Energy and Climate Change 6 (2025) 100205

Contents lists available at ScienceDirect

Energy and Climate Change

journal homepage: www.sciencedirect.com/journal/energy-and-climate-change

Full Length Article

Decarbonizing the Dutch industrial sector: between maintaining domestic production and partial relocation

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ARTICLE INFO

Keywords:
Industrial sector
Decarbonization
Energy system model
CCUS

ABSTRACT

Industry is one of the most challenging sectors to decarbonize in the Dutch energy system. This is due to several factors such as the difficulty in moving away from existing technologies and the availability of still relatively cheap natural gas. In this study, we introduce two scenarios to investigate possible energy transition pathways for the Dutch industrial sector. The first scenario focuses on keeping industrial production largely in the Netherlands. The second explores relocating part of it abroad to regions in which low–cost sustainable energy sources are available. We employ an energy system optimization model to analyze these scenarios. Our results for the first scenario show a reduction of about 80% in fossil fuel consumption by 2050 in the industrial sector, primarily achieved by substituting fossil fuels with hydrogen, bioenergy, and synthetic fuels. To achieve the carbon-neutrality target by 2050, a cumulative total of about 552 $MtCO_2$ needs to be captured from the industrial sector, with 52% utilized and the rest stored. The second scenario does not yield a large difference in the relative energy mix compared to the first. However, it results in substantial changes in terms of more rapid decarbonization, with less final energy consumption, lower investment costs, and more limited deployment of CO_2 capture technology. In both scenarios, a radical technological transformation of the industrial sector is necessary for reaching the energy system carbon-neutrality target, with industry contributing to this goal by achieving net-negative CO_2 emissions in 2050.

1. Introduction

In alignment with the European Commission's climate legislation (e.g. European Green Deal and Fit-for-55 package), the Netherlands has amended its Climate Act, incorporating more stringent greenhouse gas (GHG) reduction targets for 2030 [1]. A major challenge in achieving these targets lies in the industrial sector, which was responsible for 26% of the country's GHG emissions in 2021. The sector's energy mix has remained largely unchanged since 1990, being heavily reliant on fossil fuels, as illustrated in Fig. 1. This stability results, in part, from the availability of relatively cheap natural gas — even under the present geopolitical circumstances — as well as the strategic geographical location of the Netherlands, which facilitates the import of other fossil fuels such as oil.

In addition, the Dutch economy is characterized by a strong export orientation, with key sectors such as agriculture and chemicals. This

Abbreviations: BECCS, Bioenergy Coupled with Carbon Capture and Storage; CBAM, Carbon Border Adjustment Mechanism; CCS, Carbon Capture and Storage; CCUS, Carbon Capture, Utilization and Storage; CO_2, Carbon dioxide; DF, Direct Firing; DME, Dimethyl ether; DRI, Direct Reduced Iron; FT, Fischer-Tropsch; F-gases, Fluorinated gases; GHG, Greenhouse Gas; GCF, Green Climate Fund; GEF, Global Environment Facility; HB, Haber-Bosch; HBI, Hot Briquetted Iron; HT, High Temperature; HVCs, High-Value Chemicals; HVO, Hydrotreated Vegetable Oil; I-ELGAS, Integrated Electricity, Hydrogen, and Gas Markets Model; LP, Linear Programming; MVR, Mechanical Vapor Recompression; O&M, Operation and Maintenance; OPERA, Option Portfolio for Emissions Reduction Assessment; PEM, Proton Exchange Membrane; P2L, Power-to-Liquid; PSA, Pressure Swing Adsorption; SDE++, Sustainable Energy Production and Climate Transition Incentive Scheme; SOEC, Solid Oxide Electrolysis Cell; SMR, Steam Methane Reforming; TGR-BF, Top Gas Recycling Blast Furnace; TYNDPs, Ten-Year Network Development Plans; UCO, Used Cooking Oil; WSA, World Steel Association.

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https://doi.org/10.1016/j.egycc.2025.100205

Available online 1 July 2025

specialization, while economically beneficial, complicates efforts to reduce GHG emissions without impacting economic performance. The availability of sustainable energy commodities, such as renewable electricity and green fuels, is a critical aspect of the required transition. The large–scale production of these energy commodities might not be immediately feasible within the Netherlands. Companies could, therefore, seek to relocate their industrial activities to countries where such energy commodities are readily available at lower prices.

In that case, there are several potential outcomes: production in the Netherlands could decrease or even cease entirely. However, companies manufacturing products outside the EU might incur import duties, e.g. the Carbon Border Adjustment Mechanism (CBAM), when shipping products to the EU. This could lead to a scenario in which parts of the production chain are relocated abroad to regions from where semi-manufactured products or feedstocks can be exported to the Netherlands to complete the production process.

This paper examines the efforts of the Netherlands in decarbonizing the industrial sector as part of its broader goal to achieve carbon neutrality across the entire energy system by 2050. Several studies have discussed industrial transformation in relation to specific technologies or subsectors. For instance, the roles of low–carbon hydrogen, carbon capture, and waste heat recovery in decarbonizing the industrial sector have been assessed [3–9]. The decarbonization of the industrial sector as a whole has also been investigated with a focus on specific countries [10]. However, variations in industrial structure and technological readiness limit the applicability of their findings to the Dutch case. In the context of the Netherlands, long–term national scenario studies often assumed a business-as-usual future for the Dutch industry without major technological transformation—maintaining current production and energy technologies rather than adopting advanced low-carbon alternatives—and more mitigating measures, such as carbon capture and storage (CCS) [11,12]. Another study has explored both a moderate technology-mix and more extreme decarbonization pathways, such as fully bio-based and hydrogen-based industry scenarios [13]. However, it places less emphasis on practical constraints such as the feasibility of large-scale technology deployment within realistic timelines. The authors also highlight the absence of targeted policy measures such as subsidies in their study as a critical area for further investigation.

To complement and expand prior research, we employ an energy system model (ESM) to analyze two scenarios for decarbonizing the Dutch industrial sector. The first scenario explores a shift in fuels and a fundamental technological transformation, aimed at achieving carbon neutrality across the entire energy system by 2050. The second scenario extends the first one by assuming the partial relocation of energy-intensive production processes within Dutch industry to countries where renewable energy is more abundant and affordable. This scenario reflects a pragmatic response to market realities, in which industries seek cost-competitive green energy abroad—a crucial aspect that has not been explored in previous research.

Our analysis focuses on the systemic implications of industrial transformation in the Netherlands, in terms of the energy mix, greenhouse gas emissions, Carbon Capture, Utilization, and Storage (CCUS) deployment, capital investment requirements, and operational costs under each scenario. Our two scenarios are designed to reflect plausible, stepwise changes in energy sources and technology use. We reflect these aspects in the model by incorporating key elements in both scenarios that were not considered in previous studies: 1) soft-linking advanced electricity and gas market models with our ESM to assess the combined effects of changes in electricity and gas markets on the overall energy system. Previous studies have primarily focused on linking ESMs to electricity market models, with less attention given to the gas market, which in our present work we compensate for — doing so is particularly pertinent against the background of a growing role for the production and use of green hydrogen; 2) integrating the most recent policy frameworks as well as accounting for the technological deployment limitations based on relevant recent studies (e.g. [14,15]); 3) adjusting the investment costs of clean technologies in line with the Dutch government's Sustainable Energy Production and Climate Transition Incentive Scheme (SDE++).

In the remainder of this article, we detail our methodology in Section 2, describing the scenarios and tools employed. We present our findings in Section 3, followed by a discussion in Section 4. Section 5 summarizes our key insights and offers recommendations for future research.

2. Methodology

The energy consumption of the Dutch industry is predominantly concentrated in four sectors: Oil refineries, High–value Chemicals, Steel, and Fertilizers, which together accounted for 81% of the total industrial energy consumption in 2022, with respective shares of 18%, 52%, 3%, and 8% [2]. In light of this, our study focuses on these four industries. Their current operational status, prevailing technologies, and

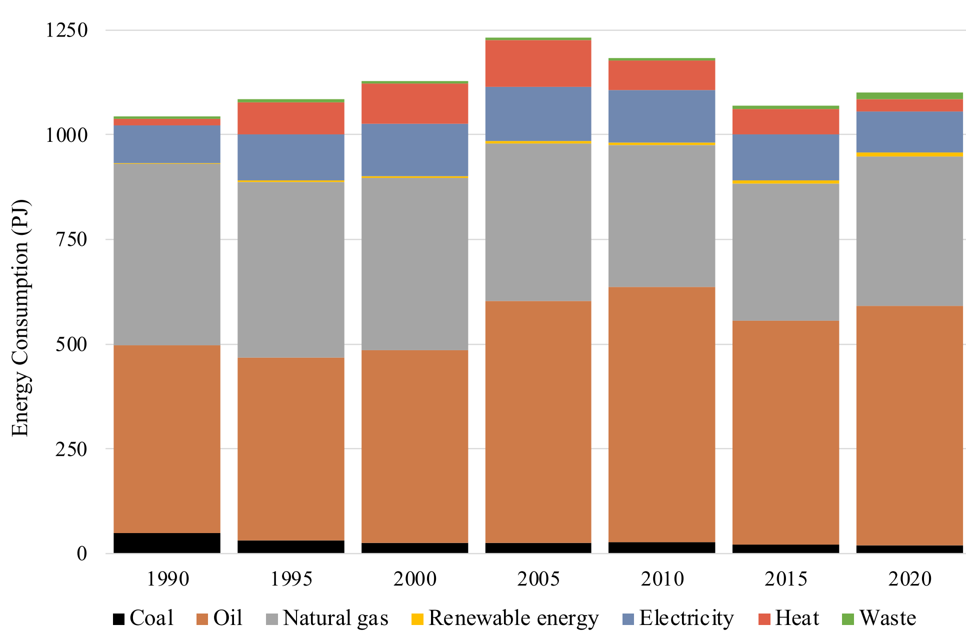


Fig. 1. Total energy consumption of the Dutch industrial sector by source [2].

decarbonization challenges are described in Appendix A. Alternative low-carbon technologies relevant to each sector are also discussed, with an overview provided in Table A1, Appendix A.

2.1. Tools

This study employs the OPERA (Option Portfolio for Emissions Reduction Assessment) ESM developed, maintained, and used at the Netherlands Organization for Applied Scientific Research (TNO) and the Netherlands Environmental Assessment Agency (PBL). OPERA is based on Linear Programming (LP). Its objective function aims to identify the lowest–cost energy system in a specific year while adhering to a set of constraints, such as GHG emissions, energy demand, and technological limitations. The database of the model includes a vast array of around 600 technologies that represent multiple options for energy production, conversion, transport, and storage [16].

For the latter, only electricity and hydrogen storage options are considered. Additionally, it covers different technologies for CO_2 capture, transport, and storage. As a national ESM, OPERA divides the Netherlands into 14 regions: seven on land (five of which correspond to industrial clusters); and seven offshore, each with unique wind conditions and proximities to the coast. Fig. 2 shows the reference energy system of OPERA and outlines its boundaries.

To accurately account for the import and export of energy commodities such as hydrogen, we soft–link OPERA with the Integrated Electricity, Hydrogen, and Gas Markets Model (I-ELGAS) [17]. The I-ELGAS model covers nine countries: the Netherlands, Germany, Norway, Sweden, Denmark, England, Ireland, Belgium, and France. The Netherlands is represented in high spatial detail (20–30 nodes per carrier), including explicit offshore hub areas, allowing for realistic simulation of congestion and regional market behavior. The model optimizes hourly electricity and hydrogen system dispatch for each target year based on least-cost allocation. Typical outputs include system dispatch insights (hourly production, transport, and storage) and marginal system costs (used as proxies for energy prices). The I-ELGAS database represents the current and planned installed generation capacities, transmission system, and demand profiles. These data are extracted from national energy generation and infrastructure plans such as the Ten–-Year Network Development Plans (TYNDPs) [18]. For the soft–linking, I-ELGAS generates a first run based on these data and passes the results to OPERA. We then run OPERA and feed the relevant output (for the Netherlands) back to I-ELGAS for its second run, after which we conduct the final OPERA run for our study. Fig. 3 illustrates the iterative linking framework between the two models; arrows pointing in opposite directions depict the bidirectional flow of data.

2.2. Main input and assumptions

The key parameters and assumptions in OPERA applied for the present study, are:

- The base year is 2025;
- The model spans from 2025 to 2050 with five–year intervals;
- The annual energy and industrial production demand for the Netherlands is calibrated based on current trends and future projections, primarily derived from the Climate and Energy Outlook 2022 [19];
- The energy pricing structure for fossil fuels is informed by recommendations from the European Commission, from which the median price scenario for natural gas is adopted [20]. These valuation metrics are consistent with those applied in the Climate and Energy Outlook 2022 [19]. In essence, GHG emissions reduction targets affect fossil fuel prices indirectly by embedding the costs of carbon, which is a shadow price calculated endogenously by the model to incentivize the transition to cleaner energy sources. Biofuel prices, including for biodiesel and bioethanol, are presumed to remain stable throughout the evaluation period, which aligns with data from the AdvanceFuel project [21].

While OPERA incorporates a broader range of technologies for the

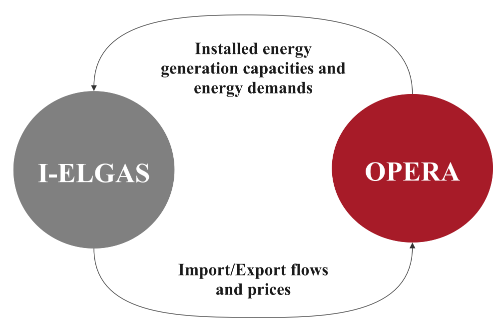


Fig. 3. Bidirectional data exchange between OPERA and I-ELGAS.

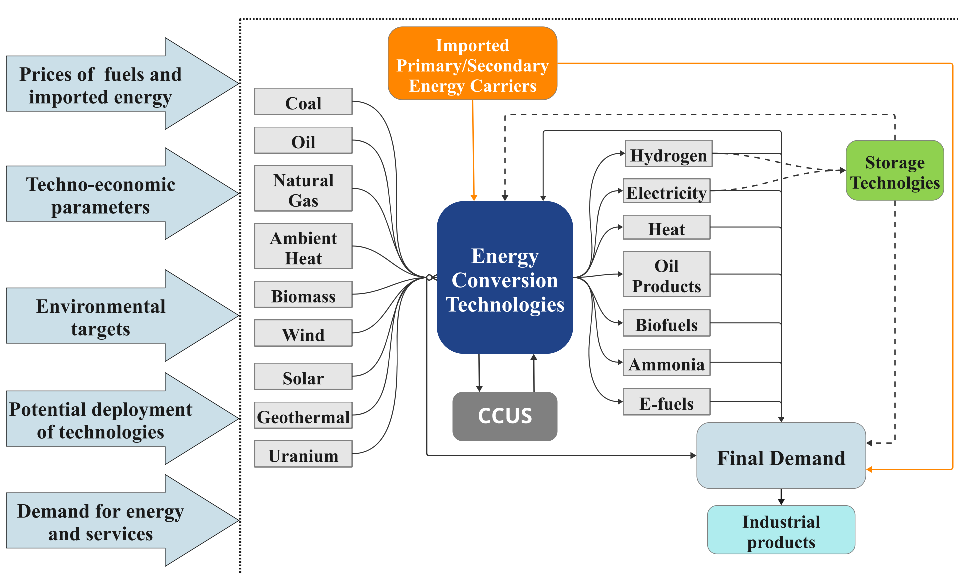


Fig. 2. Schematic diagram of the reference energy system of OPERA.

entire energy system that covers residential, transportation, and agriculture sectors, 385 of these technologies are specifically focused on the industrial sector. These technologies along with their relevant techno-economic parameters are listed in Tables 1A and 1B, Appendix B [22]. These parameters account for technology learning effects, i.e. cost reductions as a result of R&D and wide deployment. For technologies with undefined learning rates, a 20% investment cost reduction is assumed over the analysis period. Investment costs have been updated in line with the SDE++, which supports sustainable energy production and CO_2–reducing technologies [23,24].

Parameters related to the overall climate targets (e.g. carbon neutrality by 2050) remain uniform across scenarios. Yet specific goals, technological constraints, and specifications may vary across them, as detailed in Tables 3A and 4A, Appendix A. Section 3.3 introduces the scenarios considered in this study and clarifies the principal distinctions between them in addressing the overarching climate goals.

2.3. Scenarios

We develop two scenarios to understand the impact of different energy transition strategies for the four energy-intensive industries on the long–term energy system of the Netherlands. Targets for energy efficiency, share of renewable energy sources, and decarbonization across the whole energy system (including the transport sector) were considered while designing these scenarios.

2.3.1. Transform

This scenario is based on a fundamental transformation of the energy system with a reliance on new innovative technologies rather than trying to conform to existing technologies while deeming CCS as the predominant way to mitigate emissions.

2.3.2. Import

This scenario is a duplicate of the TRANSFORM scenario, but it is modified by assuming the partial relocation of the energy-intensive stages of the industrial production processes to a location outside the Netherlands. Semi-finished products are shipped to the Netherlands for the manufacturing of final goods. The IMPORT scenario is inspired by the National Energy System Plan (NPE) of the Netherlands, which explores strategies for the Dutch energy system and its industrial transformation [25]. The imported products considered in this scenario include biomass, biofuels, hydrogen, ammonia, synthetic fuels, plastic waste, and Hot Briquetted Iron (HBI). For synthetic fuels and ammonia, we consider imports from regions with significant export potential to the Netherlands, such as Australia, Canada, Morocco, Iceland, Saudi Arabia, and Oman. Biomass, biofuels, plastic waste, and HBI are assumed to be sourced from Europe. This geographic focus reflects both logistical feasibility and insights from prior studies [26,27], which identify these regions as key suppliers to the Netherlands based on their production capabilities and resource availability. We assume relocated production uses cheaper, renewable energy due to the natural advantages of partner regions. In OPERA, the modelling of feedstock imports depends on the commodity in question. For imported material inputs such as HBI, we introduce a new production technology that exclusively uses imported HBI, characterized by lower capital and operational expenditures compared to domestic iron and steel production technologies. In contrast, for imported energy carriers, we model them as distinct commodities from their domestic counterparts. For example, imported ammonia is treated separately from domestic ammonia, and in the IMPORT scenario, we impose a constraint that enforces a specific share of ammonia demand to be met by the imported variant. For this, the price of imported ammonia is based on external cost projections from [26].

The key details for both the TRANSFORM and IMPORT scenarios, including assumptions about shifts in production and import reliance, are listed in Table 5A, Appendix A.

2.4. Indicators

We use the following indicators to compare the results across our two scenarios:

- Final energy consumption by source and annual GHG emissions in the industrial sector:
  - Final energy consumption by source measures the total energy consumed by end–users.
  - Annual net GHG emissions refer to the total amount of CO_2 and other GHGs released into the atmosphere as a result of activities in the energy system over the course of a year.
- Annual CCUS deployment in the industrial sector, which reflects the total carbon dioxide captured, stored, and reused, including details on the amounts and the sectors where the carbon dioxide is utilized.
- Total investments in the industrial sector, represent the financial requirements for adopting new technologies or expanding existing ones through the analysis period. This also includes investments in the relevant infrastructure and equipment.
- Total operational cost of the industrial sector, which encompasses all costs associated with the production processes in the industrial sector. It includes the operational and maintenance costs (O&M) and energy costs.

3. Results

3.1. Final energy consumption by source and annual net GHG emissions

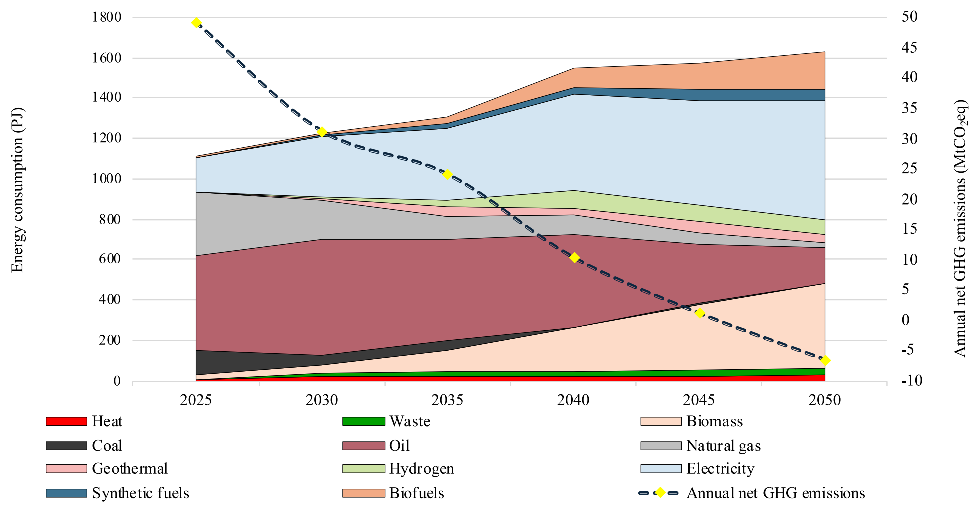
Fig. 4 presents the total final energy consumption of the Dutch industrial sector under the two scenarios from 2025 till 2050. In both scenarios, fossil fuel consumption is reduced by approximately 80% through the projection period (2025–2050), with coal consumption almost entirely phased out by 2040. This significant shift reflects industries transitioning to cleaner energy sources, as seen in the increased use of biofuels, hydrogen, biomass, and electricity throughout the projection period.

The IMPORT scenario shows a significant reduction in total energy consumption, down by approximately 250 PJ compared to the TRANSFORM scenario; this is primarily driven by increased low–carbon fuel imports and the accelerated phase-out of coal by 2035. The energy profile in the IMPORT scenario also differs, with a noticeable reduction in the use of electricity, biomass, and natural gas. Notwithstanding this, the consumption of hydrogen, biofuels, and synthetic fuels increases between 2025 to 2040 compared to TRANSFORM. This increase does not reflect higher domestic production. Rather, the hydrogen previously produced within some industries (e.g. ammonia production) using electricity and natural gas is now imported directly as a feedstock or as a fuel for direct use in other sectors, as shown in Fig. 5.

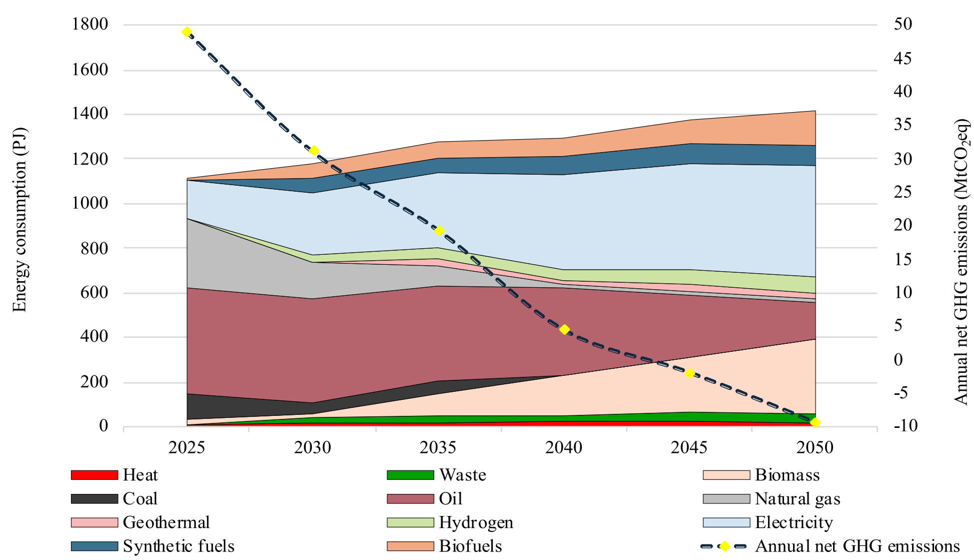
Fig. 5 further indicates higher average annual imports of ammonia (~4 times higher), biofuels (~78 times higher), and synthetic fuels (~82 times higher) in the IMPORT scenario compared to TRANSFORM (averaged across years). Fig. 4 also depicts the net GHG emissions for the Dutch industrial sector. The shift to a green energy mix, featuring a considerable increase in biomass consumption, results in a sharp downward trajectory, with net emissions plummeting to negative values of -6.5 and -9.3 $MtCO_2eq$ by 2050 under the TRANSFORM and IMPORT scenarios, respectively.

3.2. Annual CCUS deployment

Fig. 6 compares the annual CCUS deployment across the two scenarios. It shows that the CCUS begins modestly in 2025, with approximately 0.017 Mt of CO_2 captured by the fertilizer industry. After that, CCUS deployment grows significantly over the rest of the projection period, which aligns with the increase in biomass consumption. In the TRANSFORM and IMPORT scenarios, the total captured CO_2 over the



(a) TRANSFORM



(b) IMPORT

Fig. 4. Final energy consumption (incl. feedstock) of the Dutch industrial sector by source (left y-axis) and annual net GHG emissions (right y-axis) for the two scenarios.

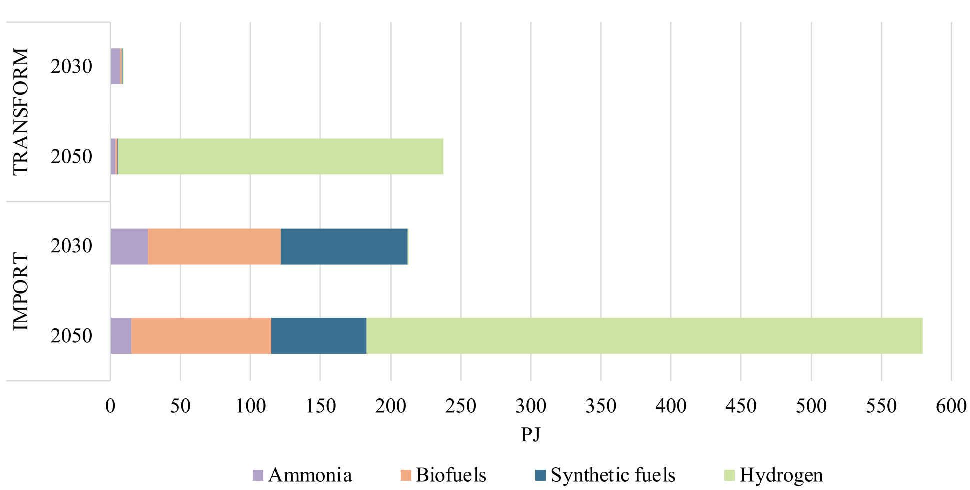


Fig. 5. Low–carbon fuel imports for the two scenarios for the years 2030 and 2050.

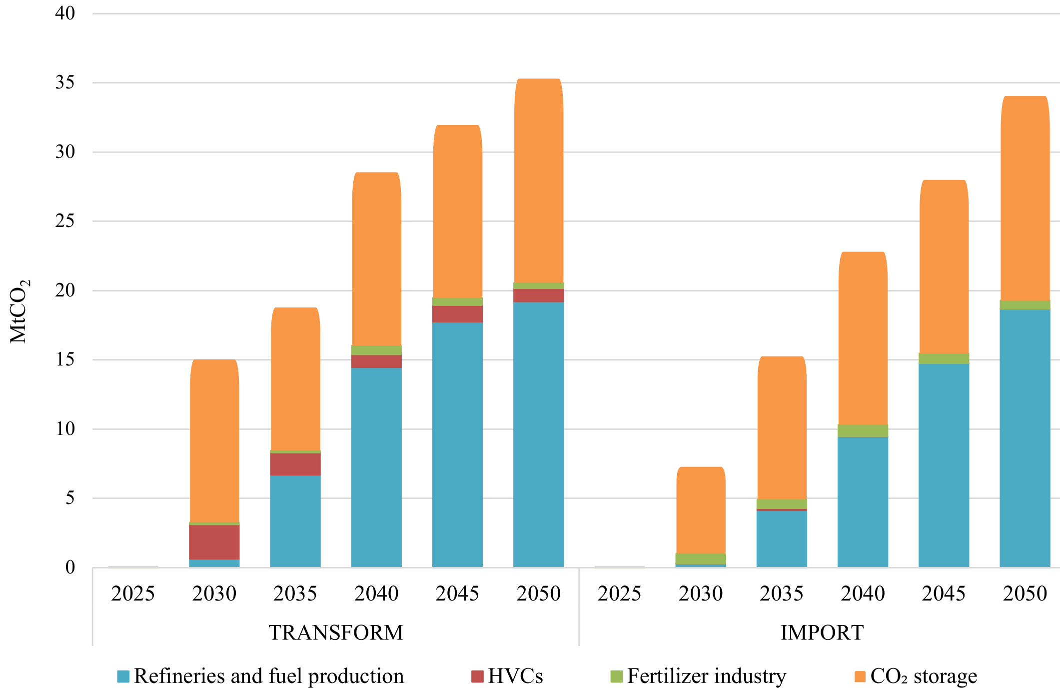


Fig. 6. Annual CCUS deployment for the two scenarios.

projection period amounted to 552 and 458 $MtCO_2$, of which 68% and 51% were utilized while the rest were geologically stored, respectively.

The primary utilization of the captured CO_2 is in the refineries and fuel production sector, specifically directed towards the production of bunker fuels like methanol. This corresponds to the increasing demand of the maritime industry for low–carbon fuels (see Fig. 11, Appendix C). For the differences between the two scenarios, two key observations can be drawn: 1) CCUS deployment is less in the IMPORT scenario, which is logical as biofuels and synthetic fuels are less produced and more imported (see Fig. 5); and 2) CO_2 utilization is slightly higher in the fertilizer sector in the same scenario. This is because biofuels are not produced domestically at the same level as TRANSFORM, there is more captured biogenic CO_2 available for utilization in this industry.

3.3. Investments

Fig. 7 shows the capital investments of the Dutch industrial sector for the two scenarios, with the left y-axis representing the sectoral distribution of investments, while the right y-axis indicates the total cumulative investments required for each scenario. The total cumulative

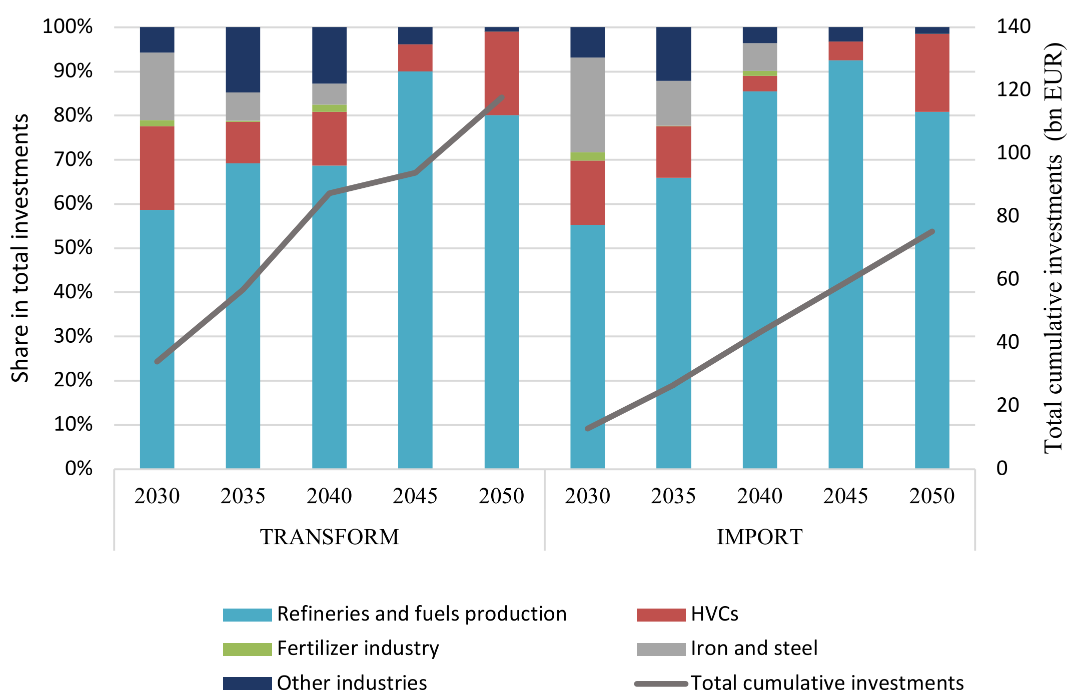


Fig. 7. Capital investments of the Dutch industrial sector for the two scenarios. Investment values represent cumulative numbers over the preceding 5-year period. For example, the value for 2030 includes investments made between 2025 and 2030.

investments for the IMPORT scenario are represented by a straight line, indicating a steady increase in investments over the years. In contrast, the TRANSFORM scenario features a stepped line: large early investments are made during the early phases to drive the domestic transformation, which then decreases between 2040 and 2045 as key technologies and infrastructure become established. A modest increase follows from 2045 to 2050 to finalize the transition and meet the final decarbonization targets. By 2050, the total cumulative investments for the former scenario reach approximately 90 billion euros, while for the latter, this figure is about 115 billion euros. This emphasizes the higher domestic investment requirements when relying on extensive local production rather than imports.

For the TRANSFORM scenario, the main investments throughout the analysis period are in the refineries and fuels production sector as it is responsible for meeting the growing demand for low-carbon fuels across various industries. The investments in the 'other industries' are higher in the first half of the analysis period; however, in smaller amounts after that. The relevant investment percentage of the fertilizer industry is pronounced in 2040 but declines in the subsequent years. The iron and steel industry has investments almost only in 2030, 2035 and 2040. Apart from those years, investment in this industry is non-existent. The trend across the fertilizer and iron and steel industries suggests that by 2040, much of the technological shift is done, requiring only maintenance or incremental updates.

For the IMPORT scenario, the investments per industry display a different pattern compared to the TRANSFORM scenario. Investments in the refineries and fuels production industry are still the most prevalent during the analysis period. However, the relative investment share of the HVCs industry is lower, and in the iron and steel industry, it is higher. We reflect on this in the discussion section.

3.4. Total operational cost

Fig. 8 shows that the total operational cost of the TRANSFORM scenario is initially higher than for the IMPORT scenario. However, during the rest of the analysis period, the cost gradually increases for the latter and eventually surpasses the former. The total operational cost for the TRANSFORM and IMPORT scenarios exhibits an increase of 61% and 88%, respectively, over the analysis period.

The energy component constitutes the dominant share of the total operational cost in both scenarios, as illustrated in Fig. 9. In the TRANSFORM scenario, the energy cost share decreases by 4% in 2050 compared to 2030 along with an increase in the shares of the fixed and variable O&M costs. On the other hand, the share of energy costs decreases by only 1% in the IMPORT scenario over the analysis period

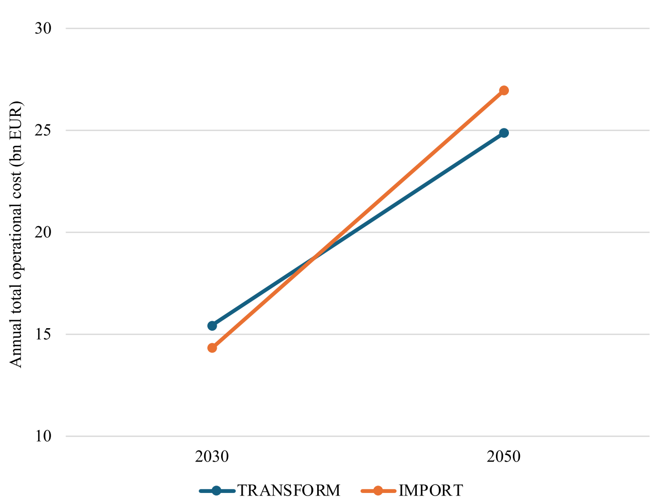


Fig. 8. The total operational cost of the industrial sector from 2030 to 2050 for the two scenarios.

whereas the fixed O&M cost increases by 1% and the variable O&M remains unchanged. The reasons behind these patterns are discussed in the following section.

4. Discussion

Decarbonizing the Dutch industrial sector under both scenarios results in a major shift in the energy mix—away from fossil fuels and toward low-carbon and renewable fuels such as hydrogen, biomass, and synthetic fuels. Among these, biomass combined with carbon capture and storage (BECCS) plays a central role in decarbonizing the industrial sector. These findings are consistent with both national and global long-term energy transition scenarios [13,28], which emphasize the importance of low-carbon fuels and CCUS in industrial decarbonization. The contribution of BECCS, in particular, to achieving a net-zero energy system has also been highlighted in other scenario studies [29,30]. Although net GHG emissions become negative in the industrial sector by 2050 under both scenarios, this does not imply that the entire energy system achieves net-negative emissions. Rather, it is only the industrial sector that does, whereas the entire system is to be neutral by 2050. This is in line with findings from other studies [28,31], which indicate that negative emissions across the power, heat, and industrial sectors are essential to achieve overall carbon neutrality in the energy system.

The lower net GHG emissions observed in the IMPORT scenario, compared to TRANSFORM, are attributed to the greater reliance on energy imports rather than domestic production, as also reflected in the reduced total final energy consumption. This shift in energy sourcing also influences the pattern in which CCUS is deployed. Between 2045 and 2050, the substantial volume of hydrogen imports in IMPORT appears to create favorable conditions for combining hydrogen with captured CO_2 to produce synthetic methanol, primarily used as bunker fuel. In TRANSFORM, biogenic CO_2 is scarce, and we find that, instead of synthetic methanol, more ammonia is used for shipping (see Fig. 11, Appendix C).

The increased use of ammonia in TRANSFORM is further explained by the limited availability of biofuels, whereas in IMPORT, larger quantities of biofuels can be imported to meet the energy demand of both the maritime sector and the HVCs industry. In the latter, for example, bio–feedstocks (e.g. bio–naphtha) is imported to produce ethylene and propylene. These differences, in turn, impacts the investment shares and values across industries in both scenarios, leading to lower investments in IMPORT. The 'other industries' are, however, an exception, since they exhibit higher investments in 2050 in the IMPORT scenario in comparison to TRANSFORM. The reason behind this was revealed to be the higher investments in hydrogen and biomass boilers, owing to the fact that these fuels are readily available in the former scenario.

In TRANSFORM, we find that across the five sectors analyzed, energy-related technologies[1] hold a significant share of the total investments. Specifically, in the basic metals, food, and beverages sectors, energy-related technologies dominate, with hydrogen boilers and geothermal energy representing the largest shares. This is because these sectors primarily rely on heat for their processes (e.g. food processing) and are already less dependent on chemical transformations (unlike steelmaking). For refineries and fuels production, HVCs, and fertilizers, the majority of investments are directed toward process-related technologies.[2] Examples include H-DR in the iron and steel industry, methanol production from lignocellulosic feedstocks with carbon capture

[1] Technologies focused on producing, storing, or distributing energy (e.g. electricity or heat). They do not create physical products but supply the power needed for processes.

[2] Technologies that transform raw materials into finished products through physical, chemical, or industrial processes. They are dedicated to manufacturing rather than energy generation.

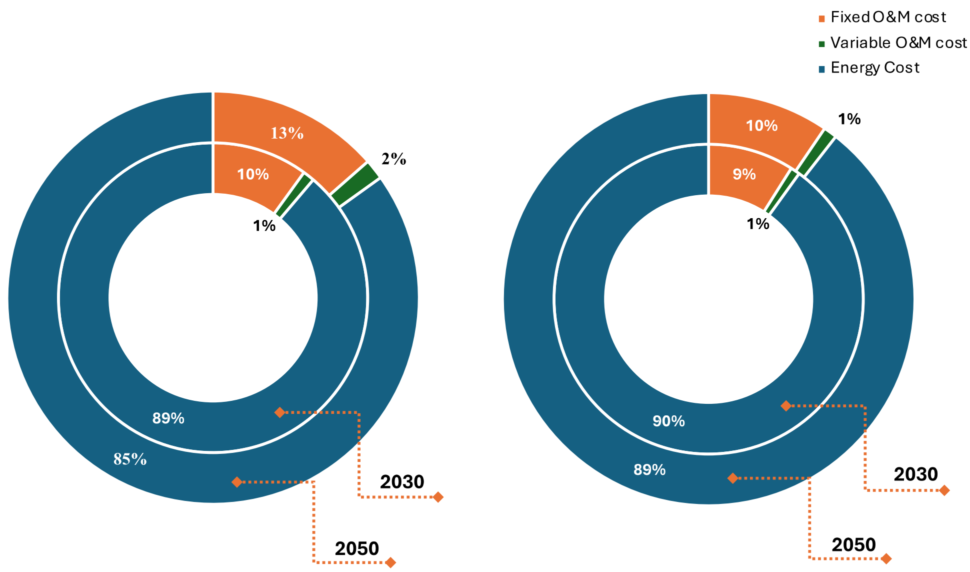


Fig. 9. Share of fixed O&M costs, variable O&M costs, and net energy cost in the total operational cost of the Dutch industrial sector in 2030 and 2050 for the TRANSFORM (left) and IMPORT (right) scenarios.

(CC) in the HVCs, and the hydrogen-based Haber-Bosch process for ammonia production in fertilizers. However, investments in energy-related technologies still claim a considerable share in these sectors. Although the IMPORT scenario follows a similar trend, there is noticeably less emphasis on energy-related technologies that rely on natural gas combined with CC (see Tables 1C and 2C, Appendix C).

While capital investments in the IMPORT scenario remain lower, its total operating costs exceed those in TRANSFORM, which is mainly due to the elevated energy costs associated with energy imports. In both scenarios, the total operating costs followed a growing pattern over the analysis period, which can be attributed to four different reasons: 1) the higher industrial production of some commodities; 2) the higher energy demand, not only due to the higher production but also due to the use of new clean technologies that are less efficient—requiring more energy to produce the same output; 3) companies that fall under the emission trading system can no longer receive emissions allowances from 2040 onwards; 4) higher bioenergy and fossil fuel prices (see Table 2A, Appendix A).

Our results on net GHG emissions should be interpreted in light of the relevant emission scopes. The emissions reported in this study primarily include Scope 1 emissions, which encompass direct emissions from the consumption of final energy products such as onsite fuel combustion in refinery processes and steel furnaces. While some aspects of Scope 2 emissions are also considered such as the use of purchased steam or other non–electrical energy forms, electricity is explicitly excluded—-over 90% of the electricity generation in OPERA is based on clean technologies (see Fig. 10, Appendix C). In terms of Scope 3, although the emissions related to purchased goods and services are crucial, not all categories are fully accounted for. For example, emissions from employees commuting and downstream transportation of finished products are not included in our analysis

Our study's exploration of nationally focused industrial transformation versus the partial relocation of production activities illustrates how different decarbonization strategies can affect domestic and global emissions outcomes. Although overseas emissions are not directly modeled in OPERA, the IMPORT scenario assumes that relocated production is powered by renewable energy in partner regions, which could result in net global emissions reductions. This assumption, however, depends on the willingness and capacity of exporting countries to produce low-carbon energy carriers using renewable electricity. In practice, such production may be motivated by export demand from high-income regions like Europe, rather than domestic decarbonization targets. One might argue that some partner countries may generate renewable fuels or feedstocks primarily for export, while still relying on fossil fuels at home due to affordability, infrastructure gaps, or differing policy agendas.

From a system perspective, such strategies can obscure the full picture of global impacts, particularly when supply chains are extended into regions with weaker environmental constraints or less public accountability [29,30]. Recent studies using Integrated Assessment Models (IAMs) and global ESMs show that industrial decarbonization through international supply chains is technically feasible, but requires coordinated policies to ensure outcomes are equitable and transparent. For example, the modeling work of Groppi et al. shows that unilateral decarbonization (EU-only policies) can prompt relocation of emissions-intensive industries to other regions, raising global emissions, whereas coordinated action (e.g. EU + China) largely eliminates this leakage [32]. Similarly, Pappas et al., in a comparative emissions-intensity study, found that relocating heavy industry from China to countries such as India or Southeast Asia would likely increase global CO_2 emissions due to dirtier fuel mixes and lower efficiency in these regions [33]. These findings stress that without mechanisms to govern emissions in the production origin and destination, relocation risks becoming a convenient way to shift emissions outside national accounting boundaries. This dynamic also raises equity concerns where environmental and social burdens are shifted to lower-income regions, even as richer countries reap the climate gains. Addressing these concerns may require targeted financial and technological support for developing countries to enable industrial decarbonization, with mechanisms such as the Green Climate Fund (GCF) or Global Environment Facility (GEF), which could play a central role in facilitating this shift [34].

At the same time, Europe is increasingly implementing regulations to ensure that certain imported products adhere to stricter sustainability and emissions standards. For example, the Delegated Act on a methodology for renewable fuels of non-biological origin (RFNBO) sets clear criteria for classifying hydrogen, hydrogen-based fuels, and other energy carriers as renewable. Meanwhile, CBAM is to be applied to specific sectors such as steel, cement, and fertilizers. However, these regulations currently do not cover all products, leaving gaps in the oversight of emissions embedded in other imported goods [35]. Industry stakeholders, particularly those exporting to Europe, can also contribute by improving supply chain transparency and ensuring traceability of emissions and sustainability attributes across traded products, in accordance with evolving EU and Dutch verification rules.

5. Conclusions

This study employs the OPERA model to investigate the energy transition in the Dutch industrial sector. Our results show that with a fundamental change in the energy mix, the carbon-neutrality target for the overall energy system is reachable by 2050. We demonstrate that a shift from the use of fossil fuels towards that of green fuels—centered on hydrogen, bioenergy, and synthetic fuels—is not the single factor enabling this change. Rather, a wide deployment of CCUS, with a primary focus on biogenic CO_2, as well as a rapid technological change at both the process and energy levels across all different industries, is required. To analyze the decarbonization process for the industrial sector of the Netherlands, we introduce two scenarios: TRANSFORM and IMPORT.

The TRANSFORM scenario promotes innovation and self-sufficiency. It is centered around maintaining most of the entire industrial production process within the Netherlands. Maintaining the majority of current industrial activity within the country can stimulate the development of local economies and ensure that environmental regulations are well administered. However, it might also pose challenges such as high initial costs associated with capital investments, which can render Dutch industries globally uncompetitive.

The IMPORT scenario prioritizes cost efficiency and demonstrates that relocating energy-intensive production to other countries can accelerate the Dutch decarbonization goal. This scenario provides a more realistic path for achieving carbon neutrality within the defined time frame until 2050. It conforms to current market realities and seeks to optimize resources and costs by integrating into global supply chains. However, this scenario raises concerns about: 1) reliance on global sourcing networks, which are prone to geopolitical tensions and global market fluctuations; and 2) potential job losses. Furthermore, the IMPORT scenario depends on the assumption that strict criteria on imports are enforced to prevent outsourcing environmental harm. With regard to this, Dutch policymakers should advocate for an expansion of existing frameworks, such as CBAM, to include a wider set of traded goods, with attention to feedstocks relevant to industrial decarbonization. Additionally, targeted financial and technological support for exporting countries, many of which are developing countries, may be required to ensure that global supply chain decarbonization is both feasible and fair.

In our scenario set-up, we are able to simulate that the Dutch industrial sector achieves net-negative emissions by 2050 in both scenarios, while the broader Dutch energy system reaches carbon neutrality. This insight, which is one of the notable findings of our research, highlights the crucial role that the industrial sector can play in enabling the entire energy system to meet the carbon-neutrality target by 2050. To sustain and scale these outcomes, policy measures should focus on incentivizing technological innovation and providing subsidies for capital investments essential for infrastructure development for CCUS and transitioning to more sustainable practices.

In practical terms, the outcome of either scenario will largely depend on a range of factors including, the required infrastructure, availability of funds, global political landscape, and the potential macroeconomic impacts. The latter, in particular, requires further research that might include employing relevant models to examine key macroeconomic indicators such as unemployment, labor migration, and GDP. Also, other studies are required to identify the optimal global supply chains with an emphasis on economic and political stability dimensions. This includes evaluating where emissions are redistributed, how supply chains are governed, and who is affected; questions that require broader modeling frameworks such IAMs and interdisciplinary analysis.

The transition to a sustainable energy system is a complex challenge that necessitates concerted efforts in all countries and sectors around the world, in such a way that these efforts are orchestrated globally as much as possible. The pathways presented in this article for decarbonizing the Dutch industrial sector can serve as a case study for other countries with similar challenges.

CRediT authorship contribution statement

Ahmed M. Elberry: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Martin Scheepers:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Joost van Stralen:** Writing – review & editing, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Juan S. Giraldo:** Software, Methodology, Data curation. **Bob van der Zwaan:** Writing – review & editing, Writing – original draft, Validation, Supervision, Formal analysis.

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.

Acknowledgments

The authors thank the two anonymous reviewers for their extensive, detailed, and constructive feedback, thanks to which this paper has improved enormously.

Supplementary materials

Supplementary data associated with this article can be found, in the online version, at 10.1016/j.egycc.2025.100205.

Appendix A

Industrial sector in the Netherlands

The industrial sector of the Netherlands is segmented into five geographical clusters: “Rotterdam-Moerdijk,” “Smart Delta Resources” (Zeeland), “Chemelot” (South-Limburg), “Noord Nederland” (Eemshaven, Delfzijl, and Emmen), and “Noordzeekanaalgebied” (Amsterdam-IJmuiden), with a sixth cluster “Zesde cluster”, accounting for industries dispersed across the rest of the country [36].

Refineries and fuel production

The Netherlands is home to six refineries with a combined annual crude oil capacity of approximately 67 million tonnes [37], which accounts for about 10% of Europe’s production. Over recent years, their production has fluctuated between 55 and 62 million tonnes per year, with a significant portion dedicated to transport fuels (e.g. gasoline). However, the refining sector is undergoing a significant shift towards greener practices, with one of the six refineries ceasing operations and transitioning towards renewable energy production. This shift includes plans for biofuel production and the development of a green ammonia facility. Moreover, a leading global fossil fuel producer, with a refinery in the Netherlands, is set to reduce its conventional fuel production by 55% by 2030 and focus on biofuels and green hydrogen instead.

Another key driver for the transformation of the refining industry is policies and legislative changes in the energy and transport sectors. These aim to reduce the reliance on fossil fuels and increase the adoption of alternative/renewable energy sources throughout the period leading up to 2050. This can substantially influence both the production focus and the operational strategies of refineries. Shifts towards increased circularity or a rise in demand for renewable intermediates within the petrochemical industry can also have a large impact on the demand for conventional refinery products. This is particularly relevant since about one–fourth of refinery output – including vital feedstocks, such as naphtha, LPG, and aromatics – is dedicated to the petrochemical sector.

Decreased demand, alongside stringent policies and environmental regulations, has collectively led to the shutdown of approximately 13% of European refining capacity over the past decade [38]. The future sustainability and resilience of Dutch refineries, therefore, hinge on their ability to navigate away from fossil fuels towards the production of renewable and low–carbon fuels.

High–value chemicals industry

In the Netherlands, the organic chemicals sector runs six steam crackers that generate essential chemicals like ethylene, benzene, and propylene, commonly known as high–value chemicals (HVCs) [39]. These chemicals contribute to around 3% of the country's total export value. A major challenge for this industry is that approximately 70% of the required feedstock is sourced from naphtha. To mitigate emissions, the industry is exploring various options, including electrification, CCS, and alternative conversion processes (e.g., methanol-to-olefins, and pyrolysis oil-to-aromatics), along with shifting to bio-based feedstocks.

Iron and steel industry

The Netherlands possesses one iron and steel plant with a production capacity of 7.5 million tons of steel per year [40]. In 2023, its output was 4.7 million tonnes, placing the Netherlands among the countries with a relatively high steel production with a global rank of 33, according to the World Steel Association (WSA) [41]. A significant part of this output is exported. It accounted for well over 2% of the country's total exports in 2021 [42,43]. At this plant, raw iron is produced from ore using coal-fired blast furnaces, and steel is manufactured from pig iron and scrap in a gas-fired oxy–steel plant. These processes were responsible for 6.1 million tons of CO_2 emission in 2022 (~16% of the total industrial sector CO_2 emissions) [44]. While the Netherlands is exploring alternatives such as CCS to address this issue, there is a growing demand for "green steel", especially in the automotive industry [45]. This production of green steel is based on the reduction of iron ore with hydrogen, which is referred to as Hydrogen-based Direct Reduced Iron (H-DRI) [46]. However, this process demands substantial amounts of green hydrogen, which is not expected to be adequately available until 2040 [40].

The availability of renewable electricity for producing green hydrogen will be the key determinant in decarbonizing the iron and steel industry. Thanks to the large potential for offshore wind energy, the Dutch steel industry is expected to become more competitive in the future in comparison to the German and other producers. However, it may still lag behind countries such as Australia and Brazil, which have abundant renewable energy sources as well as iron ores [47].

Fertilizers industry

The fertilizer plants in the Netherlands produce different nitrogen-containing compounds such as urea, ammonia, and ammonium nitrate [48]. About 95% of the Dutch fertilizers are exported to Western Europe, the US, Canada, and Brazil. As part of the Nitrate Directive Action Programme, the Netherlands is aiming to reduce the use of fertilizers in agriculture. The country is exploring solutions to recover nitrogen from wastewater and through manure fermentation, which will eventually reduce the need for synthetic nitrogen production at fertilizer plants. In 2023, Europe fertilizers announced that their ambition is to achieve climate–neutral production by 2050 [49]. Decarbonizing this industry involves adopting alternative technologies that focus on green hydrogen production and CCS.

Data availability

The data can be found in the appendices.

References

[1] European Council, Fit for 55 - The EU's Plan for a Green Transition, 2025 n.d. https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55/ (accessed June 13, 2024)

[2] Centraal Bureau voor de Statistiek (CBS), StatLine - Energy Balance Sheet; Supply and Consumption, Sector, 2024.

[3] D. Dadi, V. Introna, M. Benedetti, Decarbonization of heat through low-temperature waste heat recovery: proposal of a tool for the preliminary evaluation of technologies in the industrial sector, Sustainability 14 (2022) 12626, https://doi.org/10.3390/su141912626.

[4] D. Pivetta, C. Dall'Armi, P. Sandrin, M. Bogar, R. Taccani, The role of hydrogen as enabler of industrial port area decarbonization, Renew. Sustain. Energy Rev. 189 (2024) 113912, https://doi.org/10.1016/j.rser.2023.113912.

[5] Z. Wang, Z. Huang, Y. Huang, C. Wittram, Y. Zhuang, S. Wang, et al., Synergy of carbon capture, waste heat recovery and hydrogen production for industrial decarbonisation, Energy Convers. Manag. 312 (2024) 118568, https://doi.org/10.1016/j.enconman.2024.118568.

[6] E. Kawai, A. Ozawa, BD. Leibowicz, Role of carbon capture and utilization (CCU) for decarbonization of industrial sector: a case study of Japan, Appl. Energy 328 (2022) 120183, https://doi.org/10.1016/j.apenergy.2022.120183.

[7] G. Bianchi, G.P. Panayiotou, L. Aresti, S.A. Kalogirou, G.A. Florides, K. Tsamos, et al., Estimating the waste heat recovery in the European Union Industry, Energ. Ecol. Env. 4 (2019) 211–221, https://doi.org/10.1007/s40974-019-00132-7.

[8] R. Castro-Amoedo, J. Granacher, M.A. Daher, F. Maréchal, On the role of system integration of carbon capture and mineralization in achieving net-negative emissions in industrial sectors, Energy Env. Sci. 16 (2023) 4356–4372, https://doi.org/10.1039/D3EE01803B.

[9] F. Creutzig, C. Breyer, J. Hilaire, J. Minx, G.P. Peters, R. Socolow, The mutual dependence of negative emission technologies and energy systems, Energy Env. Sci 12 (2019) 1805–1817, https://doi.org/10.1039/C8EE03682A.

[10] Y. Ju, M. Sugiyama, E. Kato, Y. Matsuo, K. Oshiro, D. Silva Herran, Industrial decarbonization under Japan's national mitigation scenarios: a multi-model analysis, Sustain. Sci. 16 (2021) 411–427, https://doi.org/10.1007/s11625-021-00905-2.

[11] Netbeheer Netherlands, Rapport II3050 Scenario's, 2021.

[12] M. Scheepers, S.G. Palacios, E. Jegu, L.P. Nogueira, L. Rutten, J. van Stralen, et al., Towards a climate-neutral energy system in The Netherlands, Renew. Sustain. Energy Rev. 158 (2022) 112097, https://doi.org/10.1016/j.rser.2022.112097.

[13] S.D. Manuel, T. Floris, W. Kira, S. Jos, F. André, High technical and temporal resolution integrated energy system modelling of industrial decarbonisation, Adv. Appl. Energy 7 (2022) 100105, https://doi.org/10.1016/j.adapen.2022.100105.

[14] F. Taminiau, B. van der Zwaan, The Physical Potential for Dutch Offshore Wind Energy, 2022, https://doi.org/10.2139/ssrn.4109358.

[15] J. Matthijsen, A. Chranioti, S. Heshusius, S. Scholte, P. van der Kooij, Monitor RES 2023, Een voortgangsanalyse van de Regionale Energie Strategieën, Nederlands, 2023.

[16] J.N.P. van Stralen, F. Dalla Longa, B.W. Daniëls, K.E.L. Smekens, B. van der Zwaan, OPERA: a new high-resolution energy system model for sector integration research, Env. Model Assess. 26 (2021) 873–889, https://doi.org/10.1007/s10666-020-09741-7.

[17] B. Koirala, S. Hers, G. Morales-España, Ö Özdemir, J. Sijm, M. Weeda, Integrated electricity, hydrogen and methane system modelling framework: application to the Dutch infrastructure outlook 2050, Appl. Energy 289 (2021) 116713, https://doi.org/10.1016/j.apenergy.2021.116713.

[18] ENTSO-E, ENTSOG. TYNDP, 2020.

[19] PBL Netherlands Environmental Assessment Agency, Klimaat- en energieverkenning 2022, Planbureau voor de Leefomgeving, 2022.

[20] European Commission, Recommended parameters for reporting on GHG projections in 2023, 2023.

[21] ADVANCEFUEL, ADVANCEFUEL - Home. http://www.advancefuel.eu/, 2020 (accessed February 20, 2024).

[22] M. Scheepers, J. Stralen, A.M. Elberry, J.G. Chavarriaga, A. Uslu, C.M Oliveira, S. Dos, Towards a sustainable energy system for The Netherlands in 2050, Scenar. Update scenar. Var. Ind. (2024).

[23] The Netherlands Enterprise Agency (RVO), Stimulation of Sustainable Energy Production and Climate Transition (SDE++), RVONl, 2023. https://english.rvo.nl/en/subsidies-financiering/sde.

[24] S. Lensink, K. Schoots, Eindadvies Basisbedragen SDE++ 2023, Planbureau voor de Leefomgeving, The Hague, NL, 2023.

[25] The Netherlands Enterprise Agency, Nationaal Plan Energiesysteem (NPE), 2023.

[26] T. Hajonides van der Meulen, M. Sariç, I. Tyraskis, T. van Leeuwen, P. Verstraten, D7B.3 Cost analysis and comparison of different hydrogen carrier import chains and expected cost development, Zenodo (2022), https://doi.org/10.5281/zenodo.6514173.

[27] S. Afzal, A. Singh, S.R. Nicholson, T. Uekert, J.S. DesVeaux, E.C.D. Tan, et al., Techno-economic analysis and life cycle assessment of mixed plastic waste gasification for production of methanol and hydrogen, Green Chem. 25 (2023) 5068–5085, https://doi.org/10.1039/D3GC00679D.

[28] IRENA, World Energy Transitions Outlook: 1.5°C Pathway, International Renewable Energy Agency, Abu Dhabi, 2021.

[29] S. Handoyo, Public governance and national environmental performance nexus: Evidence from cross-country studies, Heliyon 10 (2024) e40637, https://doi.org/10.1016/j.heliyon.2024.e40637.

[30] M. Jakob, H. Ward, JC. Steckel, Sharing responsibility for trade-related emissions based on economic benefits, Glob. Environ. Change 66 (2021) 102207, https://doi.org/10.1016/j.gloenvcha.2020.102207.
[31] IEA, The Future of Hydrogen Seizing Today's Opportunities, 2019. Japan.
[32] D. Groppi, L.M. Pastore, B. Nastasi, M.G. Prina, D. Astiaso Garcia, L. de Santoli, Energy modelling challenges for the full decarbonisation of hard-to-abate sectors, Renew. Sustain. Energy Rev. 209 (2025) 115103, https://doi.org/10.1016/j.rser.2024.115103.
[33] D. Pappas, K.J. Chalvatzis, D. Guan, X. Li, Industrial relocation and CO2 emission intensity: focus on the potential cross-country shift from China to India and SE Asia, in: 9th International Conference on Applied Energy, ICAE, 2017, pp. 2898–2904, https://doi.org/10.1016/j.egypro.2017.12.414. Proceedings of the 9th International Conference on Applied Energy, ICAE 2017 2017.
[34] I. Ari, M. Isik, Assessing the performance of the developing countries for the utilization of the green climate fund, Front. Clim. 4 (2022), https://doi.org/10.3389/fclim.2022.813406.
[35] T. Beaufils, H. Ward, M. Jakob, L. Wenz, Assessing different European carbon border adjustment mechanism implementations and their impact on trade partners, Commun Earth Env. 4 (2023) 131, https://doi.org/10.1038/s43247-023-00788-4.
[36] OECD, Dutch Industry's Structure and Emissions, OECD, Paris, 2021, https://doi.org/10.1787/390dd28d-en.
[37] C. Oliveira, K. Schure, Decarbonisation Options for the Dutch Refinery Sector, PBL Netherlands Environmental Assessment Agency, 2020.
[38] A. López, A. Ure, A. Wolf, M. Galante, T. Scarbrough, S. Fischer, et al., What Future Role for Conventional Refineries in the Decarbonisation Transition? RICARDO, The UK, 2022.
[39] IEA, Tracking Clean Energy Progress, 2023. Paris.
[40] TATA Steel, IJmuiden. Tata Steel in Europe, 2025. https://www.tatasteeleurope.com/construction/sustainability/performance-at-our-sites/ijmuiden (accessed February 22, 2024).
[41] World Steel Association (WSA), December 2023 Crude Steel Production and 2023 Global Crude Steel Production Totals, WorldsteelOrg, 2024. https://worldsteel.org/media-centre/press-releases/2024/december-2023-crude-steel-production-and-2023-global-totals/ (accessed February 22, 2024).
[42] Centraal Bureau voor de Statistiek (CBS), StatLine - International trade. Dutch Export Specialisation With Respect to the EU, 2021.
[43] International Trade Administration, Steel Exports Report: Netherlands. The United States: The United States Department of Commerce, 2019.
[44] Centraal Bureau voor de Statistiek (CBS), StatLine - Emissions to Air by the Dutch Economy; National Accounts, 2024.
[45] FAIRFIELD, Green Steel Market, 2023. The United Kingdom.
[46] R.R.. Wang, Y.Q. Zhao, A. Babich, D. Senk, X.Y. Fan, Hydrogen direct reduction (H-DR) in steel industry—an overview of challenges and opportunities, J. Clean Prod. 329 (2021) 129797, https://doi.org/10.1016/j.jclepro.2021.129797.
[47] Guidehouse, Analyse Voor Programma Verduurzaming Industrie - Rapport - Rijksoverheid.nl, Ministerie van Algemene Zaken, 2023.
[48] M. Batool, W. Wetzels, Decarbonisation options for the Dutch fertiliser industry, PBL Neth. Environ. Assess. Agency (2019).
[49] Guidehouse, Roadmap for the European Fertilizer Industry, Fertil. Eur. (2023).