.00	45.00	45.00

Table 15

Cost of imported secondary oil products in the reference scenario.

Imported oil-based products	Units	2020	2030	2040	2050
LPG	€/GJ	10.00	17.00	19.00	27.50
Naphtha	€/GJ	14.00	28.00	42.00	56.00
Road Fuel	€/GJ	20.00	32.00	44.00	56.00
Kerosene	€/GJ	14.00	28.00	42.00	56.00
Fuel Oil	€/GJ	14.00	28.00	42.00	56.00
Other Oil Products	€/GJ	14.00	28.00	42.00	56.00

Table 16

Cost of imported biofuels in the reference scenario.

Imported biofuels	Units	2020	2030	2040	2050
Bio-ethanol	€/GJ	20.00	35.00	50.00	70.00
Bio-diesel	€/GJ	20.00	35.00	50.00	70.00
Bio-kerosene	€/GJ	14.00	30.00	53.00	70.00

Table 17

Cost of other resources in the reference scenario.

Other resources	Units	2020	2030	2040	2050
Natural gas	€/GJ	5.00	6.60	8.20	9.80
LNG	€/GJ	5.30	6.30	7.30	8.30
Green or blue hydrogen	€/GJ	72.00	48.00	36.00	30.00
Emissions economy	Units	2020	2030	2040	2050
Underground CO2 storage space	€/ton CO2	20.00	20.00	20.00	20.00
CO2 ETS Allowance	€/ton CO2	30.00	50.00	70.00	90.00

Table 18

Maximum assumed potentials for variable renewable energy sources in the reference scenario.

VRES maximum capacity	Units	2020	2030	2040	2050
Electricity from Offshore Wind (far)	GW		20.00	50.00	75.00
Electricity from Offshore Wind (near)	GW	1.10	6.00	13.00	13.00
Electricity from Onshore Wind	GW	3.50	8.00	10.00	12.00
Electricity from Solar PV Fields	GW	1.10	5.00	15.00	30.00
Electricity from Industrial Solar PV	GW	2.10	15.00	30.00	40.00
Electricity from Residential Solar PV	GW	3.50	20.00	40.00	60.00

Table 19
Maximum deployment of cross-border interconnection lines in the reference scenario.

Cross-border interconnection maximum capacity	Units	2020	2030	2040	2050
Belgium interconnector	GW	1.40	3.40	7.00	7.00
Germany interconnector	GW	4.25	5.00	10.00	10.00
Denmark interconnector	GW	0.70	0.70	1.40	1.40
Norway interconnector	GW	0.70	0.70	1.40	1.40
Great Britain interconnector	GW	1.00	1.00	2.00	2.00

Table 20
Import potentials of clean energy sources in the reference scenario.

Potential for imports of clean resources	Units	2020	2030	2040	2050
Bio-ethanol	PJ/y	10.00	20.00	75.00	300.00
Bio-diesel	PJ/y	10.00	20.00	75.00	300.00
Bio-kerosene	PJ/y	5.00	150.00	250.00	250.00
Wood	PJ/y	20.00	120.00	220.00	320.00
Vegetable Oil	PJ/y	2.00	2.00	2.00	2.00
Hydrogen	PJ/y		50.00	150.00	370.00

Table 21
National potentials for decarbonization resources in the reference scenario.

National resources availability	Units	2020	2030	2040	2050
Natural gas extraction	GWh/d	940.00	400.00	200.00	
Wood (crops, and others)	PJ/y	60.00	80.00	100.00	120.00
Grass-crops	PJ/y	15.00	25.00	25.00	25.00
Dry organic matter	PJ/y	7.00	8.00	9.00	10.00
Wet organic matter	PJ/y	3.70	4.30	5.00	5.60
Manure	PJ/y	72.00	72.00	72.00	72.00
Sugars	PJ/y	15.00	20.00	20.00	20.00
Starch	PJ/y	1.00	1.00	1.00	1.00
Vegetable Oil	PJ/y	0.50	0.50	0.50	0.50
Geothermal	PJ/y	20.00	50.00	125.00	200.00
CO2 Storage	Mton CO2/y		10.00	20.00	50.00

Appendix C. Uncertain parameters for the sensitivity analyses

A) Parameters enabling BECCS

Bioenergy with carbon capture and storage (BECCS) is important for the transition as it allows for negative emissions in sectors with more “affordable” decarbonization, opening room for higher emissions in more expensive sectors. A lot of BECCs could even displace investments in VRES and the flexible electrification that will come with them (hence also reducing the need for the so called hydrogen economy). However, enabling a lot of BECCS in the Netherlands would require two things: sufficient imported biomass at affordable prices, and plenty of underground storage capacity for captured CO_2. Both requirements are highly uncertain and come with their own challenges, for instance: first, the storage capacity resources available in the North Sea most likely will be shared with other neighbouring countries limiting the availability for the Netherlands [38]; and second, even when there will be countries with important levels of biomass production, it is likely that industries which convert these bio-resources into feedstock will move to those countries, limiting the amount of available biomass for export. The sensitivity exercise in this study consists of combining seven different imported biomass prices and five CO_2 storage potentials and combine them into different scenarios, accordingly with the data presented in Table 22.

Table 22
Values used for the BECCS enabling sensitivity analysis.

Imported biomass prices in €/GJ	Underground CO_2 storage potentials in Mton/y
5, 10, 15, 20, 30, 40, and 60	10, 30, 50, 100, and 200

The values selected for the above presented table are not intended as a guide of likely possibilities, but are selected in order to explore the response of the system to a broad range of values.

B) Parameters describing the demand for high-value chemicals

The two most energy-intensive sectors in the Netherlands energy system are the high-value chemicals production and the refineries. Both sectors are strongly dependent on external dynamics as most of their production is exported. The main driver for refineries correspond to the transport configuration in the world, where most of the road fleet is expected to electrify at some point, ships are likely to diverge from heavy oils, and aviation demand for bio and synthetic fuels is expected to grow greatly. However, the whole world will not carry out the transition at the same pace, and it is likely that many countries will still depend on traditional refined oil products to supply their activities. The uncertainty here is whether the Netherlands’ refineries will have a chance to supply the fuel demand of this market in competition with other potential suppliers around the world.

Similarly, the production of virgin monomers based on hydrocarbons such as ethylene, propylene, and other olefins is strongly interlinked to two factors: the demand for plastics and the recycling levels, both loaded with significant uncertainties. Even when it is known that the

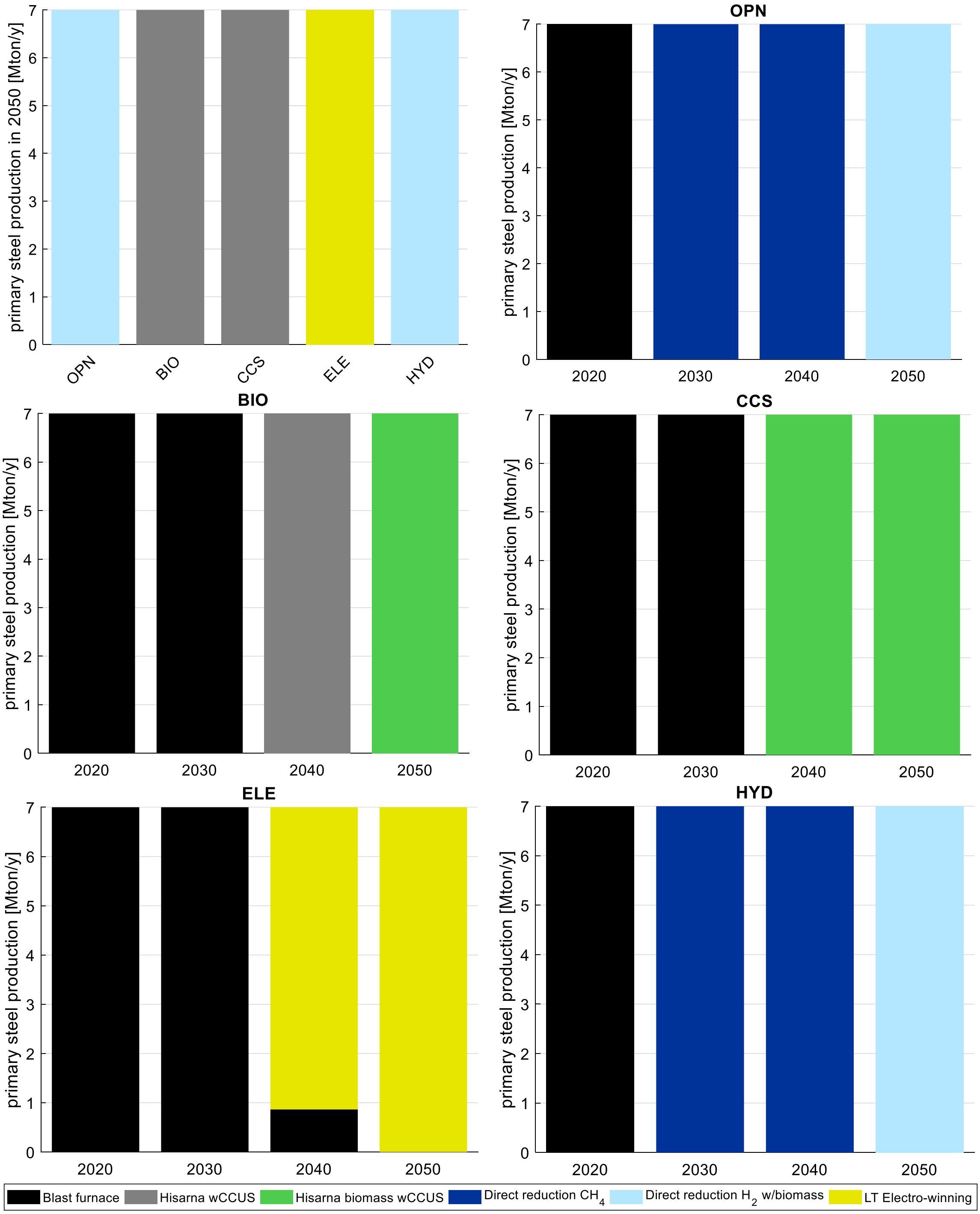


Fig. 16. Technological evolution of the steel sector in the five scenarios.

Netherlands and the EU directives point towards high levels of circularity and materials efficiencies, the future volumes of materials demand or its shifting to alternative materials (e.g. a higher adoption of paper packaging or bio-plastics) could drastically change the current outlook. The market of virgin monomers will most likely shrink in the world, but it could be the case that the Netherlands keeps an important part of the current production, especially if they can produce them in a more sustainable way. The sensitivity exercise in this study consists of varying the demand in 2050 for high-value chemicals between zero and ten Mton per year accordingly with:

C) Parameters describing the maturity of revolutionary green technologies

The unfolding of the energy transition will be determined by which technologies are available to decarbonize economic activities. There are currently many green-novel technologies in sight; however, they are not yet mature enough to be considered certainly available be cost-effectively deployed at large scale. At which moment they become available and the learning curve followed by the required investments are the two largest unknowns of these technologies. For this study we prepared two scenarios in which the cost progression and time availability

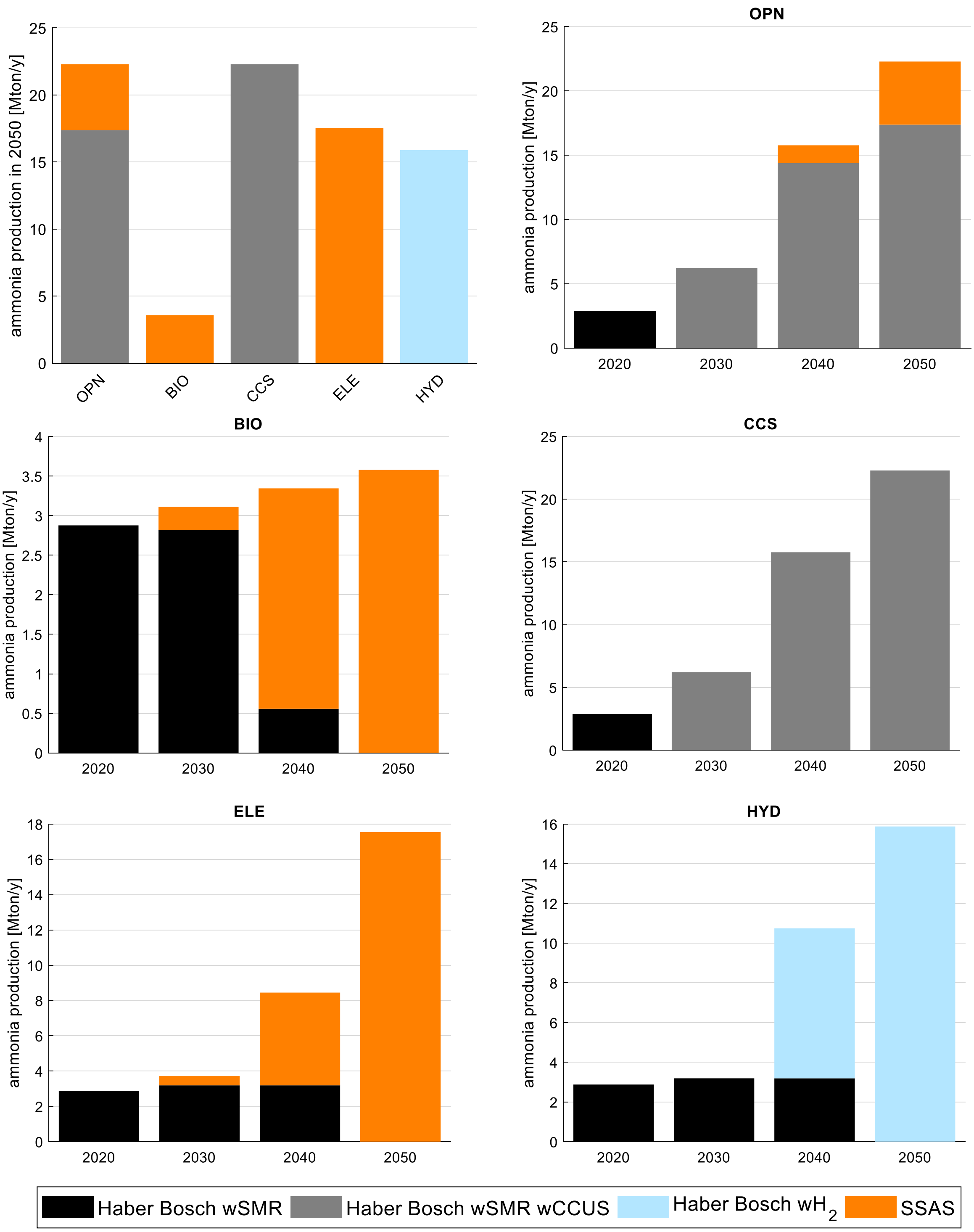


Fig. 17. Technological evolution for ammonia production in the five scenarios.

of key novel technologies are presented in two spectrums: a realistic and an optimistic (30% lower cost estimates progression than in the reference). This with the intention of quantifying the impact that accelerated progress in technology innovation could yield for the transition. Table 24 present the list of technologies and their respective parameters which were modified in the two scenarios.

Again, the selected value of 30% lower investment costs used for this sensitivity is not intended as a prediction of what can happen in reality. Technological learning (and hence cost projections) is highly uncertain, so the lower and higher ranges of expected values in literature (e.g. TNO factsheets [39]) vary significantly as compared to the expected values. The intention with the adoption of these values is to understand the impact of lower investment costs in the selected portfolio of technologies in the scenario.

D) Influences of import prices of hydrogen and natural gas

Currently Europe is witnessing an unprecedented rise in natural gas prices. The TTF spot price has increased tenfold in less than two years, and is driving the price projections far from the typical business-as-usual scenarios. These values, reaching almost to 200 €/MWh, diverge considerably from the projections of the natural gas price of most sources and

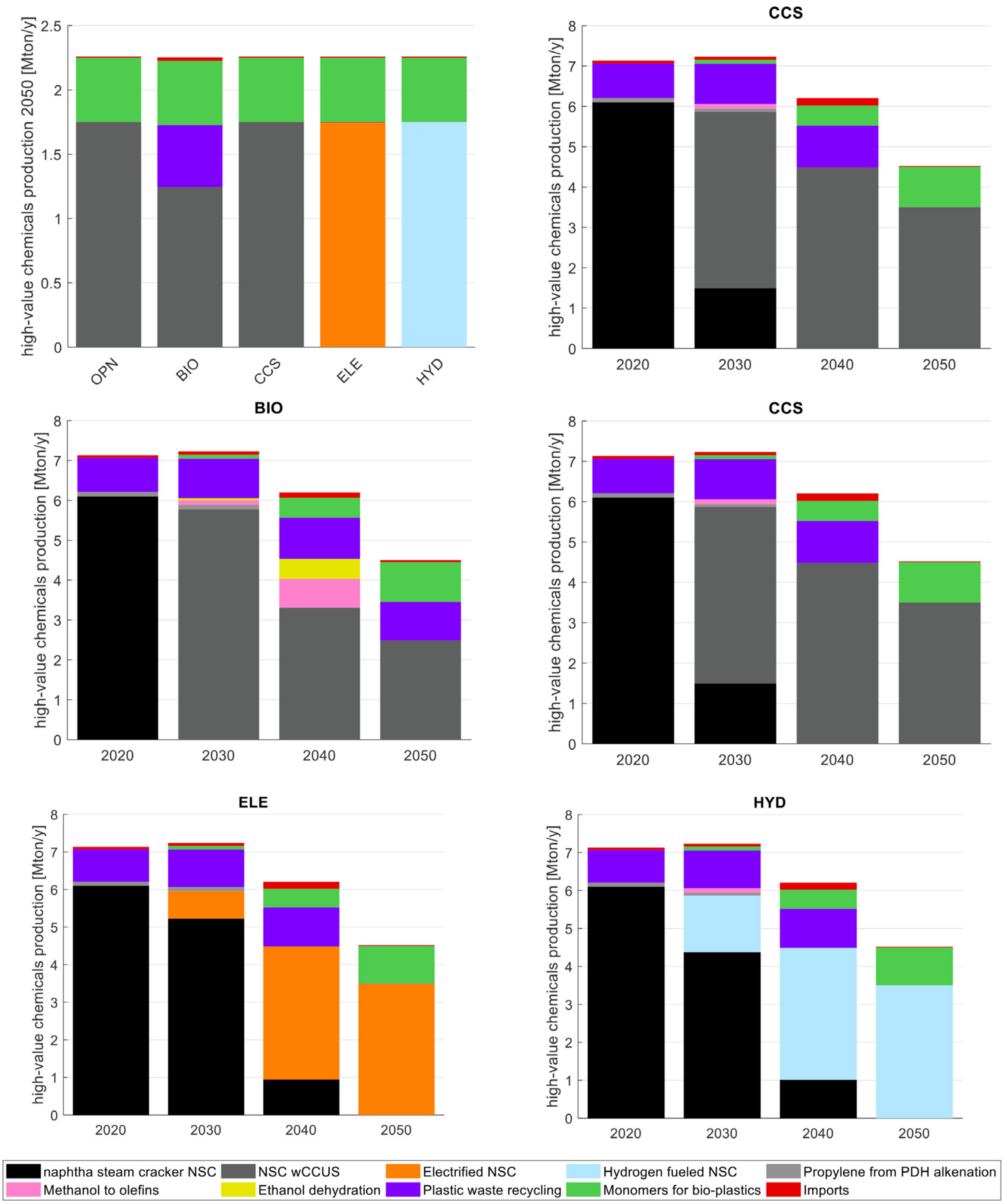


Fig. 18. Technological evolution of the high-value chemical sector in the five scenarios.

analyses, which typically place natural gas under 50 €/MWh in 2050 (including the reference scenario in this study). Therefore, it is important to evaluate what could possibly happen to the transition if natural gas prices maintain as they currently are and never go back to the values sustaining most national and continental plans. By default, some “clean technologies” which by now are not considered cost-effective, will become the preferred choice in many sectors and activities. This effect could be further boosted if hydrogen becomes available in Europe at affordable prices, burying the business case for natural gas under a rich portfolio of decarbonization options. For this reason, in this study we performed a bi-dimensional sensitivity analysis in which the evolution path up to 2050 of natural gas and hydrogen prices were combined ranging between 10 and 50 €/GJ (36 and 180 €/MWh). The sensitivity exercise in this study consists of combining five different imported hydrogen prices and five natural gas prices, both for the years 2030, 2040, and 2050, into combined different scenarios, accordingly with the data presented in Table 25.

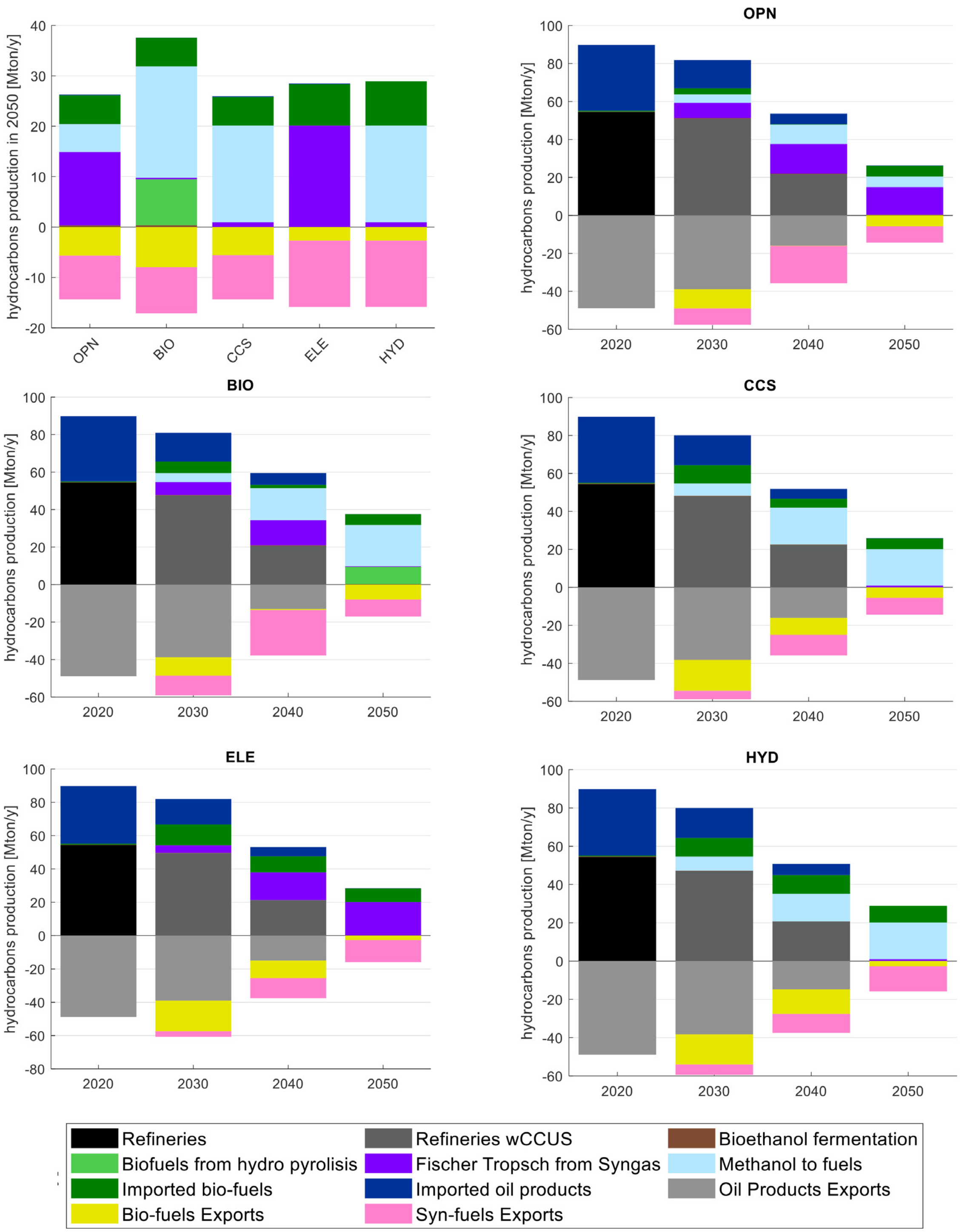


Fig. 19. Technological evolution of hydrocarbons production in the five scenarios.

Table 23
Values used for the HVC demand sensitivity analysis.

	Demand of HVC in Mton/y		
Sensitivity No.	2030	2040	2050
0	7.10	3.55	0.00
1	7.10	4.05	1.00
2	7.10	4.55	2.00
3	7.10	5.05	3.00
4	7.10	5.55	4.00
5	7.10	6.05	5.00
6	7.10	6.55	6.00
7	7.10	7.05	7.00
8	7.10	7.55	8.00
9	7.10	8.05	9.00
10	7.10	8.55	10.00

Table 24
Parameters modified between the two different scenario considerations the maturity of revolutionary green technologies. Note: OCIC stands for Overnight Capital Investment Costs. Source: MIDDEN database [23].

		Reference				Higher TRL			
Parameter	Units	2020	2030	2040	2050	2020	2030	2040	2050
OCIC of LT electro-winning for steel production	€-y/ton	1000	900	770	640	1000	630	539	448
OCIC of HT electro-winning for steel production	€-y/ton	1100	950	830	710	1100	665	581	497
OCIC of bioethanol dehydration (olefins)	€-y/ton	1200	850	750	650	1200	595	525	455
OCIC of methanol-to-olefins	€-y/ton	2500	2200	1800	1600	2500	1540	1260	1120
OCIC of waste recycling	€-y/ton	930	930	930	930	930	830	730	630
OCIC of SSAS for ammonia production	€-y/ton	1000	884	771	660	1000	620	540	460
OCIC of bioethanol from fermentation	€-y/GJ	77	77	77	77	77	50	50	50
OCIC of bio-pyrolysis for fuels	€-y/GJ	70	65	60	50	70	45.5	42	35
OCIC of Fischer-Tropsch process for fuels	€-y/GJ	60	25	22	20	60	17.5	15.4	14
OCIC of Methanol-to-fuels for fuels	€-y/GJ	45	30	22	15	45	21	15.4	10.5
OCIC of Syngas from biomass	€-y/GJ	9.5	7	5	4	9.5	4.9	3.5	2.8
OCIC of Syngas from reverse water gas shift	€-y/GJ	2	1.6	1.4	1.2	2	1.1	1	0.8
OCIC of Syngas from SOEC electrolysis	€-y/GJ	8	5	2	1	8	3.5	1.4	0.7
OCIC of Methanol from Syngas	€-y/ton	20	20	20	20	20	18	16	14
OCIC of Methanol from CO2 and H2	€-y/ton	180	160	60	36	180	112	42	25
OCIC of Alkaline electrolyzers	€/kW	1600	1100	1070	1050	1600	770	750	740
OCIC of PEM electrolyzers	€/kW	2000	1750	1650	1550	2000	1230	1160	1090
OCIC of solid-oxide electrolyzers	€/kW	4000	2200	1500	1200	4000	1540	1050	840

Table 25
Values used for the import prices of hydrogen and natural gas sensitivity analysis.

Imported hydrogen prices for 2030, 2040, and 2050 in €/GJ	Natural gas prices for 2030, 2040, and 2050 in €/GJ
10, 20, 30, 40, and 50	10, 20, 30, 40, and 50

Appendix D. Transition in key industrial sectors in the alternative paths for industry

Here we show the transition paths follow for the technological choices in steel production, high-value chemicals, ammonia, and hydrocarbon (refineries) sectors.

Appendix E. Dutch industrial context

High-value chemicals

Using traditional naphtha steam crackers, the Netherlands produces roughly 7,000,000 tons of olefins each year, of which ethylene constitutes over 55% and propylene over 33%. Most of this production is exported directly as monomers, and half of the 2,000,000 tons which are polymerized in the country end up being exported as processed plastics {Source CBS}. For this reason, there are a lot of uncertainties around the size of the challenge that it will represent to decarbonize the most energy-intensive industrial sector of the Netherlands. What the local plastic market is able to do in terms of recycling and reconfiguration would not have as strong an impact as what the foreign partner markets will do. However, that does not mean that the sector is unable to clean its production of monomers. On the contrary it can make a case to keep the production inland by finding alternatives to substitute fossil feedstock, adopting circular carbon practices, and profiting from the sectoral structural potential to sell EU ETS allowances by achieving negative emissions.

Hydrocarbons

In a similar fashion than for high value chemicals, the future of hydrocarbons production in the Netherlands will strongly depend on what happens in the international arena, as the Netherlands is a crucial hub supplying fuels and chemicals to all of Europe. The car fleet in the Netherlands and in Europe in general is quickly being electrified and the national demand for road fuels will significantly decrease. At the same time the demand in the aviation sector is steadily increasing, and the social and political pressure to shift towards synthetic and bio-based fuels will drive kerosene production away from crude oil at some point. Analogously, maritime transport is looking away from fuel oils into cleaner options like natural gas, bio-based or synthetic fuels and ammonia. Even there are appearing more alternatives to fossil based naphtha such as ethanol, methanol, synthetic naphtha, and bio-plastics. However, this does not mean that the oil refining industry (and much less the production of hydrocarbons) will be dead by 2050. It is highly likely that regions such as Latin America or Africa will lag behind in the transition and will still require traditional hydrocarbons to run their car

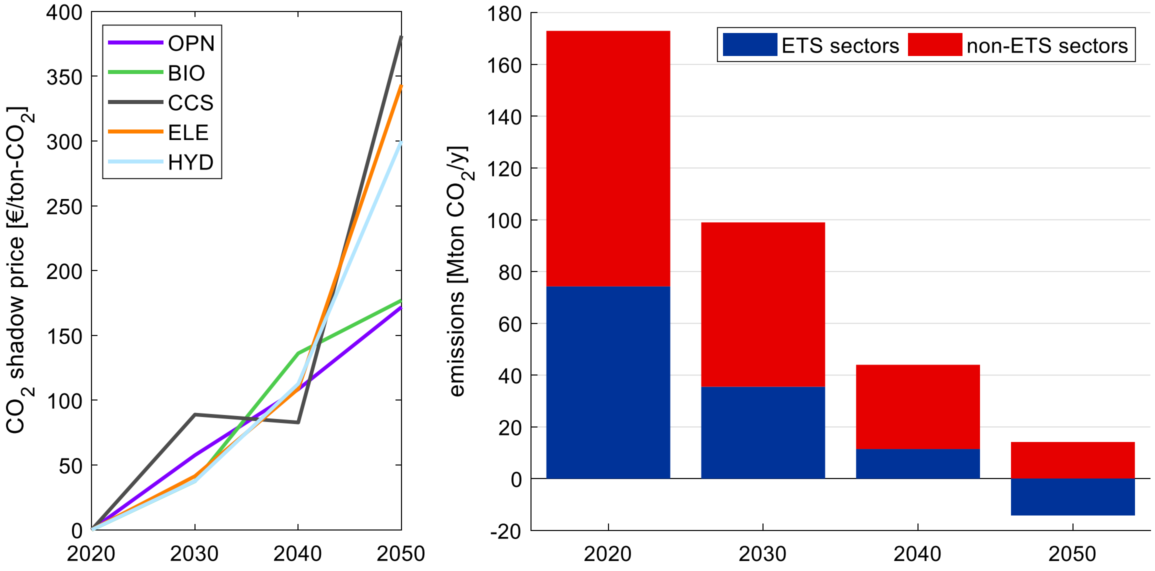


Fig. 20. CO_2 emissions and shadow prices for the decarbonisation transition in the five scenarios. Left: evolution of CO_2 shadow prices. Centre: total emissions inventory for ETS and non-ETS sectors. Right: evolution of the CO_2 shadow price for international transport emissions.

and transport fleet as well as their industry. Then, on one hand, those regions could become more competitive in hydrocarbons production, especially if they are going to continue extracting oil. However, on the other hand, the Netherlands and specifically the Port of Rotterdam, in its role of one of the largest and most efficient hubs in Europe and its strong links with the petrochemical sector, could exploit its privileged position to become one of the largest producers of sustainable synthetic fuels (for road transport and aviation). Hence, the scenario definition for the demand of hydrocarbons in foreign markets is crucial to define the transformation of this sector.

Steel

Although steel can also be recycled using electric arc furnaces (secondary steel), the vast majority of the steel manufactured in the Netherlands is from virgin iron ore (primary steel). Currently there is only one steel production site in the Netherlands, which uses two blast furnaces with a total production capacity of more than 7,000,000 tons of primary steel per year. The factory faces a lot of social pressure in the locality not only for the emitted CO_2, but also due to the harmful particles contamination in the air. Because of this, the factory already publicly stated that it will replace at least one of the blast furnaces with direct reduction of iron with natural gas by 2030. However, the resulting configuration would be far from decarbonized, and further efforts would be required to help achieve national targets. For this purpose, the direct reduction could be retrofitted to use hydrogen instead of natural gas at some point, and the remaining blast furnace could be retrofitted or substituted with a cleaner alternative.

Ammonia

Learning how to manufacture ammonia was so important for mankind that it became the only scientific achievement with two Nobel prize recognitions, in 1918 for Fritz Haber and in 1931 for Carl Bosch, both behind the development of the high-temperature and high-pressure Haber-Bosch process for ammonia synthesis. With it we were able to produce synthetic fertilizers to fuel the agricultural revolution which enabled the high rates of urbanization experienced in the last century. Currently ammonia is the second highest volume chemical produced in the world, and over 85% of it is used in the fertilizer industry. In the Netherlands there are two companies responsible of producing over 2,700,000 tons of ammonia, aimed almost entirely for fertilizers manufacture. Both ammonia suppliers rely on the traditional Haber-Bosch process with hydrogen from steam methane reforming (SMR).

Appendix F. Other results from the scenario comparison

National emissions

The net emissions for the five scenarios follow the same target path of 55%, 80%, and 100% emission reductions in 2030, 2040, and 2050, respectively, compared with the levels in 1990. The results displayed in Fig. 20, therefore, indicate only the evolution of net emissions in the ETS and non-ETS sectors in the energy system for the OPN scenario. Decarbonisation is more aggressive in the ETS than non-ETS sectors owing to their higher potential for emission reduction and the incentive provided by EU pricing incentives resulting in more cost-effective green processes. The CO_2 shadow prices for the five scenarios are also displayed in Fig. 20. The CO_2 shadow prices remain under 200 €/t in the OPN and BIO scenarios, with a positive Fig. considering that the Dutch CO_2 levy is expected to exceed 100 €/t by 2030. The HYD, ELE, and CCS scenarios exceed 300 €/t, which demonstrates the burden of carbon neutrality objectives on such systems.

Energy costs

Fig. 21 provides a comparison between the energy prices in 2050 for the five different scenarios and indicates that the key to the energy transition is the evolution of energy prices. A comparison between the different scenarios shows substantial variations in the reported prices of some energy carriers in 2050, such as hydrogen, ammonia, synthetic fuels, industrial heat, electricity, and biomass. The OPN scenario provides the best price profile of all, followed quite closely by the CCS scenario, which are the only two scenarios where natural gas is significantly used in 2050. The ELE and HYD scenarios resulted in higher electricity, hydrogen, and ammonia prices, whereas industrial heat reached an extremely high value in the ELE scenario. Biomass prices respond to the demand for biomass, as there is limited availability of cheaper bioresources, which gives rise to a doubling in price between the BIO and OPN scenarios. The evolution of the prices in the OPN scenario is modest, with the most notable pattern being the 40% increase in the average electricity price from 2020, a moderate rise in ammonia prices, and a decrease in synthetic fuel prices after their appearance in the system. In general, we can conclude that a mixed-technology approach in the

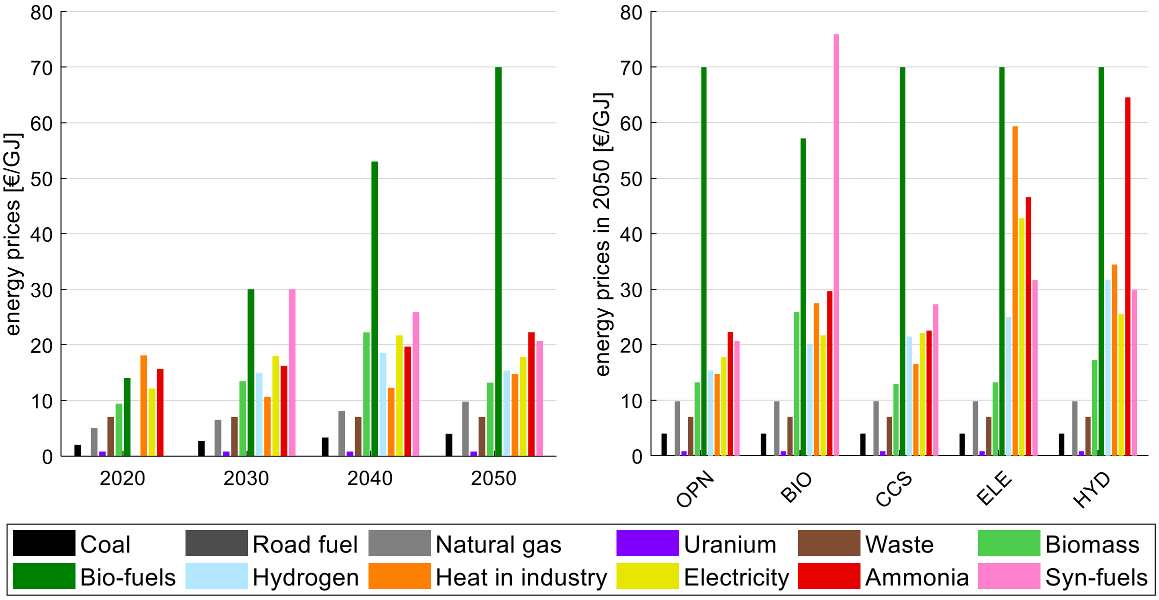


Fig. 21. Energy prices of key energy carriers for the five scenarios in 2050.

decarbonisation transition, where resources and technologies are used skilfully, will prove beneficial for society, avoiding abrupt increases in energy prices and contributing to easing the energy poverty problem.

Energy mix in key industrial sectors

The absence of fossil fuels in the energy usage within industrial sectors, which is displayed in Fig. 22 is notable. Only natural gas is used to produce ammonia and heat in the OPN and CCS scenarios, with few traces of natural gas and oil products in other activities. Electricity, hydrogen, biomass, and synthetic fuels become the dominant energy supply, with shares varying by sector and scenario. The energy mix for steel demonstrates the consequences of technology choices in the energy system, where biomass for BIO and CCS, hydrogen for OPN and HYD, and electricity for ELE are the predominant energy sources. Because the carbon neutrality constraint was also included for Scope 3 emissions, biomass was used in all scenarios to extract the carbon from the steel alloy. Similar to steel, the energy mix in the ammonia sector displays an identifiable profile based on the technologies adopted. The scenarios which make use of SSAS tend to use more electricity, whereas the scenarios where SMR is still being used (OPN and CCS) use a substantial amount of natural gas and heat.

The energy mix in the high-value chemical sector is slightly more complex, where synthetic naphtha is used as a feedstock source for steam crackers in all scenarios except for BIO, where biofuels are used. In contrast, in the ELE and HYD scenarios, the crackers operate on electricity and hydrogen-to-fuel feedstock conversion. The biomass usage in all scenarios corresponded to bioplastic production, in which exogenous demand was not modified between scenarios.

Similarly, the hydrocarbon sector has the most extensive portfolio of technology options, which is observed in the resulting energy mix, where different combinations of biomass, hydrogen, and electricity are evident for each scenario. First, the OPN scenario uses biomass and electricity to produce syngas and hydrogen to produce methanol, thus indicating the most diverse combination of feedstock sources. Second, the BIO scenario uses biomass to produce biofuels via the bio-pyrolysis oil path and hydrogen to produce methanol from captured biogenic CO_2, and syngas in the ELE scenario is sourced from electricity and CO_2 captured directly from the atmosphere. Third, both the CCS and HYD scenarios use hydrogen to produce methanol, which in turn is used to produce fuel and naphtha.

Fourth, the industrial heat-energy mix indicates the diverse portfolio of solutions available to produce heat in a carbon-neutral future. The BIO, ELE, and HYD scenarios source heat almost exclusively (because geothermal heat is available in all scenarios) from biomass, electricity, and hydrogen. In contrast, the CCS scenario hybridises boilers and CCS and keeps current bio-based heat technologies with CCUS retrofits to maintain a source of biogenic CO_2 that can offset (with BECCS) the CO_2 from fossil fuel sources. Finally, the OPN scenario adopts heat pumps for low-temperature heat generation and combines with gas CHP CCUSs to produce high-temperature heat and electricity. This results in positive emissions, which of all scenarios requires the largest DAC and CO_2 storage combination to offset. Emissions are discussed in more detail in the next section.

Appendix G. Detailed results of the sensitivity analyses

BECCS: Biomass price and CO_2 storage capacity

Negative emissions resulting from the storage of captured biogenic CO_2 are crucial for the energy decarbonisation transition because they facilitate the achievement of carbon neutrality when sectors that are challenging to decarbonise still produce emissions. To evaluate the role of BECCS in facilitating the transition, we performed a sensitivity analysis of the price of imported biomass and the capacity to store CO_2 underground. By modifying both parameters simultaneously, we perform a bi-dimensional sensitivity analysis, in which the feedback between both changes can be the focus. For example, Fig. 23 presents the results of the experiment, where four indicators are presented, including the CO_2 shadow price in 2050 and the use of biomass, hydrogen, and natural gas in 2050. Here, biomass usage illustrates the benefits of performing bi-dimensional analysis because the inherent value of biomass for the transition, regardless of the availability of CO_2 storage capacity, is demonstrated because its adoption is a response to the biomass import price. The same graph indicates a dominant tipping point for biomass adoption between the prices of 20 and 30 €/GJ. Below 20 €/GJ the system is highly elastic to biomass prices because usage remains almost constant. However, when the price of imported wood exceeds 40 €/GJ, the biomass imports are halted, and only the national available bio-resources are used.

Similarly, it is important to highlight the role of hydrogen in the system as an alternative to BECCS, as evidenced by the steeped adoption

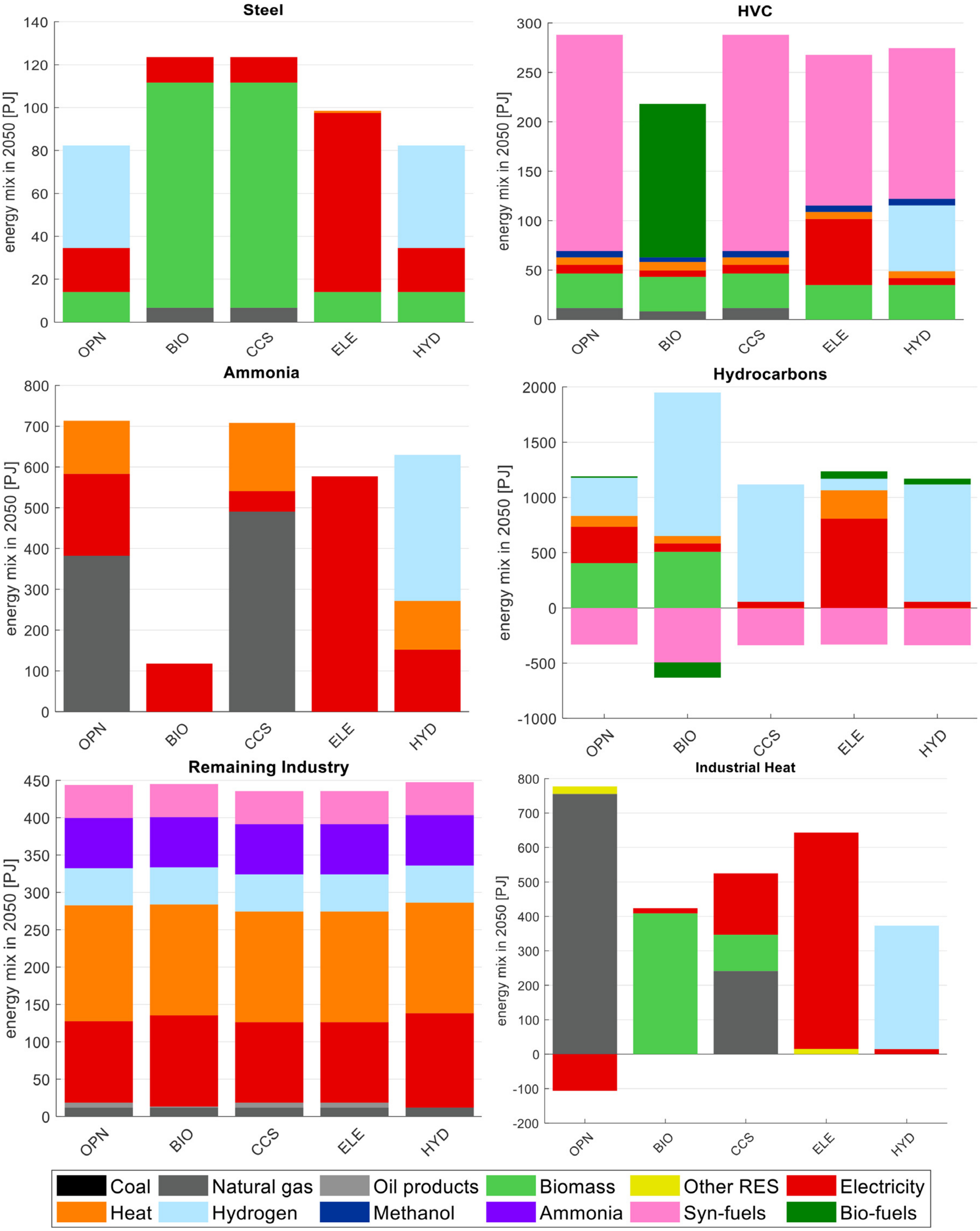


Fig. 22. Energy mix in industry for the five scenarios in 2050.

of hydrogen in the region with low availability of CO_2 storage and high biomass import prices. In contrast, the adoption of natural gas has a limited link to the biomass import price. These results clearly demonstrate that natural gas adoption in a carbon-neutral future depends almost exclusively on the availability of CO_2 storage.

Several industry choices are not affected by differences in the scenarios. For example, in 2050, all steel production is based on hydrogen direct reduction, and the predominant technology for HVC manufacturing in 2050 is always synthetic-naphtha-based steam crackers combined with CCUS. However, other choices are severely affected by the industry. For example, in the most extreme scenario with the highest biomass import price and the lowest CO_2 storage capacity, by 2050 ammonia is produced only by SSAS (approximately 350 PJ), and synthetic fuels are produced by FT with syngas originating from biomass and electrolysis at a ratio of 5:1. In the opposite scenario, 420 PJ of ammonia is manufactured from SMR with CCUS and SSAS at a ratio of 3:2, and half of the synthetic fuels are produced by MTF and the other half by FT from syngas originating from biomass and electrolysis at a ratio of 5:1. In the most rigid scenario, natural gas is rarely used (~1.5 PJ) in the power sector to alleviate demand peaks, whereas in the most flexible

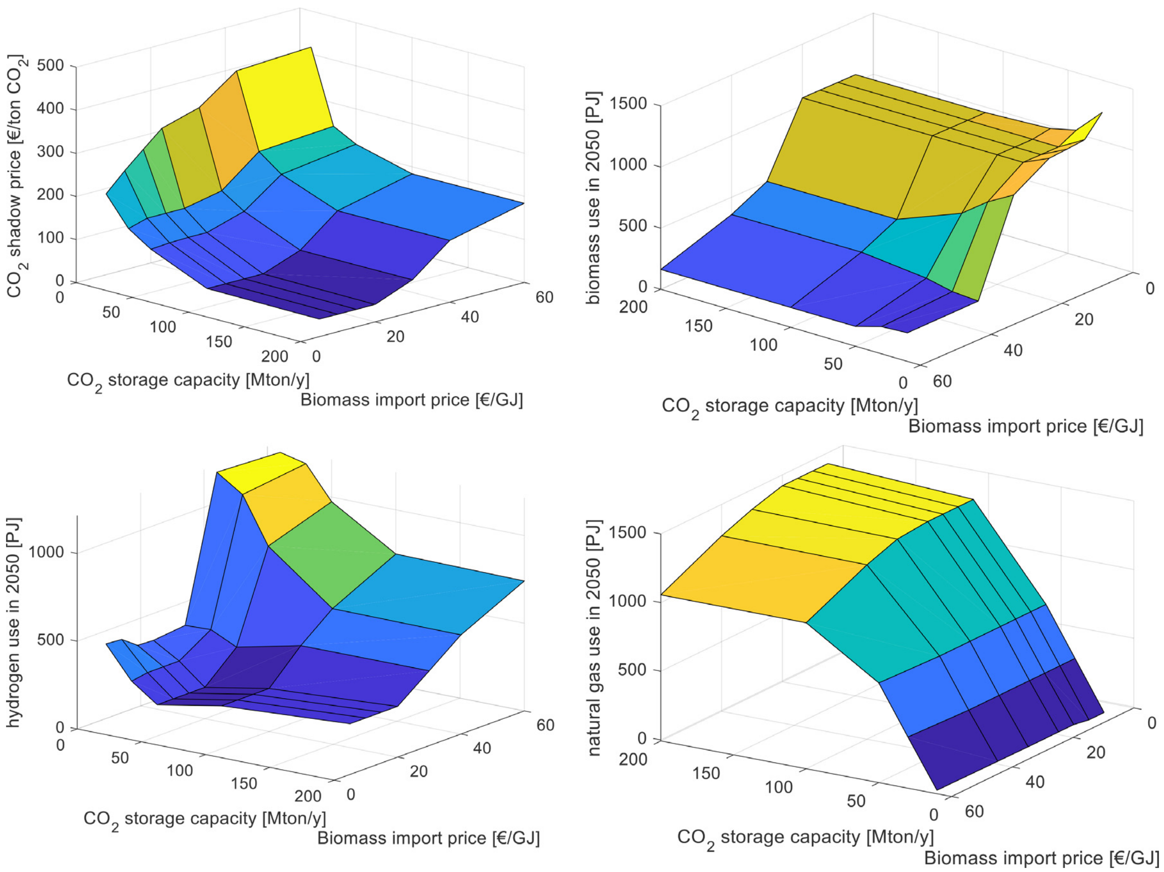


Fig. 23. Results of the sensitivity analysis between biomass import price and underground CO_2 storage availability. Top right: shadow price on the CO_2 emission reduction constraint. Top left: use of biomass in 2050. Bottom left: use of hydrogen in 2050. Bottom right: use of natural gas in 2050.

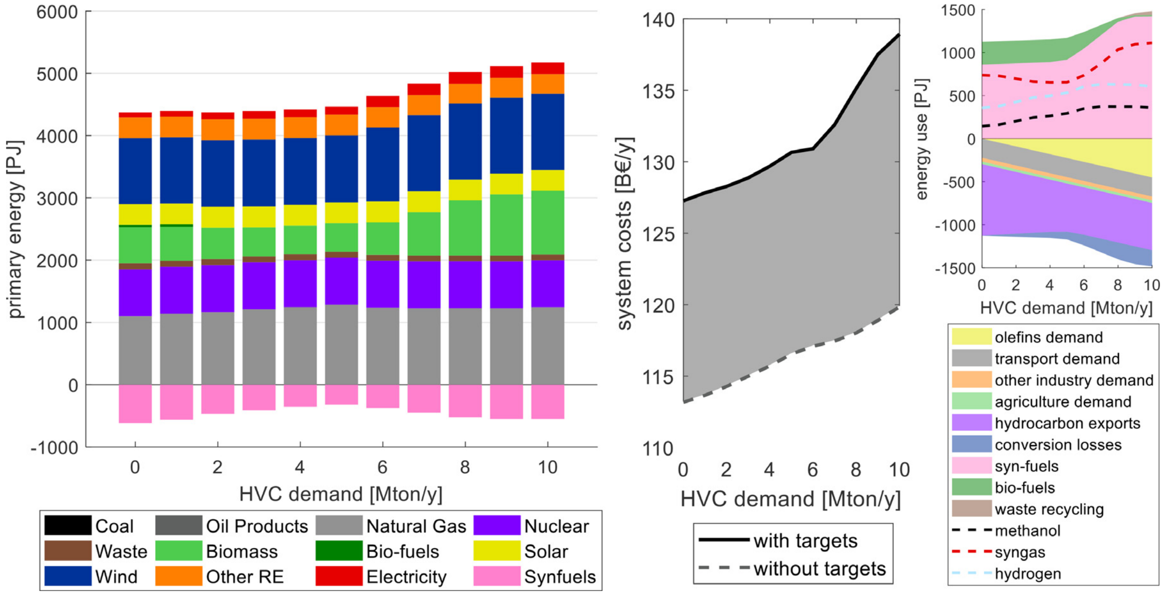


Fig. 24. Results of the sensitivity analysis performed on the external demand of high-value chemicals. Left: primary energy mix in 2050. Centre: increase in system costs as a consequence of full decarbonisation targets in 2050 for the different levels of HVC demand. Right: Supply and demand of hydrocarbons in 2050 for the different assumed HVC demands.

scenario, natural gas is used substantially in boilers, hybrid boilers, and CHPs with CCUS.

EU circularity directive, the impact of foreign demand for olefins

High-value chemical production is the largest energy consumer in the Dutch industry, and most olefins produced are used internationally. The sector is therefore highly sensitive to the recycling behaviour and plastic use of the rest of Europe. Both are volatile; thus, the demand for virgin olefins and the role of the sector in the transition could be impacted by abrupt changes by 2050. For this reason, we modelled the energy decarbonisation transition of the Netherlands 11 times, assuming a different scenario for the olefin demand on each. Each scenario begins with an expected olefin demand of 7 Mt/y in 2030 and changes linearly to the value in 2050, which ranges from zero to ten. The results of this experiment are presented in Fig. 24, which displays the changes in the 2050 primary energy mix, differences in average system transition costs, and a comparison of the use of hydrocarbons in each scenario.

The changes in the primary mix indicate that the main change is an increase in biomass adoption when the olefin demand exceeds 7 Mt/y. At lower levels, the system can accommodate the same resources by exporting fewer synthetic fuels. Thus, the external demand for kerosene must be covered with biofuel imports, which are not represented in the net primary energy consumption, as the net biofuel balance in the country is zero. Hydrocarbon use is displayed in Fig. 24 on the right, which explains the zero net biofuel balance. However, it is necessary to understand that synthetic fuels are produced either from syngas via the FT process or from methanol via the MTF process. Both processes result in a mixture of hydrocarbon compounds, and even when the processes can be set to produce a higher amount of a specific carbon-chain length (i.e., more kerosene or diesel), the output will always be outside of the desired range, resulting in excess. Because kerosene demand continues

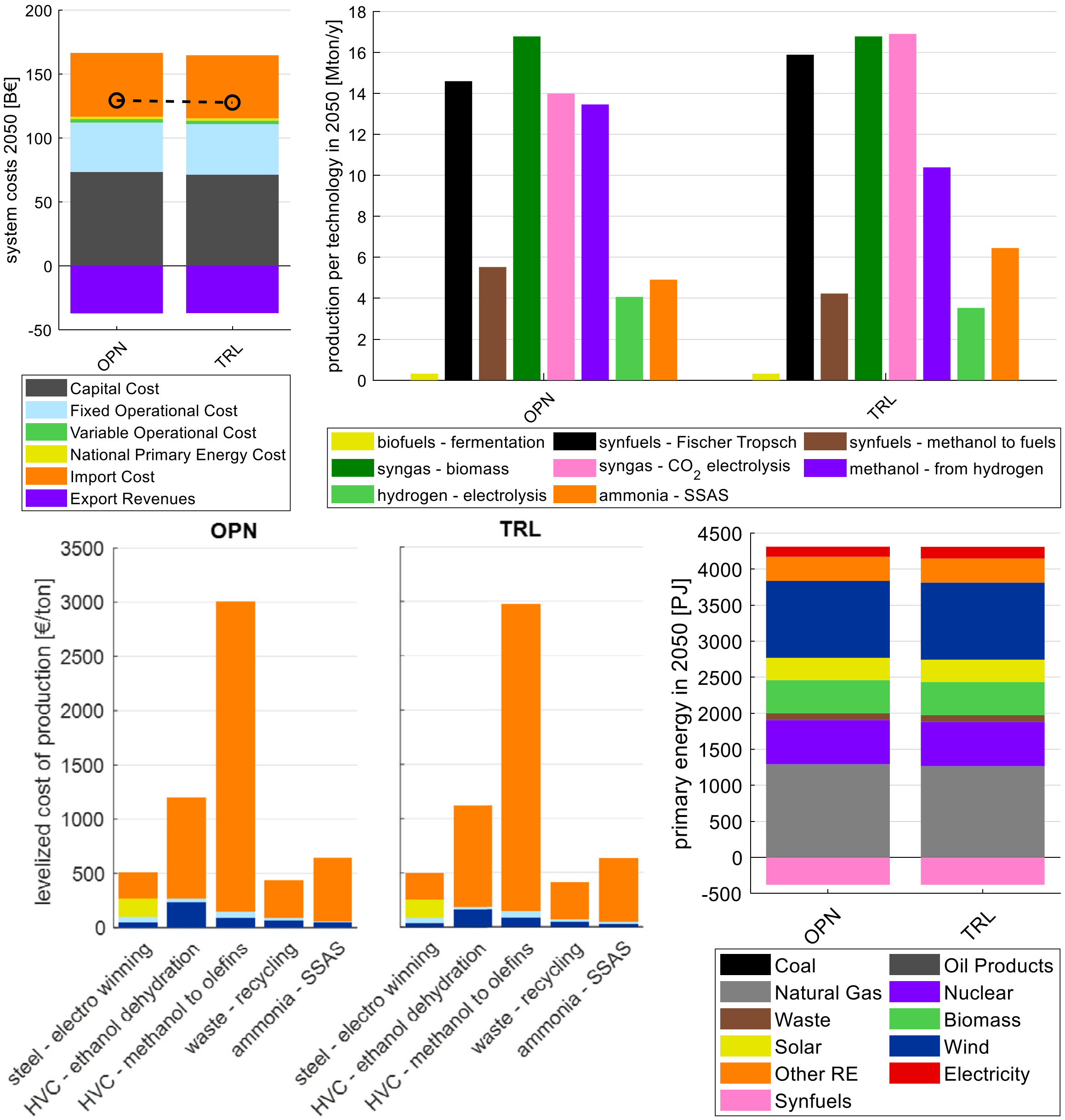


Fig. 25. Results of the sensitivity analysis performed on the overnight investment cost (ONIC) of novel green technologies in industry. Top left: comparison of system costs between the OPN and high TRL scenario. Top right: comparison of the utilisation of technologies with modified overnight investments. Bottom left: levelised production cost comparison between technologies in both scenarios. Bottom right: comparison of the primary energy mix between the two scenarios.

to drive these processes, when olefins are produced in the Netherlands at low levels, the excess output from the MTF and FT processes can be used in the existing steam crackers to produce olefins rather than be exported. The demand for olefins then becomes the driver for hydrocarbon production, which increases the system costs considerably. This effect is also evident in the decrease in biofuel flows in the Netherlands, because more synthetic kerosene is available for export. The demand for hydrocarbons in the agriculture, transport, and other industrial sectors remains mostly unaffected by these changes.

The impact on the system costs is also interesting to observe. The change in the system costs when the demand for olefins is 7 Mt/y indicates that reaching the emission targets under these demand volumes becomes increasingly difficult. To strengthen this observation, in the same graph, we plotted the system costs for the different demand levels in a scenario with no decarbonisation targets in place. The shaded area considered between the two system cost curves remains constant up to the 7 Mt/y demand point, where the difference starts increasing. Thus, under these circumstances, it is beneficial for the system to have the demand for kerosene as the driver for synthetic fuel production and to use the co-produced synthetic-naphtha to manufacture HVC. It is not beneficial for synthetic fuel production to be driven by naphtha demand, as this would increase the need for biomass to meet the feedstock requirement for the country. It is important to mention that changes in the hydrocarbon market can substantially affect the observed behaviour, as well as the development of technologies with a higher selectivity in the desired ranges of carbon chain lengths for hydrocarbon production.

Development of green technologies

A sensitivity analysis was performed on the expected evolution of the investment costs of novel green technologies in the decarbonisation transition. This analysis focused on the 18 technologies listed in Table 24, where two technologies correspond to the steel sector, three to the HVC sector, one to ammonia production, nine to hydrocarbon manufacture, and three to electrolyser technologies. However, not all the technologies were selected within the scenarios. In Fig. 25 we provide a comparison between the outcome of the OPN scenario and the TRL scenario, where higher technology-readiness levels are assumed for those technologies, that is, lower overnight capital investment costs (OCICs). The results clearly indicate that the overnight investment costs of these technologies are not crucial for the transition. The almost indistinguishable differences in the system costs and primary energy mix demonstrate that both scenarios resulted in almost identical system configurations and solutions. Only two differences are triggered by the lower OCICs, and both are related to electrified processes with load-shedding capabilities, namely SASS and solid-oxide electrolysis of CO_2 and water to produce syngas. The adoption of these technologies is enhanced by lower investment requirements.

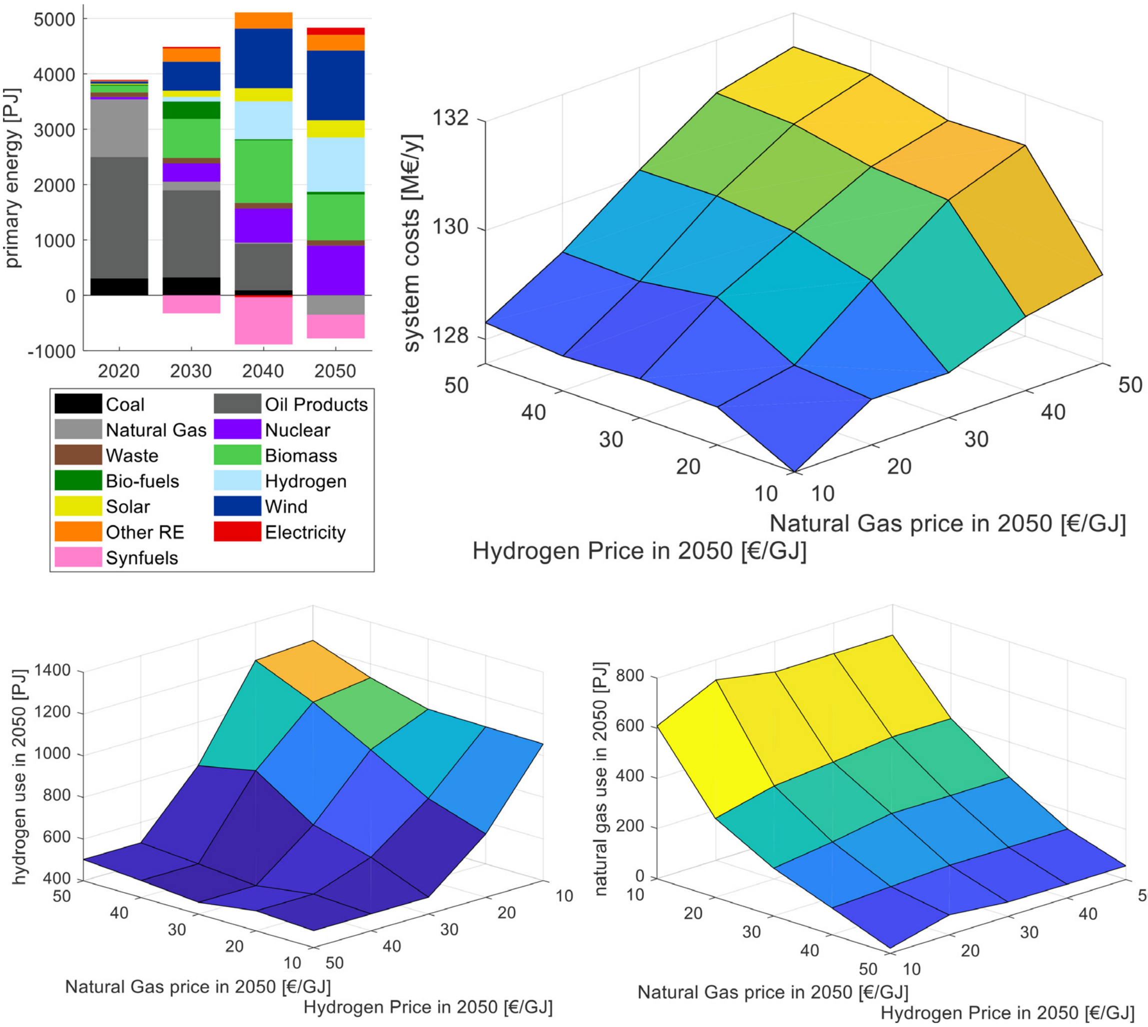


Fig. 26. Results of the sensitivity analysis on the imported hydrogen and natural gas prices. Top left: evolution of the primary energy mix in the Netherlands for a scenario where the current natural gas prices (~50€/GJ) remain at present values until 2050. Top right: average system costs for the transition. Bottom left: hydrogen use in 2050. Bottom right: natural gas use in 2050.

This unexpected behaviour can be explained as follows. The levelled cost of production of the analysed commodities, namely steel, ammonia, HVCs, hydrocarbons, and hydrogen, is dominated by the fuel component. Thus, even large savings in the capital component of the LCOPs result in only marginal gains which are not sufficient to compensate for higher fuel costs. Nevertheless, this is not an indication that technological advancement is not necessary. On the contrary, if technological development results in notable efficiency gains, then LCOPs could be lowered sufficiently to trigger cost-effective choices. In addition, technological advancement resulting in lowered investment costs outside the industrial sector, such as batteries and VRES, could yield cheaper electricity, which could affect technology options in the industrial sector considerably.

Dependency on the price of imported fossil fuels and hydrogen

An interesting topic for sensitivity analysis relates to the current situation of global oil and natural gas prices. Typically, when optimising the energy transition, the scenarios are designed with moderate fossil fuel price projections to avoid slanted outcomes. If low price projections are used, the transition becomes costlier and the shadow price on the emission constraint increases. In contrast, if high price projections are used, many decarbonisation technologies become cost-effective and displace fossil-based technologies, resulting in an accelerated and more cost-effective energy transition. For the last two years, gas prices have been three to six times higher than the typical projections for the transition, and crude oil prices have fluctuated between half and triple the value typically used in projections. In Fig. 26 displays two types of results. First, the primary mix evolution for a scenario where the current prices of natural gas (~50 €/GJ) and crude oil (~20 €/GJ) are maintained until 2050 are presented on the top-left graph. Second, the remaining Fig.s present the results of a bi-dimensional sensitivity analysis in which hydrogen and natural gas prices are meshed for a range between 10 and 50 €/GJ for each.

The first exercise, as illustrated in the top left of Fig. 26, demonstrates that with the current gas and oil prices, natural gas is fully displaced from the primary mix and oil consumption is reduced by 60% by 2040, and all fossil fuels are displaced from the primary mix by 2050. The CO_2 shadow price is zero for all periods in this model run. This is a substantial finding, because under current fossil prices, emission reduction targets are not necessary to achieve the desired decarbonisation path because clean technologies are ultimately more cost-effective than fossil fuel-based technologies.

The second exercise corresponds to a bi-dimensional sensitivity analysis, where we simultaneously compared the effect of imported hydrogen and natural gas prices in the system in the range between 10 and 50 €/GJ. This experiment demonstrates the importance of the natural gas price for the energy decarbonisation transition because it is evident that the system costs in 2050 are almost exclusively affected by the natural gas price. Nevertheless, if imported hydrogen becomes considerably cheaper (i.e., below 10 €/GJ or 1.2 €/kg), then the costs of the transition can be reduced substantially. At higher prices of imported hydrogen, the use of natural gas is affected only by price, as opposed to that of hydrogen. Hydrogen use is affected by both natural gas and imported hydrogen prices because a higher natural gas price increases the use of hydrogen if imported hydrogen is cheaper than natural gas.

For the two opposing scenarios in this exercise, namely cheap natural gas and expensive imported hydrogen, and vice versa, different industry choices are observed. For example, the cheap natural gas exercise uses HIsarna with biomass and CCUS to produce steel, whereas the cheap hydrogen exercise uses direct reduction with hydrogen. Similarly, for the cheap natural gas extreme, the system produces 420 PJ of ammonia with SMR and CCUS, whereas the expensive hydrogen produces 490 PJ of ammonia with SSAS. For HVC production, both scenarios adopt synthetic-naphtha-based steam crackers with CCUS, but each produce synthetic fuels in different ways. Only 200 PJ of MTF are deployed when using cheap natural gas, which contrasts with the 480 PJ for cheap hydrogen, and both scenarios produce a similar amount (~900 PJ) of synthetic fuels. In conclusion, the 760 PJ contrast in hydrogen use in the two opposing scenarios, 470 PJ with cheap natural gas compared to 1,230 PJ with cheap imported hydrogen, can be allocated to the following uses: 1) 315 PJ to produce methanol, 2) 305 PJ to produce methane, 3) 90 PJ for hydrogen boilers in industry, and 4) 50 PJ for hydrogen direct reduction in steel.

References

[1] V. Masson-Delmotte et al., “Global warming of 1.5°C An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change„” 2018.

[2] Ruyssenaars PG, et al. Greenhouse gas emissions in the Netherlands 1990–2019 National Inventory Report 2021. Bilthoven; 2021.

[3] Anderson B, et al. Policies for a climate-neutral industry lessons from the Netherlands. OECD Sci Technol Ind Policy Pap 2021(108).

[4] “EU Emissions Trading System (EU ETS) | Climate Action.” [Online]. Available: https://ec.europa.eu/clima/policies/ets_en. [Accessed: 20-Jul-2021].

[5] “CO2 levy industry | Dutch Emissions Authority.” [Online]. Available: https://www.emissieautoriteit.nl/onderwerpen/themas/co2-heffing. [Accessed: 17-Feb-2022].

[6] “Stimulating sustainable energy production and climate transition (SDE++) | RVO.nl | National Service.” [Online]. Available: https://www.rvo.nl/subsidie-en-financieringswijzer/sde. [Accessed: 20-Jul-2021].

[7] Fritzsche K, Niehoff S, Beier G. Industry 4.0 and Climate Change—Exploring the Science-Policy Gap. Sustain Nov 2018;10(12):4511 *2018, Vol. 10, Page 4511*.

[8] K. Van Kranenburg, E. Schols, H. Gelevert, R. De Kler, Y. Van Delft, and M. Weeda, “Empowering the chemical industry,” 2016.

[9] B. Den Ouden et al., “Electrification in the Dutch process industry In-depth study of promising transition pathways and innovation opportunities for electrification in the Dutch process industry,” 2017.

[10] O. Roelofsen, A. de Pee, E. Speelman, and M. Witteveen, “Energy transition: mission (im)possible for industry? A Dutch example for decarbonization,” 2017.

[11] A. de Pee, D. Pinner, O. Roelofsen, K. Somers, E. Speelman, and M. Witteveen, “Decarbonization of industrial sectors: the next frontier,” 2018.

[12] “Climate and Energy Outlook 2021 | PBL Planbureau voor de Leefomgeving.” [Online]. Available: https://www.pbl.nl/publications/climate-and-energy-outlook-2021. [Accessed: 06-Dec-2021].

[13] Toktarova A, Karlsson I, Rootzén J, Göransson L, Odenberger M, Johnsson F. Pathways for low-carbon transition of the steel industry—a Swedish case study. Energies 2020 Jul 2020;13(15):3840 *Vol. 13, Page 3840*.

[14] Blanco H, Nijs W, Ruf J, Faaij A. Potential for hydrogen and Power-to-Liquid in a low-carbon EU energy system using cost optimization. Appl Energy Dec 2018;232:617–39.

[15] Griffin PW, Hammond GP, Norman JB. Industrial decarbonisation of the pulp and paper sector: A UK perspective. Appl Therm Eng Apr 2018;134:152–62.

[16] Helin K, Käki A, Zakeri B, Lahdelma R, Syri S. Economic potential of industrial demand side management in pulp and paper industry. Energy Dec 2017;141:1681–94.

[17] Zhang X, Hug G. Bidding strategy in energy and spinning reserve markets for aluminum smelters’ demand response. 2015 IEEE Power Energy Soc. Innov. Smart Grid Technol. Conf. ISGT 2015; Jun 2015.

[18] Brückner S, Liu S, Miró L, Radspieler M, Cabeza LF, Lävemann E. Industrial waste heat recovery technologies: An economic analysis of heat transformation technologies. Appl Energy Aug 2015;151:157–67.

[19] Fattahi A, Sijm J, Faaij A. A systemic approach to analyze integrated energy system modeling tools: a review of national models. Renew Sustain Energy Rev 2020;133:110195 Elsevier Ltd01-Nov-.

[20] Brown T, Schäfer M, Greiner M. Sectoral interactions as carbon dioxide emissions approach zero in a highly-renewable european energy system. Energies Mar 2019;12(6):1032 *2019, Vol. 12, Page 1032*.

[21] Fais B, Sabio N, Strachan N. The critical role of the industrial sector in reaching long-term emission reduction, energy efficiency and renewable targets. Appl Energy Jan 2016;162:699–712.

[22] Sánchez Diéguez M, Fattahi A, Sijm J, España GMorales, Faaij A. Modelling of decarbonisation transition in national integrated energy system with hourly operational resolution. Adv Appl Energy Aug 2021;3:100043.

[23] PBL Netherlands Environmental Assessment Agency, “MIDDEN: Manufacturing Industry Decarbonisation Data Exchange Network | PBL Netherlands Environmental Assessment Agency,” 2021. [Online]. Available: https://www.pbl.nl/en/middenweb. [Accessed: 22-Jul-2021].

[24] Morales-España G, Martínez-Gordón R, Sijm J. Classifying and modelling demand response in power systems. Energy Mar 2022;242:122544.

[25] Fattahi A, Sánchez Diéguez M, Sijm J, Morales España G, Faaij A. Measuring accuracy and computational capacity trade-offs in an hourly integrated energy system model. Adv Appl Energy Feb 2021;1:100009.

[26] Martínez-Gordón R, Sánchez-Diéguez M, Fattahi A, Morales-España G, Sijm J, Faaij A. Modelling a highly decarbonised North Sea energy system in 2050: a multinational approach. Adv Appl Energy Feb 2022;5:100080.

[27] Sánchez Diéguez M, Fattahi A, Sijm J, España GMorales, Faaij A. Linear programing formulation of a high temporal and technological resolution integrated energy system model for the energy transition. MethodsX Jan 2022;9:101732.

[28] “StatLine - Energy balance sheet; supply and consumption, sector.” [Online]. Available: https://opendata.cbs.nl/statline/#/CBS/en/dataset/83989ENG/table?ts=1645108206302. [Accessed: 17-Feb-2022].

[29] Montgomery DR. Growing a revolution : bringing our soil back to life. WW Norton & Company; 2018.

[30] Keys A, Daniels B, van Hout M. Decarbonisation options for the Dutch steel industry. The Hague: PBL Netherlands Environmental Assessment Agency; 2019.

[31] Kortes H, van Dril T. Decarbonisation options for the Dutch aluminium industry. The Hague: PBL Netherlands Environmental Assessment Agency; 2019.

[32] Kortes H, van Dril T. Decarbonisation options for the Dutch zinc industry. The Hague: PBL Netherlands Environmental Assessment Agency; 2019.

[33] M. Batool and W. Wetzels, “Decarbonisation options for the Dutch fertiliser industry, PBL Netherlands Environmental Assessment Agency,” The Hague, 2019.

[34] Oliveira C, Van Dril T. Decarbonisation options for Large Volume Organic Chemicals production. The Hague: SABIC Geleen | PBL Netherlands Environmental Assessment Agency; 2021.

[35] M. Wijngaard et al., “Roadmap to circular plastics in 2050 | TNO,” 2020.

[36] Eerens H, Scherpbierd E. Decarbonisation options for the Dutch chlor-alkali industry. The Hague: PBL Netherlands Environmental Assessment Agency; 2020.

[37] Rademaker K, Marsidi M. Decarbonisation options for the Dutch paper and board industry. The Hague: PBL Netherlands Environmental Assessment Agency; 2019.

[38] Vangkilde-Pedersen T, et al. Assessing European capacity for geological storage of carbon dioxide–the EU GeoCapacity project. Energy Procedia Feb 2009;1(1):2663–70.

[39] TNO, “Datasheets - Energy.nl.” [Online]. Available: https://energy.nl/datasheets/. [Accessed: 04-May-2022].

[40] IEA, “Simplified levelised cost of competing low-carbon technologies in steel production – Charts – Data & Statistics.” [Online]. Available: https://www.iea.org/data-and-statistics/charts/simplified-levelised-cost-of-competing-low-carbon-technologies-in-steel-production. [Accessed: 28-Feb-2022].

[41] IEA, “Simplified levelised cost of competing low-carbon technologies in chemicals production – Charts – Data & Statistics.” [Online]. Available: https://www.iea.org/data-and-statistics/charts/simplified-levelised-cost-of-competing-low-carbon-technologies-in-chemicals-production. [Accessed: 28-Feb-2022].

[42] IEA, “Simplified levelised cost of petrochemicals for selected feedstocks and regions, 2017 – Charts – Data & Statistics.” [Online]. Available: https://www.iea.org/data-and-statistics/charts/simplified-levelised-cost-of-petrochemicals-for-selected-feedstocks-and-regions-2017. [Accessed: 28-Feb-2022].

[43] IEA, “Simplified levelised cost of competing low-carbon technologies in long distance transport – Charts – Data & Statistics.” [Online]. Available: https://www.iea.org/data-and-statistics/charts/simplified-levelised-cost-of-competing-low-carbon-technologies-in-long-distance-transport. [Accessed: 28-Feb-2022].

[44] Martínez-Gordón R, Morales-España G, Sijm J, Faaij APC. A review of the role of spatial resolution in energy systems modelling: Lessons learned and applicability to the North Sea region. Renew Sustain Energy Rev. May 2021;141:110857.

[45] “Dutch goals within the EU | Climate change | Government.nl.” [Online]. Available: https://www.government.nl/topics/climate-change/eu-policy. [Accessed: 20-Jul-2021].