3. Zero-emission scenario for Dutch industry

This chapter describes and discusses a zero-emission 2050 scenario for the Dutch industry. It is based on a detailed account of the technologies currently used in the largest firms and emitting sectors in the Netherlands, and on the technologically feasible decarbonisation options for each of them. The robustness of the results is assessed through a comparison with other available decarbonisation scenarios.

Note: the zero-emission 2050 scenario for the Dutch industry described in this chapter was originally designed by Berenschot (2020[1]).

3.1. Scope and methodology for the zero-emission 2050 scenario

3.1.1. Scope of the emissions

All Scope 1 (direct emissions) and Scope 2 (emissions from electricity use) emissions are included in the modelling. Scope 3 emissions are not systematically included as the identification of these emissions would be challenging and result in double counting with the emission reduction in other sectors that would be difficult to identify. Nevertheless, the scope of this chapter includes emissions linked to energy carriers that are not used as a source of energy, but as a non-energetic feedstock. Three prominent examples are crude oil in refineries, natural gas in ammonia production and coal use in the steel making process.

3.1.2. Methodology used for determining the zero-emission scenarios

For all four sectors, the zero-emission scenarios are the result of a desk study, which comprised a review of the technologies and their future prospects along with a modelling exercise. In a second step, this scenario was discussed with experts and industry representatives through four sectoral meetings, and amended accordingly.

In most industries, there are, in fact, different options to reach zero emissions. At the 2050 horizon, the economic and technological uncertainty is such that these scenarios can only be considered as plausible and dependent on certain assumptions and choices, regarding technologies (e.g. green hydrogen production), policies (e.g. development of CO_2 pipelines to enable carbon transport) and the economic environment (e.g. ability of the Netherlands to maintain a comparative advantage in heavy industries).

The price evolution of different technologies and energy carriers, including due to public policies, is one of the main sources of uncertainty surrounding the scenario. The scenario is not based on cost-optimisation and does not rely on a price trajectory for the energy carriers and corresponding technologies. It rather rests on an analysis of the feasibility of the different options based on the available knowledge[1], the current fuel prices and some expected developments (such as the construction of hydrogen or CO_2 infrastructure for the main clusters). The report includes an analysis of the impact of the cost of energy carriers on the Dutch economy.

Rather than using available global scenarios, a particular effort has been made to design these routes according to the specificities of the Dutch industry and its clusters. These have been validated with industry representatives and experts. This chapter also comprises a comparison of this scenario with other available scenarios.

Scenarios were modelled using the Energy Transition Model (ETM) of Quintel Intelligence. This model simulates the Dutch energy system and allows users to adjust parameters such as demand developments, efficiency improvements and new technologies. The ETM does not provide cost-optimal dynamic paths to carbon neutrality but quantifies the impact of external technological and economic assumptions on all energy carriers from supply to conversion, final demand and CO_2 emissions. The ETM is an open source model and is publicly available at www.energytransitionmodel.com.

3.2. A zero-emission chemical sector

The chemical sector in the Netherlands consists of 445 companies, representing 45 000 employees and 1.7% of gross domestic product (GDP)[2] in 2018. It is organised around five main clusters and three main economic activities: NACE 2014 - manufacture of organic basic chemicals (including petrochemicals), NACE 2015 - manufacture of fertilisers and nitrogen compounds (including ammonia and its derivatives) and NACE 2013 - manufacture of other non-organic chemicals.

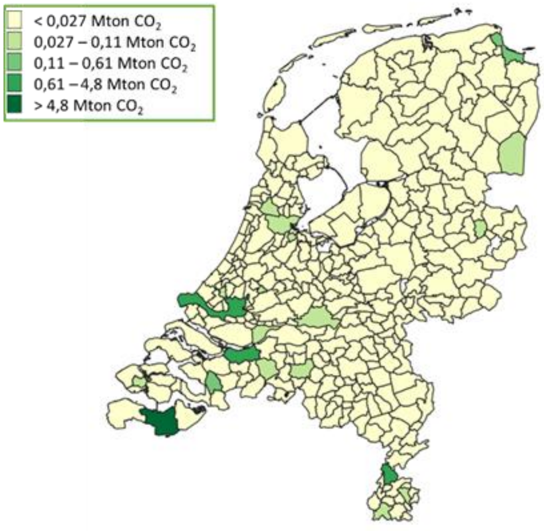
The chemical sector is responsible for 44% of Scope 1 industrial emissions in the Netherlands and is the top emitter in the industry. The chemical sector is also the main user of electricity, and is responsible for a sizeable part of Scope 2 emissions. Finally, the widespread use of oil and natural gas as a non-energetic feedstock in the petrochemical industry is also a major source of indirect emissions.

In this section[3], hydrogen production is not considered to be part of the chemical sector (Box 2.1 gives further details on the different ways to produce hydrogen). In theory, hydrogen production is included in the chemical sector (NACE 2011 – Manufacture of industrial gases). Since the production of hydrogen is for the time being limited and hydrogen is considered as an energy carrier, rather than as a chemical product, the production of hydrogen is left out of the scope of this chapter. However, it is briefly discussed in the final section of this chapter and the challenges of a carbon-neutral hydrogen production is discussed in Chapter 7.

3.2.1. Description of the sector and the main processes

The majority of the Dutch chemical industry is based around the **five industry clusters**: Rotterdam, Chemelot, Smart Delta Resources, Noord-Nederland (Delfzijl and Emmen)[4], and Amsterdam/ Noordzeekanaal (Box 3.1, Box 2.2 and Figure 3.1). These clusters are integrated parks with pipeline grids for a whole range of chemical substances including acetic acid, acetylene, chlorine, ethylene, hydrogen chloride, methanol, naphtha petroleum, natural gas, nitrogen, oxygen, propylene and steam. The clusters are well connected with multiple transport options and pipelines for chemical products and industrial gases between them.

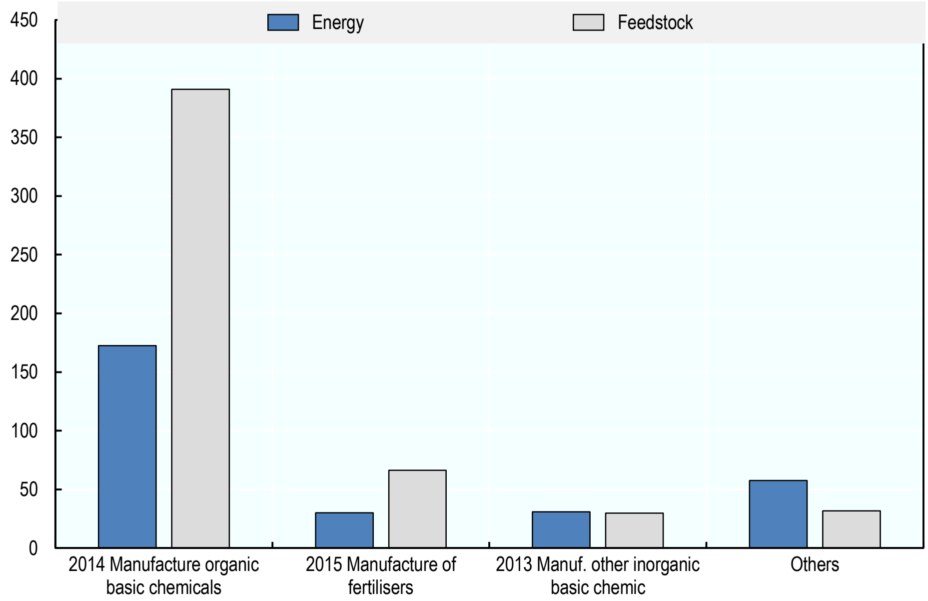
Figure 3.1. CO_2 emissions of the Dutch chemical industry by community



Source: www.emmissieregistratie.nl, Berenschot calculations.

Petrochemicals make up the largest part of the chemical industry with about 60% of the energy use and 75% of feedstock within the chemical industry (Figure 3.2). Ammonia and derivatives represent 10% of the energy use of the chemical industry and use about 13% of feedstock. Non-organic base chemicals take up about 10% of the total energy demand of the chemical industry, but use less feedstock compared to the other product groups, about 6% of the total. Industrial gases, rubber and plastics, colouring and paints, and other chemicals make up the rest of the energy usage (20%) and feedstock usage (6%) within the chemical industry.

Figure 3.2. Consumption of energy carriers, as energy and feedstock, in the chemical sector, 2015 (PJ)



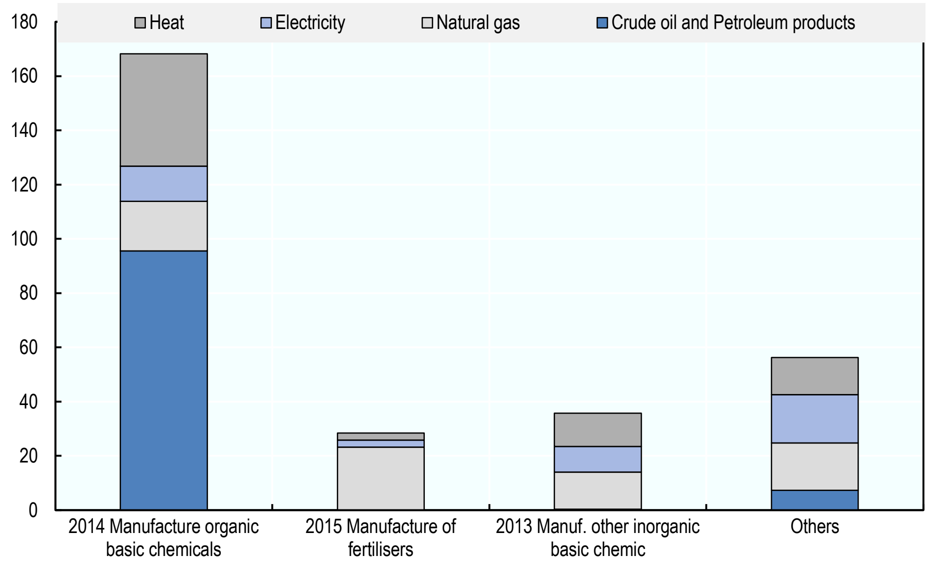
Source: CBS, Energy balance sheets by sector.

The **petrochemical industry** uses naphtha, benzene, diesel and other products from refineries as inputs. The chemical companies then produce, for example, propylene and ethylene by cracking naphtha. Six naphtha crackers produce most of the petrochemical building blocks (e.g. ethylene, propylene and BTX) and intermediates. These intermediates are used by many economic sectors, including downstream firms in other chemical industries. Many products, ranging from construction materials to paints and from car parts to mobile phone components, rely on these intermediates. This industry mainly rests on petroleum products and heat as energy sources Figure 3.3). Even if not linked to Scope 1 or 2 emissions, this sector relies heavily on petroleum products as a non-energetic feedstock (Figure 3.4), which are cracked to produce smaller molecules. In the Netherlands, the petrochemical industry is based in Chemelot, Smart Delta Resources (Zeeland) and Rotterdam-Moerdijk.

The **fertilisers and nitrogen compounds industry** produces urea, nitric acid, melamine, acrylonitrile and caprolactam. Most of these nitrogen compounds require the production of ammonia via Haber-Bosch synthesis, which consists of combining hydrogen and nitrogen. The hydrogen (in this part of the industry) is obtained through steam-methane reforming (combining methane/natural gas with steam).[5] Therefore, the main source of energy and the main feedstock in this industry is natural gas (Figure 3.3 and Figure 3.4). In the Netherlands, the fertiliser industry is located in Chemelot and Smart Delta Resources (Zeeland).

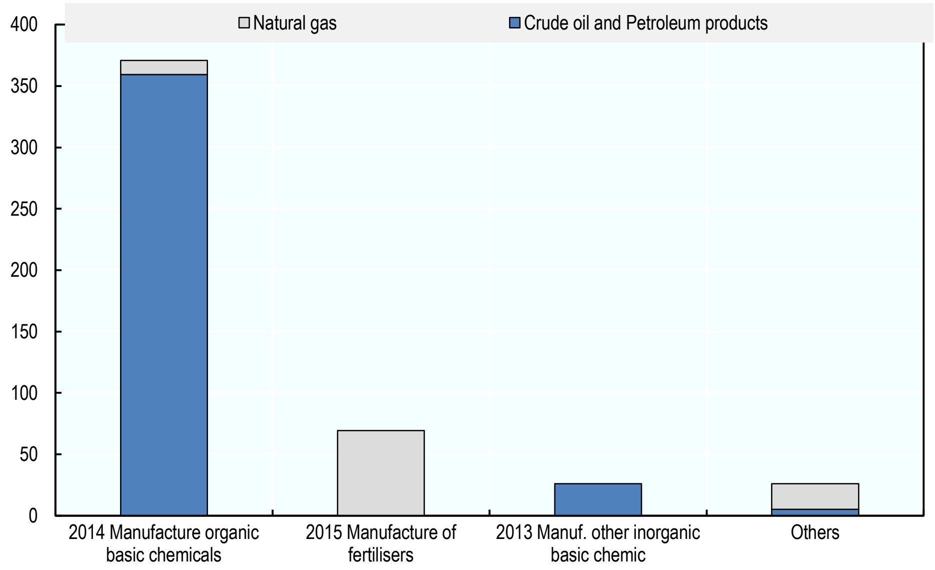
The Dutch chemical sector also produces non-organic base chemicals such as chlorine, caustic soda and vinyl chloride. These products are made with the help of an electrolysis process. In this part of the industry, the main energy carrier is natural gas, along with heat and electricity. Petroleum products are the main feedstock.

Figure 3.3. Consumption of energy carriers as energy source, by type and subsector, 2015 (PJ)



Source: CBS, Energy balance sheets by sector.

Figure 3.4. Consumption of energy carriers as feedstock, by type and subsector, 2015 (PJ)



Source: CBS, Energy balance sheets by sector.

3.2.1. Main technologies to be implemented for the reduction of emissions

The sectoral professional association of the Dutch chemical industry published a roadmap towards emission reduction. It identifies six solutions that can be used in combination (Figure 3.5): closure of the material chain, alternative feedstock, energy efficiency, renewable energy, carbon capture and storage (CCS), and sustainable products. It is likely that the sector will decarbonise by deploying these technologies sequentially. For example, CCS could be a first option to reduce emissions in the near-term for certain chemicals (e.g. CCS is relatively affordable in ammonia production because of the concentration of the CO_2 stream), whilst in the intermediate future the electrification of processes may become viable (e.g. electrification of crackers), and in the long-term be followed by a shift towards circular feedstock.

Renewable energy and **energy efficiency** are promising routes for the three main products of the chemical industry. Research into electric crackers is being undertaken and could reduce direct CO_2-emissions. Electric boilers, heat pumps and mechanical vapour recompression can contribute to the electrification of the heat production within the industry. Using heat pumps and mechanical vapour recompression would also lead to energy savings due to high coefficients of performance.[6] Once the electricity from the grid is also carbon free, electrification will lead to further emission reductions. However, in the short term, depending on the electricity source, electrification might also lead to higher emissions.

Geothermal heat could be used to supply sustainable heat to the chemical industry, but the applicability is low. Not all locations are suitable, especially for high-temperature geothermal heat in the Netherlands. According to Platform Geothermie, DAGO, Warmtenetwek and EBN (2018[2]), only 25 PJ is projected to be used by the manufacturing industry and mostly by the food processing industry and the paper industry.

Box 3.1. The five clusters and the chemical sector

Amsterdam has an upcoming chemical industrial area. Currently, only chemical companies with a relatively limited energy consumption are located here. Potential connections with Tata Steel in IJmuiden to exchange hydrogen, oxygen and CO_2 are being investigated by Dow and by Nouryon. The cluster is connected to two universities: Vrije Universiteit (VU) Amsterdam and the University of Amsterdam (UvA). The Amsterdam cluster is also strongly connected to institutes of the Science Park, for example the Van't Hoff Institute for Molecular Sciences.

Chemelot, located in the South of Limburg, produces petrochemicals and nitrogen compounds. Historically built as a one company site, it is characterised by a strongly integrated energy infrastructure. The site now houses multinational companies like SABIC (petroleum chemicals and plastics) and OCI Nitrogen (ammonia, fertilisers and derivatives). The cluster also comprises the Brightlands Chemelot Campus and is strongly connected to the University of Maastricht. Chemelot has a river harbour, railway, pipeline and highway connections and an airport in close vicinity.

Delfzijl is characterised by its availability of salt and natural gas, thanks to a sea harbour, railway, pipeline and highway connections, which provide multiple transport opportunities. The focus of this chemical cluster is on chlorine (non-organic base chemicals) and methanol (organic base chemicals) and their derivatives. Emmen is a relatively small chemical cluster with a strong focus on high-tech development and the production of polymers, composites, fibres and yarns. It has the ambition of being a knowledge hub for innovation and applied research into green fibre chemistry.

Rotterdam is the largest chemical cluster in the Netherlands with its focus on base chemicals and petrochemicals. It houses 45 chemical companies and 5 oil refineries. The port of Rotterdam aims to integrate its complex with those of Antwerp (Belgium), Moerdijk (also in the Rotterdam Cluster), Terneuzen and Vlissingen (both in Zeeland/Smart Delta Resources) to create one large chemical cluster. The pipeline of Air Liquide is an example of integration of these clusters. The combination of the Rotterdam Harbour, a rail connection to Germany and pipelines to transport raw materials and products provides outstanding transport opportunities for the Rotterdam cluster.

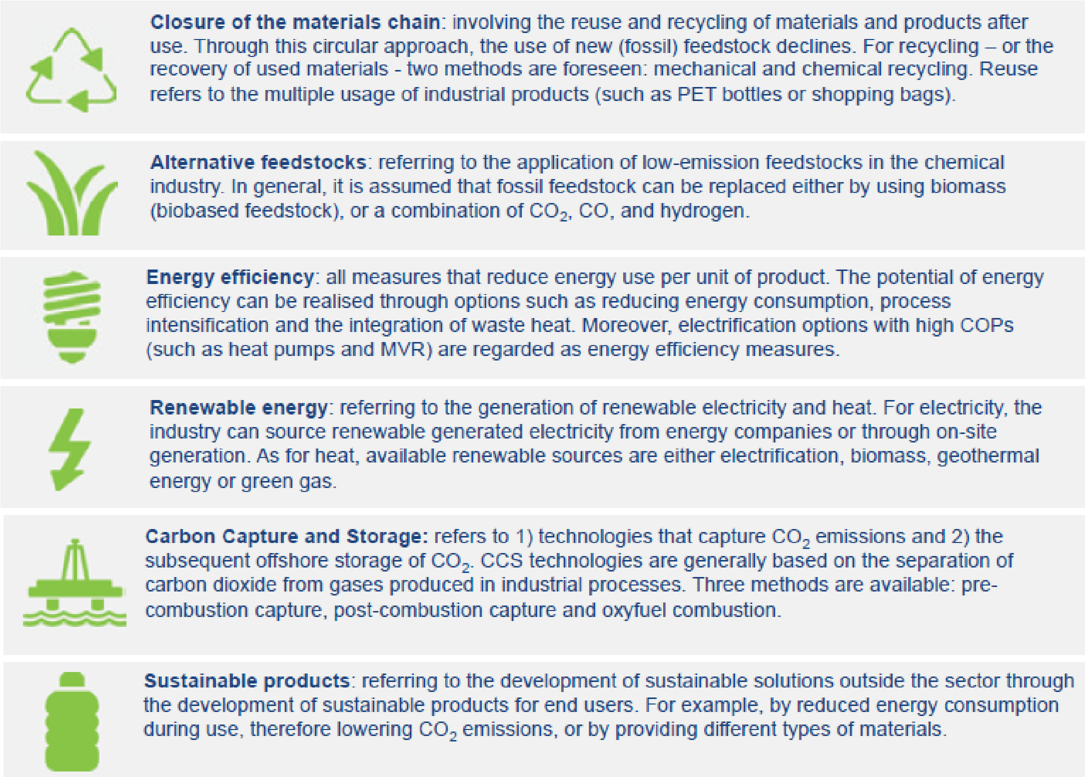
The Zeeland (Smart Delta Resources) chemical cluster is connected to the Terneuzen mainport, which enables deep sea transport. It houses large chemical companies like Dow, Yara, and Sabic. The focus of the cluster is on petrochemicals and ammonia and derivatives. In this cluster, there is a strong aim to use each other's (waste) products, targeting industrial symbiosis. The cluster is tightly connected to the Belgian industry in East-Flanders.

For some processes that require high temperatures, electrification may be difficult or costly. In that case, the industry is expected to rely on alternative and sustainable fuels such as **hydrogen, pyrolysis oil or biomass**.

Finally, **CCS** will be required to capture CO_2 emitted by the remaining fossil fuel combustion and the industrial processes themselves.

Regarding feedstock, a combination of circular, bio-based and synthetic feedstock should replace fossil feedstock. Nowadays, the chemical industry uses mainly virgin fossil feedstock to produce chemical products. Once these products are at their end-of-life, they are typically burned in waste incinerators and emit CO_2. The only way to avoid these Scope 3 emissions (from the point of view of the chemical industry) is to capture carbon in waste incinerators or to compensate for these emissions elsewhere.

Figure 3.5. Main technological options for a carbon-neutral chemical sector



Closure of the materials chain: involving the reuse and recycling of materials and products after use. Through this circular approach, the use of new (fossil) feedstock declines. For recycling – or the recovery of used materials - two methods are foreseen: mechanical and chemical recycling. Reuse refers to the multiple usage of industrial products (such as PET bottles or shopping bags).

Alternative feedstocks: referring to the application of low-emission feedstocks in the chemical industry. In general, it is assumed that fossil feedstock can be replaced either by using biomass (biobased feedstock), or a combination of CO_2, CO, and hydrogen.

Energy efficiency: all measures that reduce energy use per unit of product. The potential of energy efficiency can be realised through options such as reducing energy consumption, process intensification and the integration of waste heat. Moreover, electrification options with high COPs (such as heat pumps and MVR) are regarded as energy efficiency measures.

Renewable energy: referring to the generation of renewable electricity and heat. For electricity, the industry can source renewable generated electricity from energy companies or through on-site generation. As for heat, available renewable sources are either electrification, biomass, geothermal energy or green gas.

Carbon Capture and Storage: refers to 1) technologies that capture CO_2 emissions and 2) the subsequent offshore storage of CO_2. CCS technologies are generally based on the separation of carbon dioxide from gases produced in industrial processes. Three methods are available: pre-combustion capture, post-combustion capture and oxyfuel combustion.

Sustainable products: referring to the development of sustainable solutions outside the sector through the development of sustainable products for end users. For example, by reduced energy consumption during use, therefore lowering CO_2 emissions, or by providing different types of materials.

Source: Ecofys and Berenschot (2018[3]).

Mechanical or chemical recycling, in contrast, could transform these products into new feedstock, thereby **closing the materials chain**. Mechanical recycling (e.g. of plastics) does not involve any chemical reaction. In chemical recycling, the molecules are usually broken down into smaller components that can be used as feedstock. Mechanical recycling could be performed on 40-50% of the end-of-life streams. Chemical recycling could recycle potentially 30% of the streams, through the production of pyrolysis oil, which can then be used as a feedstock for crackers in the petrochemical industry.

However, this will not suffice to decarbonise the feedstock of the chemical sector. First, recycling all materials is unfeasible. Second, recycling itself is not a 100% efficient process. Third, virgin materials will be needed to meet a growing future demand. Still, a well-functioning recycling industry will be necessary to decarbonise chemical products.

In order to become to a fully carbon-neutral system, the use of alternative sustainable feedstock is necessary: bio-based feedstock and synthetic feedstock.

Bio-based feedstock can be carbon-neutral if it is harvested in a sustainable way.[7] The carbon released when burning bio-based chemical products at the end of their life corresponds to carbon that was captured in the air by the biomass. This cycle is thus neutral on the amount of carbon in the atmosphere.

Synthetic organic feedstock is produced from two types of molecules:

- Hydrogen required for ammonia production or the petrochemical industry can be blue (methane – possibly green methane – combined with CCS) or green (electrolysis from water). As reaching a 100% capture rate is technologically difficult and potentially very costly, blue hydrogen entails residual CO_2 emissions, which need to be compensated elsewhere to reach carbon-neutrality. Green hydrogen as a by-product from cracking of bio-based feedstock is a route that could be interesting for some ammonia plants that already benefit from integration with the petrochemical industry (e.g. in Smart Delta Resources). For ammonia production at sites that receive renewable electricity, green hydrogen from electrolysis might be more logical, electricity is then also required to produce the nitrogen with air separation units and to supply the compressors for the Haber-Bosch process.
- Synthetic carbon monoxide or carbon dioxide is also fully carbon neutral as long as the carbon comes from a sustainable source (e.g. waste).

Applying these technologies in the subsectors

Regarding the **petrochemical industry**, decarbonisation could occur, in particular, from electrification, and also from the use of hydrogen as an energy source, sustainable heat, CCS, closure of the material chain and the use of alternative feedstock. Electrified crackers are under development and together with heat pumps, mechanical vapour recompression (MVR) and electric boilers will lead to large electrification within the chemical industry. For some chemical processes requiring high temperatures, hydrogen, pyrolysis oil or biomass will provide the solution to supply energy to the processes. CCS would require the development of transport and storage capacities, such as the Porthos project, which would connect the Rotterdam cluster and depleted oil fields of the North Sea via a pipeline (for storage).The relative weight of naphtha-based routes is an asset to the sector in case a share of feedstock is replaced by biobased materials (e.g. bioethanol) because of the relative flexibility of crackers. An alternative route is based on the methanol-to-olefins process. This option would ensure the reduction of Scope 3 emissions, but at the expense of a higher energy consumption, since the methanol production is energy-intensive. It is assumed that synthetic methanol will be produced out of hydrogen in 2050, combined with sustainable sources of CO_2 (Wong and van Dril, 2020[4]) or obtained through the recycling of polymers (gasification process).[8] The 2050 scenario therefore assumes that the hydrogen needed for methanol can become green hydrogen produced from electrolysis. This could either be made on site or bought from suppliers from other origins:

- The plausible pathway for **fertilisers and nitrogen compounds** is based on hydrogen, CCS to capture the process emissions and renewable electricity (Batool and Wetzels, 2019[5]).
- Hydrogen could both be produced on site as well as supplied via a pipeline. If produced onsite, green hydrogen, although more costly to produce, may be chosen for landlocked-sites that cannot easily ship the CO_2 captured for the production of blue hydrogen. This is especially the case for Chemelot (about a third of the ammonia production), where the green hydrogen route via green methane from the crackers with sustainable feedstock is preferred. The site in Zeeland is capable of producing green hydrogen on site from electrolysis, because of the close proximity to offshore wind power.
- Renewable electricity is needed to supply the nitrogen through air separation units and to drive the compressors for the Haber-Bosch process.

For **other non-organic base chemicals**, the route to zero-emission focuses on electrification and, to a lesser extent on the use of biomass (Scherpbier and Eerens, 2020[6]).

3.2.2. Sectoral assumptions

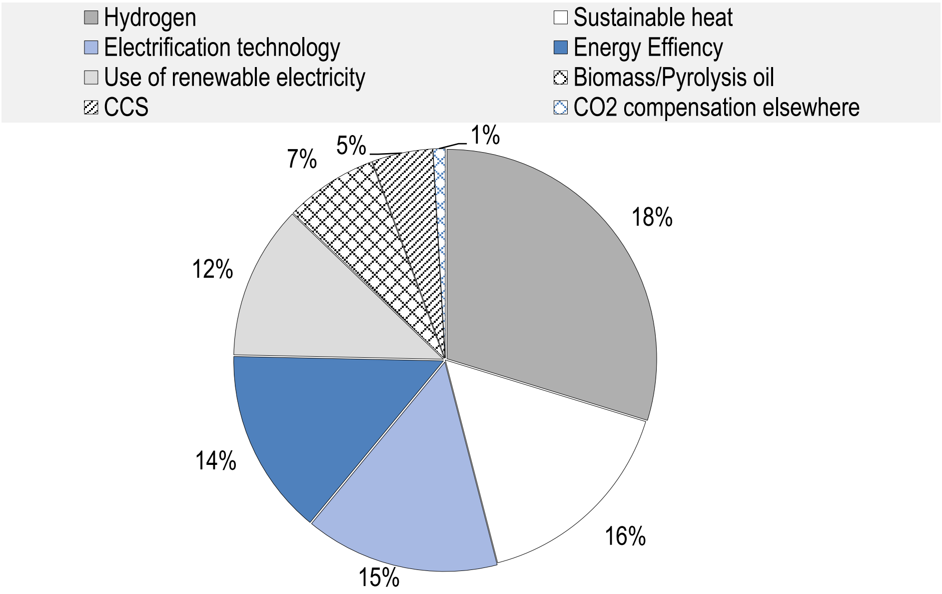
For the chemical sector, a 1% annual growth from 2020 to 2050 is assumed, except for fertilisers and nitrogen compounds, for which a 0.5% annual growth is assumed, due to the implementation of a more circular agriculture and a smaller increase of fertiliser use.

The energy efficiency of the sector will increase over the same period by 0.5% annually, which is half of the historical trend. It is in the lower range of estimates available in other analyses such as Wong and van Dril (2020[4]). However, the switch to new technologies could lead to higher energy usage. For the fertilisers and nitrogen compounds industry, the energy efficiency improvements follow the historical trend of 1% growth per year, since the processes will remain similar.

3.2.3. Zero emission scenario: Impact on energy carriers and emissions

Scope 1 and 2 business as usual (BAU) emissions from the Dutch chemical sector would reach 32 $MtCO_2$, which can be reduced to net-zero by 2050 using the scenario above. Figure 3.6 shows the contributions of each technology to the reduction of emissions. The uptake of hydrogen as an energy source will contribute to around 30% of emission reductions. Electrification and the transition to renewable electricity will contribute to 27% of emission reductions. The rest of emission reductions come from the shift to sustainable heat (16%), energy efficiency (14%) and the use of biomass (7%). The latter will not only reduce Scope 3 emissions, but also reduce direct emissions when used as a source of energy in crackers.

Figure 3.6. Emission reductions in the Dutch chemical sector by technology in 2050 compared to BAU under zero-emissions scenario

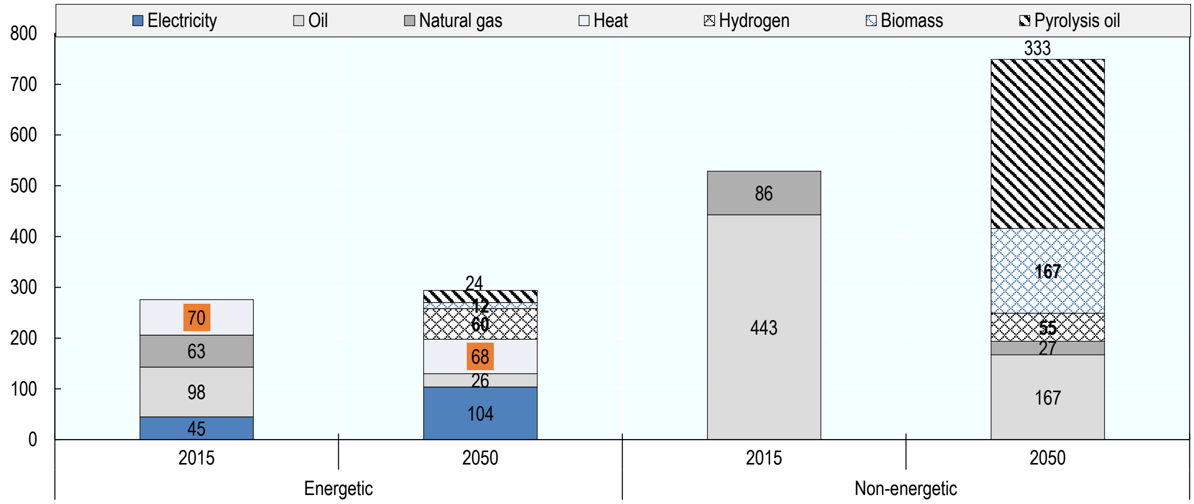


Note: The contribution of "use of renewable electricity" corresponds to the abatement of the 2015 Scope 2 emissions, which would be overturned by completely shifting to renewable electricity sources by 2050. The contribution of "electrification technology" corresponds to additional electricity needed to reach the carbon neutrality objective in 2050, assuming that this additional electricity is also renewable and carbon-neutral.
Source: Berenschot.

Regarding the energy carriers used as an **energy source** (Figure 3.7), hydrogen would provide 60 PJ by 2050. Due to electrification, electricity demand rises from 45 PJ in 2015 to 104 PJ in 2050. Finally, 36 PJ of pyrolysis oil and biomass are used in 2050. In parallel, the use of fossil fuels (petroleum products and natural gas) is reduced to 26 PJ of oil, compensated with CCS. It would correspond to crackers operated in clusters with an easy access to CO_2 transport and storage under the North Sea.

Regarding the energy carriers used as **non-energetic feedstock** (mainly in the petrochemical sector), a significant part of the petroleum products and natural gas are replaced with hydrogen, biomass and pyrolysis oil. To ensure sustainability, the 27 PJ of methane required in 2050 can be produced through green methane. In this scenario, however, 167 PJ of oil would be used as non-energetic feedstock by the chemical sector. The strong interactions between the petrochemical sector and the refineries requires a joint effort, as refineries should produce the decarbonised feedstock that is necessary for the petrochemical sector. Some of the main petrochemical plants are indeed owned by firms operating in the refinery sector, and highly integrated with the refineries (Shell Moerdijk, Shell Pernis and ExxonMobil Rotterdam plants).[9]

Figure 3.7. Energy carriers for Dutch chemical sector (energetic and non-energetic) in 2015 and 2050 (PJ)



Source: Berenschot.

3.3. A zero-emission refineries sector

The refineries sector in the Netherlands consists of 20 companies, representing 5 000 employees[10] and 0.2% of GDP[11] in 2018. The refineries sector corresponds to the ISIC sector 192 “Manufacture of refined petroleum products”.

The Dutch refineries sector is responsible for 21% of Scope 1 industrial emissions, and is the second main emitter in the industry. The sector heavily relies on crude oil as an energy source, but firstly, as a feedstock for the production of the petroleum products.

3.3.1. Description of the sector and the main processes

The six main refineries are located near the North Sea. Five of them are located in the port of Rotterdam: BP, Gunvor Petroleum Rotterdam, Vitol (Koch) and ExxonMobil. The five refineries are affiliated with the organisation “Port of Rotterdam”, which is the authority that manages, operates and develops the port and industrial area of Rotterdam and is responsible for all shipping activities. Zeeland Refinery is located in Zeeland and is part of the Smart Delta Resources cluster (Figure 3.8). The sea ports lead to a high accessibility for supply of crude oil. Therefore, all refineries have excellent sea transport facilities.

When crude oil is refined into smaller products, it is sold and transported to other sectors, and notably to the chemical industry. Petroleum products are transported to the hinterland via pipelines, rail and inland shipping. In total, the Dutch refineries have access to an extensive pipeline network of 1 500 kilometres. These pipelines connect Rotterdam with different chemical clusters in the Netherlands, Germany and Belgium. This infrastructure for intermediates offers a safe, efficient and environmentally-friendly transport solution. Most pipelines are ‘dedicated connections’ that transport one particular product to one particular company. However, some pipelines are used by multiple companies.

Figure 3.8. CO_2 emissions of the Dutch refineries by community

Source: www.emmissieregistratie.nl, Berenschot calculations.

In the refining process, useable oil products are produced from crude oil. This consists of four main processes: distillation, cracking in order to process the intermediates into lighter products, increasing the quality of the intermediates, and blending.

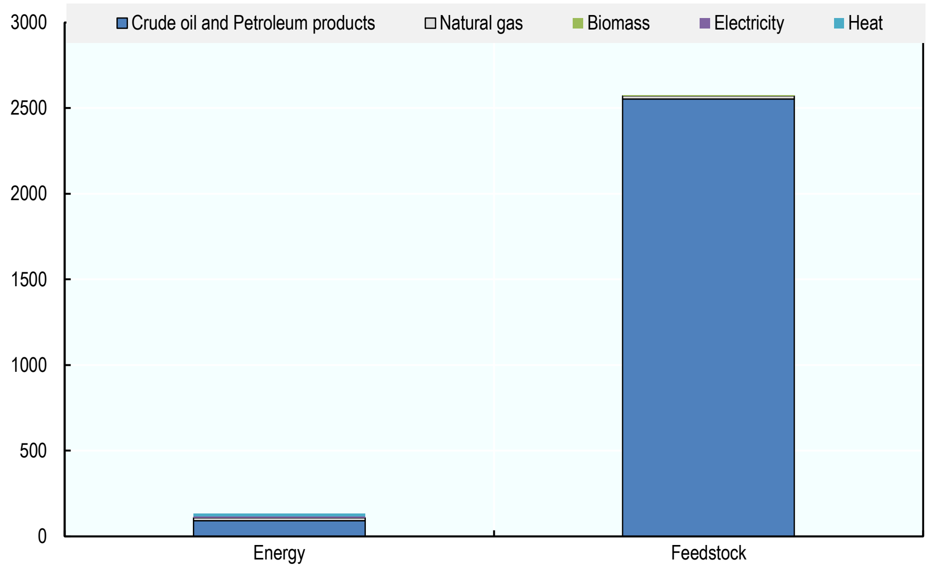
In the **distillation** process, crude oil is separated into products as naphtha, gasoline, kerosene and gasoil. The first distillation is performed at atmospheric pressure, and the remaining parts are distilled under vacuum condition, resulting in vacuum gasoil. All six Dutch refineries are able to carry out these processes.

Some products from the distillation process, such as vacuum gasoil, need a further treatment to be converted into lighter products, using **catalytic cracking** (‘hydrocracking’).

Some products are then processed to increase their quality. For example, the amount of sulphur is decreased for the production of fuels (due to fuel standards). Catalytic reformers are used to increase and stabilise this product quality.

Unsurprisingly, the main energy carrier in this industry is crude oil and petroleum products. However, 13% of the energy consumed in this sector comes from natural gas and 11% from heat (Figure 3.9).

Figure 3.9. Consumption of energy carriers, as energy and feedstock, in the refineries, 2015 (PJ)



Source: CBS, Energy balance sheets by sector.

3.3.2. Main technologies to be implemented for the reduction of emissions

Oliveira and Schure (2020[7]), as part of **the MIDDEN project** (Manufacturing Industry Decarbonisation Data Exchange Network), analysed different decarbonisation options for the refinery sector. These options, shown in Table 3.1, are divided into four categories: 1) Carbon capture; 2) Fuel substitution; 3) Feedstock substitution; 4) Process design.

Table 3.1. Relevant decarbonisation options for the refinery sector

Category	Technology	Relevant process
Carbon capture	Carbon capture and storage	For the production of blue hydrogen (see below), for fluid catalytic cracking and for gasification units
Fuel substitution	Electric furnaces	Replacement for all gas-fired equipment
	Electric boilers	Steam boilers
	Electric shaft equipment	Steam Turbine replacement
	Blue/green hydrogen as fuel	Replacement for all gas-fired equipment
Feedstock substitution	Co-Processing (5-10%) pyrolysis bio oil	CO-feed for fluidised catalytic cracking
	Blue/green hydrogen as feedstock	Hydro treating and hydrocracking processes
Process design	Standalone plant for biofuels production via pyrolysis bio oil upgrading	Alternative for production of liquefied petroleum gas (LPG), gasoline, kerosene and diesel
	Biomass gasification using the Fischer-Tropsch process for fuels production	Alternative for production of LPG, gasoline, kerosene and diesel

Source: Berenschot, from Oliveira and Schure (2020[7]).

The **port of Rotterdam** (2018[8]) made a clear pathway towards zero emissions. This pathway consist of three consecutive steps, which include the four options of Oliveira and Schure (2020[7]). The three steps can roughly be described as: 1) energy efficiency & infrastructure; 2) change in processes; 3) change in feedstocks.

The first step takes place between 2020 and 2025 and focuses on energy efficiency through the optimisation of processes and the use of excess energy. In parallel, infrastructure for heat, CO_2, steam, electrification and hydrogen is further developed. For instance, excess energy can be supplied as heat towards green houses and residential housing. To prepare for future electrification, the electricity grid is upgraded. Carbon Capture and Storage is used in prototypes and test facilities. The reinforcement of the electricity grid and CCS rather apply to other sectors of this cluster, in particular the chemical sector.

In the second step (2025-30), the first changes towards a new energy system are made. In this step, electrical and hydrogen infrastructure is further reinforced. The first pilots of renewable heating processes are performed through electrification (low and middle temperature) or the use of hydrogen fuelled boilers (high temperature).

Electrification of heating process is possible in multiple ways, e.g. heat pumps for water or electric boilers for steam. The cracking in the refinery industry uses high temperatures that cannot be produced with electricity, but hydrogen (blue and green) can be a solution.

One example of the use of the production of blue hydrogen in the refinery industry is the project H-Vision. The project partners are piloting a large-scale production and utilisation of blue hydrogen. In H-vision, blue hydrogen is produced using natural gas and refinery fuel gas. CO_2 captured during production will be safely stored in depleted gas fields under the North Sea or used as a building block for basic chemicals such as methanol (Section 3.2). H-vision anticipates the development of green hydrogen, which will produced via electrolysis using power sourced from renewable sources like offshore wind farms.

The third step (2030-50) relies on the assumption that green electricity and green hydrogen are largely available. It will require an extensive infrastructure for both energy carriers and be well connected to the industrial facilities in the Rotterdam-Moerdijk cluster. Under these conditions, hydrogen and electrical heating can be implemented on a large scale.

This step also entails the development of a recycling and biomass hub in Rotterdam, through pilots. Dutch refineries would in particular use the pyrolysis process to transform polymers into naphtha.

3.3.3. Sectoral assumptions

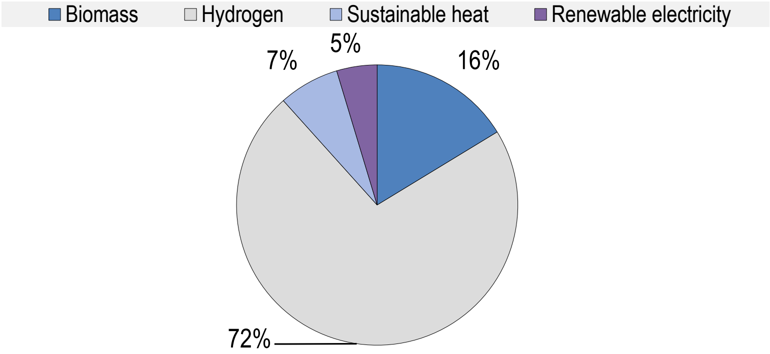
Refineries' capacity is projected to decrease by 40% between 2020 and 2050, since the demand for fossil fuels will significantly drop.

The energy efficiency of the sector is assumed to remain constant over the period, since investments will mainly be directed towards new sustainable technologies.

3.3.4. Zero emission scenario: Impact on energy carriers and emissions

Scope 1 and 2, BAU emissions from the Dutch refineries sector would reach 4.3 $MtCO_2$, which can be reduced to net-zero by 2050 using the scenario outlined above. Figure 3.10 shows the contribution of each technology to the emission reduction. The uptake of hydrogen, in particular for the cracking process, will contribute to more than 70% of emission reductions. The rest of the emission reductions come from the use of biomass (16%), shift to sustainable heat (7%) and renewable electricity (5%).

Figure 3.10. Emission reductions in the Dutch refineries sector by technology in 2050 compared to BAU under zero-emissions scenario

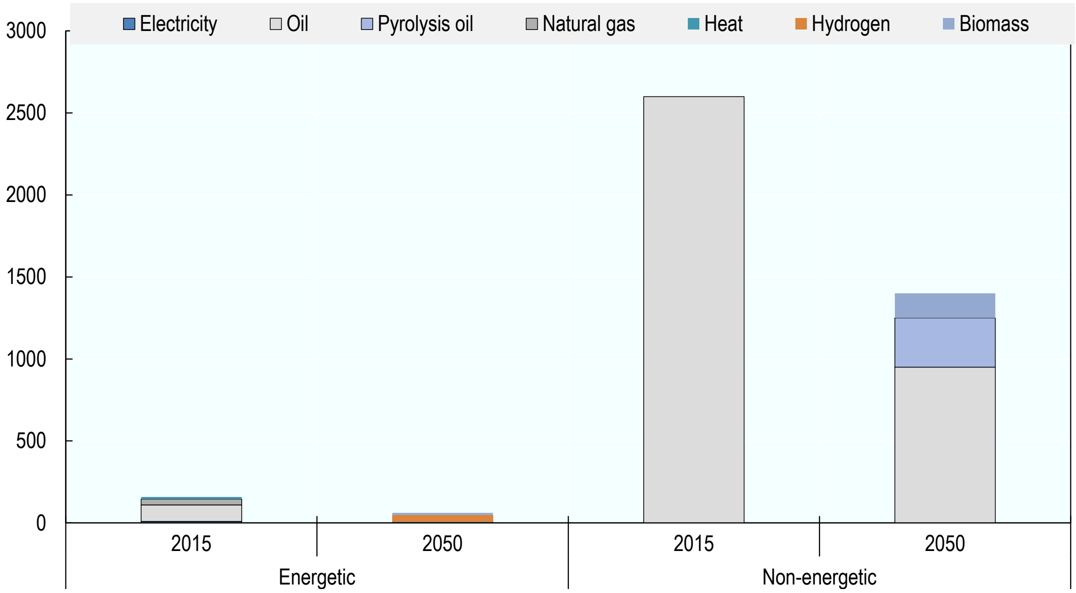


Source: Berenschot.

Regarding the energy carriers used as **energy source** (Figure 3.11), the introduction of hydrogen leads to the use of 40 PJ by 2050. In addition, 13 PJ come from biomass in 2050. The majority of the heating processes is based on hydrogen-fired boilers and, to a smaller extent biomass-fired. The heat provided by the energy sector to the refineries becomes sustainable. In parallel, the industry ceases to use fossil fuels (crude oil and natural gas) as an energy source.

Regarding the energy carriers used as **non-energetic feedstock**, a third of crude oil is replaced with biomass and pyrolysis oil. In this scenario, however, 950 PJ of oil would still be used as non-energetic feedstock by the refinery sector, and exported outside Europe. This is one of the major uncertainties of this scenario, which relies on the world demand for fossil-based refined products and the ability of the Dutch refineries to compete with foreign refineries in this market. If this would prove impossible, refineries would have to rely more on non-fossil feedstock, which raises questions on the availability of biomass and pyrolysis oil, or to downsize more than in this scenario.

Figure 3.11. Energy carriers for Dutch refineries sector (energetic and non-energetic), 2015 and 2050 (PJ)



Source: Berenschot.

3.4. A zero-emission metallurgical sector

Dutch metallurgy includes primary and secondary steel, non-ferrous metals (i.e. aluminium and zinc), and foundries. According to the OECD STAN database, 175 companies work in Dutch metallurgy, employing 21 000 people and representing 0.4% of GDP in 2018. Annual turnover is approximately EUR 9 billion, whilst the export value is EUR 5.7 billion (Berenschot, 2020[1]), of which 85% goes towards the rest of the European Union (Berenschot, 2020[1]).

Dutch metallurgy is responsible for 23% of industry's total CO_2 emissions in 2015 (9.2 $MtCO_2$ direct and indirect). Figure 3.12 depicts the spatial clustering of these emissions throughout the Netherlands. The bulk of emissions comes from primary steel production (presently owned by Tata Steel) in IJmuiden, which produces high quality steel for engineering, automotive and packaging industries. This plant produces approximately 7 Mt of steel in 2015, out of a global primary steel production of 1 800 Mt. Dutch aluminium is predominately used in planes, automotive, trains, ships, packaging and construction industries (Aldel, 2020[9]). DAMCO Aluminium is the largest producer of primarily aluminium in Delfzijl, whilst anode production for primarily aluminium production is concentrated in Vlissingen (Smart Delta Resources cluster) and Rotterdam. Smaller re-melters (for secondary aluminium production) are scattered across different sites throughout the Netherlands. Zinc is located in Budel (at Nyrstar Budel B.V.) and is not part of any cluster. Foundries mainly recast steel and aluminium, with the largest facility in Zaltbommel (again, not part of any cluster). Casting is a type of metalworking that involves pouring liquid metal into a mould or form to create complex and detailed parts. For example, steel castings are used when cast iron cannot deliver enough strength or shock resistance, for instance steel castings are found in gears, railroad truck frames, hydroelectric turbines, amongst other applications.

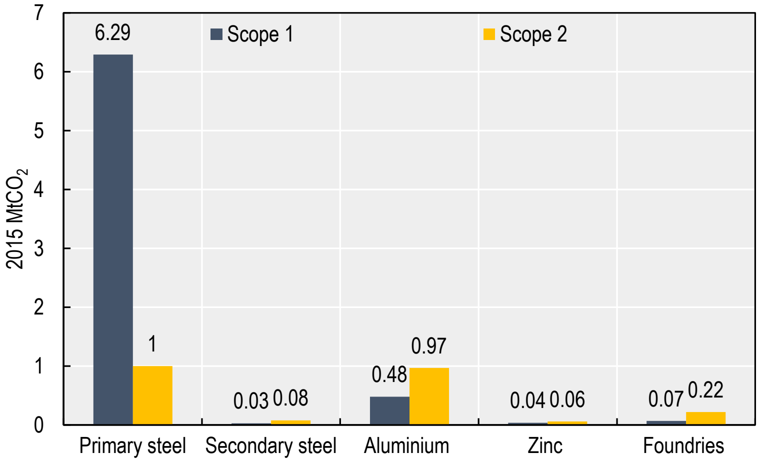
Figure 3.12. Scope 1 CO_2 emissions of the Dutch metallurgy by community

Source: www.emmissieregistratie.nl, Berenschot calculations.

3.4.1. Description of the sector and the main processes

Figure 3.13 shows that primary steel production accounted for nearly 91% of these Scope 1 CO_2 emissions from Dutch metallurgy (6.29 $MtCO_2$) in 2015. With the exception of primary steel, Scope 2 emissions (grey bars in Figure 3.13) are estimated to account for over half of the CO_2 emissions in each of the subsectors (i.e. secondary steel, non-ferrous metals and foundries) (Berenschot, 2020[1]). In other words, *indirect emissions from purchased energy* are estimated to be greater than direct emissions from facilities in these sub-sectors (blue bars in Figure 3.13), estimated by Berenschot (Berenschot, 2020[1]).

Figure 3.13. Breakdown of CO_2 emissions from Dutch metallurgical industry in 2015



Note: Scope 1 emission estimates for primary steel includes coke production.
Source: Berenschot.

Scope 1 emissions from primary steel production partly comes from the continued use of Blast Furnaces-Blast Oxygen Furnaces (BF-BOF) at their site in IJmuiden. BF-BOF converts coal to coke, which is then mixed with iron ore (imported into the Netherlands) to produce high quality steel products.

The main energy carrier in Dutch primary steel production is, by consequence, coal (as it is a feedstock which falls under Scope 3). Approximately 80.2 PJ was consumed in primary steel production in 2015 (as shown in Figure 3.14), followed by natural gas (9.7 PJ) and electricity (6.8 PJ).

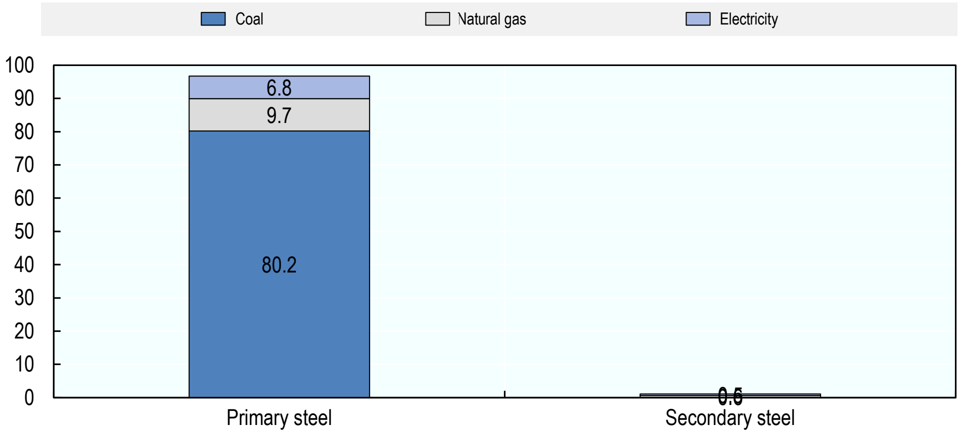
Tata Steel mill in IJmuiden already operates with very high energy performance and is one of the most efficient steel mills in the world. IJmuiden gradually reduced energy usage by 32% between 1989 and 2017 via heat insulation, innovated design, start-stop management, and hot connect – all of which reduces Scope 1 and Scope 2 emissions. Incremental energy efficiency improvements, however, have become increasingly difficult, meaning that energy efficiency improvements will be insufficient to reduce its remaining emissions (Jägers and Kiesewetter, 2018[10])).

Tata Steel used 1.4 Mt of steel scrap in 2015 (approximately 20% of its production volume). Blast furnaces, though, can only accommodate about 16% of scrap in input volume. Even with this limited amount, however, maximising scrap in BF-BOF has been shown to reduce Scope 1, 2, and 3 emissions in Sweden Germany, India, China (Rammer, Millner and Boehm, 2017[11]). This said, alternative production processes (e.g. HIsarna, see below) are likely to allow a higher share of scrap and its uptake could be constricted by its availability in addition to its quality.

In contrast to primary steel production, the majority of emissions from secondary steel production are estimated to be Scope 2 (Figure 3.13). In particular, the use of electricity, which amounted to 0.5 PJ.

The bulk of non-ferrous emissions comes from aluminium, rather than zinc, as shown in Figure 3.13. Primary and secondary aluminium production is combined in Figure 3.13, totalling 1.45 $MtCO_2$ (Scope 1 and 2). The bulk of CO_2 emissions in 2018 were indirect from electricity use (i.e. Scope 2), meaning largely depending on the Dutch electricity mix. Total Dutch aluminium production reached 180 kilotonnes (kt) in 2015 (out of a global primary aluminium production of 58 456 kt).[12] The annual production of secondary aluminium in the Netherlands is unknown. Globally, however, the share of secondary production has remained at around 32% of primary production since 2000 (IEA, 2020[12]).

Figure 3.14. Energy carriers in the production of primary and secondary steel in 2015 (PJ)



Source: Berenschot (2020[1]).

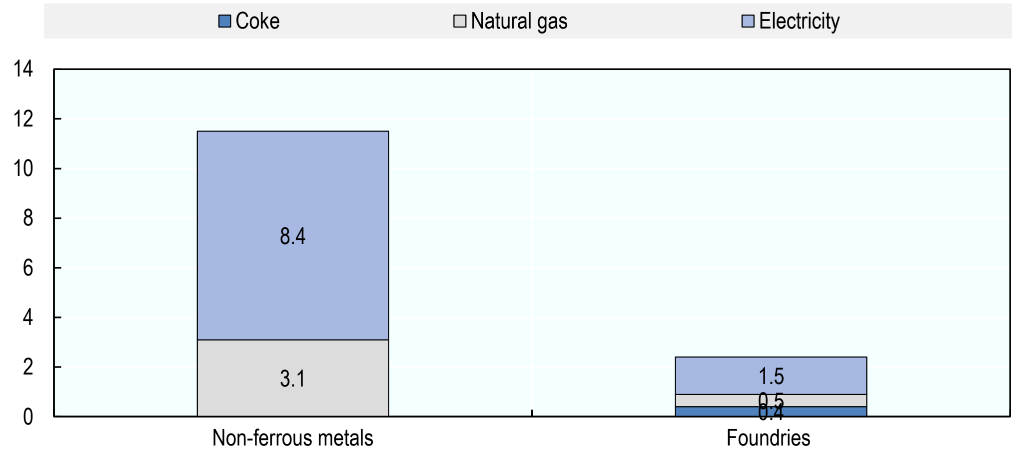
Dutch primary aluminium production uses the Hall-Héroult process for smelting, which relies on electrolysis to reduce aluminium oxide (also known as alumina) using carbon anodes. Scope 1 emissions are, therefore, a by-product of the efficiency of this process and the consumption of carbon anodes (approximately 480 kt of anodes were produced in the Netherlands in 2015, mainly for export). Scope 1 emissions additionally come from the step preceding Hall-Héroult of converting the bauxite into alumina.

Primary aluminium production is approximately ten times more energy-intensive than secondary production globally (IEA, 2020[12]) . Therefore, further reductions could be reached by greater uptake of scrap in the sector. At Aldel's aluminium production facility 33% of the inputs were scrap. Scrap-based production tends to cost less than primary production, so the key constraint is scrap availability (similar to steel). Aluminium recycling rates are relatively high, but aluminium, as many other metals, remains locked in products until their end of life, so even with better collection rates there is an upper limit on the potential for recycled production.

Dutch Zinc production led to 0.1 $MtCO_2$ in 2015 (Scope 1 and 2, as shown in Figure 3.13) (producing 283 kt of zinc in 2015). Similar to aluminium, electricity is the main energy carrier, and therefore, the bulk of emissions are indirect from electricity. Taken together (combining aluminium and zinc), non-ferrous production used 8.4 PJ of electricity and 3.1 PJ of natural gas (Figure 3.15).

Dutch Foundries produced approximately 95 kt of metal in 2015, which produced 0.2 $MtCO_2$ in 2018 (Scope 1 and Scope 2, as shown in Figure 3.13). The process for foundries is to heat metal (typically, steel and aluminium) to very high temperatures in furnaces that is then poured into moulds; these furnaces can be fuelled by coal (0.4 PJ consumed in 2015), natural gas (0.5 PJ in 2015), or electricity (1.5 PJ) (Figure 3.15). The choice of furnace depends on the alloys of the metal. Switching away from the use of coal and natural gas furnaces towards electric or hydrogen furnaces would contribute to reducing Scope 1, potentially at the expense of Scope 2 emissions, whilst decarbonising Dutch electricity would reduce Scope 2. Presently, Dutch foundries only use about 5% of scrap in production; therefore, increasing the use of scrap could further reduce emissions. Similar to aluminium, a key limitation is the availability of scrap.

Figure 3.15. Energy carriers in the production of non-ferrous metals and foundries in 2015 (PJ)



Source: Berenschot (2020[1]).

3.4.2. Main technologies to be implemented for the reduction of emissions

As shown in the previous section, the sources and processes of emissions in each of the subsectors in Dutch metallurgy are diverse.

Reducing emissions from primary steel production requires alterations to the BF-BOF production process. The options presently under consideration by Tata Steel include HIsarna, CCS and direct reduction ironmaking (DRI). If, in the future, Tata Steel sells the IJmuiden plant to SSAB, prioritisation and options under consideration could change:

- Tata Steel already has a pilot plant with HIsarna in IJmuiden and is investing in a larger scale plant in India but could see IJmuiden as another potential location for a larger-scale plant. The HIsarna process avoids the pre-processing steps that involve iron ore and coke when using BF-BOF. HIsarna is a new type of furnace in which iron ore is directly injected and liquefied in a high-temperature cyclone so that it drips to the bottom of the reactor where powder coal is injected. The two react into liquid pig iron. The pilot HIsarna plant achieves reductions of energy and CO_2 emissions of approximately 20%. In addition, the flue gas is highly concentrated CO_2, which is well suited for CCS. HIrsana can accommodate larger quantities of scrap than BF-BOF, up to 35%.
- Tata Steel is expecting to capture 4Mt of CO_2 by 2030 (from the BF-BOF). The Athos project, with the participation of Tata Steel, is exploring storage options in the North Sea. However, CCS will never capture 100% of CO_2 emissions, meaning reaching net-zero requires offsetting or negative emissions. The options for negative emissions include, for example, direct air capture and CCS at green methane sites.
- Another way to produce steel is DRI. Iron ore is reduced in a DRI reactor to Direct Reduced Iron using hydrogen, which can then be processed in an Electric Arc Furnace or BF-BOF. The Direct Reduced Iron is stable and can be transported. Therefore, iron reduction could occur in a country with abundant renewables, and then shipped to the Netherlands for steel production.

Scope 2 emissions associated with production could be reduced by investing in renewables on the Tata site or by using offshore wind farms nearby (directly or through the electricity grid).

For non-ferrous production, the biggest portion of emissions are secondary and are, therefore, dependent on the energy efficiency of processes and the decarbonisation of the electricity mix in the Netherlands. For primary aluminium production, Scope 1 emissions could be reduced by improving the Hall-Héroult process, such as prebaking carbon anodes, using liquid aluminium or further optimising electrolysis (e.g. central point feeder, magnetic compensation or slotted carbon anodes), in addition to using alternative baking methods (e.g. inert or bio based anodes).

Similar to non-ferrous metals, the Scope 2 emissions from Foundries could be tackled by improving energy efficiency and decarbonising Dutch electricity. Switching from coal and natural gas furnaces to either electricity or hydrogen would reduce Scope 1 emissions, if the electricity were from renewables.

Scope 1 and 2 emissions from Dutch metallurgy could be further reduced by greater use of scrap in production – producing greater amounts of secondary steel and aluminium, along with greater use of recycled metals in foundries. All these processes use less energy, and therefore, fewer emissions than primary production. The ability to shift towards greater use of scrap in production is restricted by its availability, in addition to technical requirements regarding the quality of the metal (e.g. steel).

3.4.3. Zero-emission scenario: Sectoral assumptions (energy efficiency, demand growth)

The plausible scenario assumes 1% annual growth for all product groups from 2020 to 2050. To reach net-zero by 2050:

- Tata Steel switches to the HIsarna production process with CCS[13]. Scrap is used to the greatest extent possible in primary production, i.e. up to 35% of inputs. As mentioned above, negative emissions will still be needed elsewhere in the Netherlands to compensate for the remaining CO_2 from primary steel production (approximately 0.9 Mt). Secondary steel companies will switch to scrap to the greatest extent possible.
- The efficiency of electrolysis in primary aluminium production improves its efficiency, whilst there is greater uptake of recycled aluminium. Both of which increase the energy efficiency of aluminium production, which means that even though the production grows by 45% by 2050, energy demand only grows by 20%.
- Foundries will largely switch to using scrap (to the greatest extent possible) and induction ovens with electric heating in 2050. In some circumstances, replacing gas-fired ovens with hydrogen will be viable. In 2050, 70% of energy consumption is assumed to be from electricity and 30% from hydrogen.

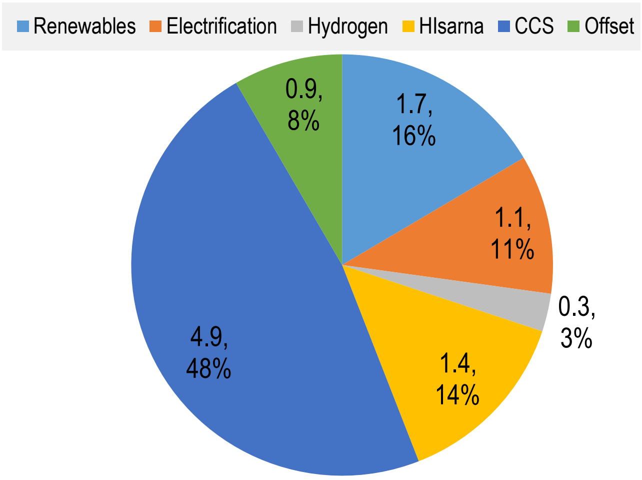
3.4.4. Zero emission scenario: Impact on energy carriers and emissions

BAU emissions from Dutch metallurgy would reach 10.3 $MtCO_2$, which can be reduced to net-zero by 2050 using the scenario above. Figure 3.16 shows the total amount of $MtCO_2$ reduced by technology in 2050 compared to the BAU and the percentage of this reduction. The uptake of CCS in primary steel production accounts for nearly half of emission reductions in Dutch metallurgy compared to BAU in 2050 (4.9 $MtCO_2$), whilst the HIsarna production process reduces 1.4 $MtCO_2$ compared to BAU, approximately 14%. It is worth noting that not all emissions from Dutch metallurgy can be reduced in 2050, and therefore, nearly 9% of emission reduction would rely on compensation. Since the capture rate of CCS is assumed to remain below 100%, HIsarna will still emit CO_2 and reaching net-zero carbon emission will need an offset via negative emissions elsewhere (green in Figure 3.16).

In 2050, Dutch metallurgy substantially decreases its usage of coal as an energy carrier for energetic use by 60%, from 25 PJ in 2015 to 10 PJ in 2050, and to a lesser extent natural gas, which decreases from 9 PJ to 7 PJ between 2015 to 2050 (Figure 3.17), but fossil fuels are still used to provide energy to the HIsarna process. Dutch metallurgy ups their usage of electricity as an energy carrier by 53% from 17 PJ in 2015 to 26 PJ in 2050 and hydrogen to 5 PJ (Figure 3.17). The **consumption of coal for non-energetic use increases from 2015 to 2050 from 55 PJ to 64 PJ**, which is due to the expected increase in production of primary steel.

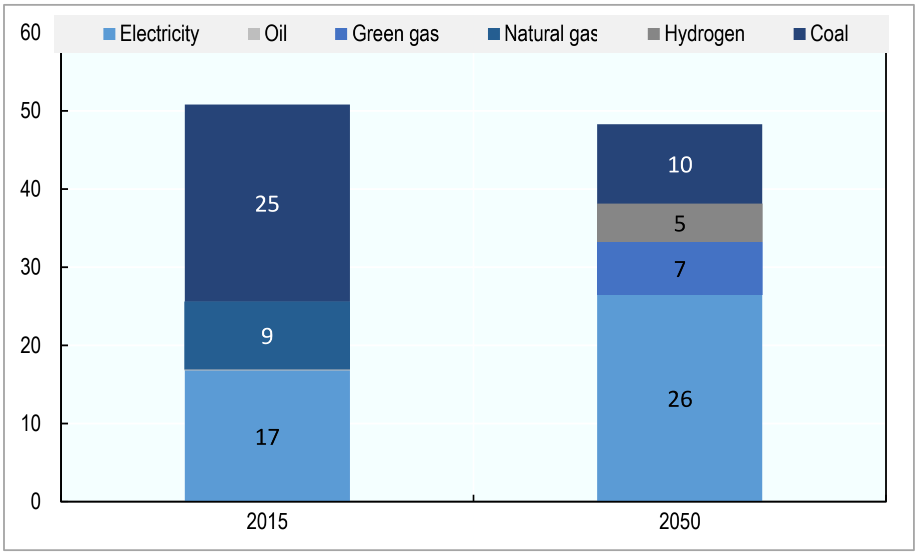
Figure 3.16. Emission reductions in Dutch metallurgy by technology in 2050 compared to BAU under zero-emissions scenario

Emissions in $MtCO_2$, percentage of emission reductions achieved with a given technology



Note: Offset means that emissions are reduced elsewhere, for example, via direct air capture and CCS at green methane sites. The contribution of "Renewables" corresponds to the abatement of the 2015 Scope 2 emissions, which would be overturned by completely shifting to renewable electricity sources by 2050. The contribution of "Electrification" corresponds to additional electricity needed to reach the carbon neutrality objective in 2050, assuming that this additional electricity is also renewable and carbon-neutral.
Source: Berenschot (2020[1]).

Figure 3.17. Energy carriers for Dutch metallurgy (energetic) in 2015 and 2050 (PJ)



Source: Based on Berenschot (2020[1]).

3.4.5. Major uncertainties in the 2050 zero emission scenario

The uncertainty in the zero emission scenario for metallurgy stems from: 1) the availability of scrap in 2050; 2) the potential change in ownership of IJmuiden steel mill; 3) the potential for negative emissions; and 4) future demand for the products:

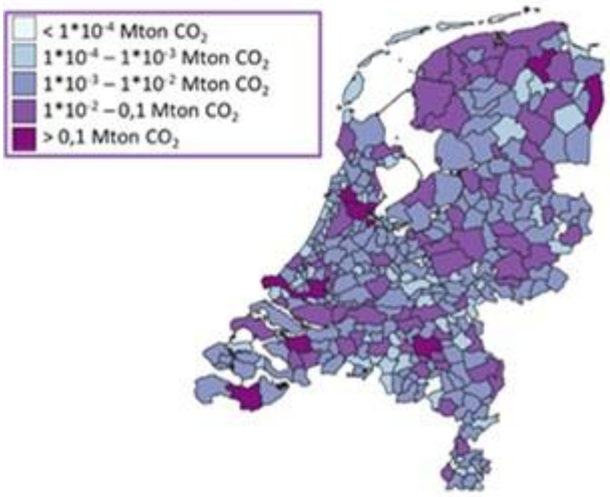
- The ETM assumes that all production processes use the maximum amount of scrap possible, e.g. 35% of the inputs into HIsarna would be scrap and foundries could conceivably use up 100%. Whether or not this quantity of scrap will be available in 2050 remains to be seen. First, many of these metals are locked into products with long lifetimes (e.g. automobiles, airplanes, buildings). In addition, the quality of the scrap varies substantially, which can affect the integrity and strength of the reprocessed metal. Therefore, even if scrap is available, not all of it may be usable, for the high quality steel products produced in IJmuiden. Moreover, the infrastructure needs to be in place to properly process scrap, e.g. waste processing facilities. If this cannot all be provided domestically, then there needs to be trade in scrap and waste. However, a number of hurdles remain to freely trade in scrap and waste. On the one hand, even within the European Union, scrap metal can be classified as waste, scrap, or even hazardous waste, all of which has varying regulations preventing it from being freely traded amongst member states. Other countries have import or export bans of scrap, e.g. Russian smelters and re-melters lobbied for an export ban on scrap aluminium to ensure greater supply domestically. As a result, a number of hurdles would need to be overcome in order to ensure access to scrap required in the zero emission scenario.
- Tata Steel may sell the IJmuiden plan to SSAB Steel in Sweden in 2021. The zero emission scenario for steel was heavily informed by Berenschot's consultation with Tata Steel and their desire to concentrate on HIsarna, Direct Reduction Ironmaking, and CCS. SSAB could prioritise these avenues differently for decarbonisation – e.g. HYBRIT –, which is under exploration in Sweden. SSAB is developing this in Sweden with LKAB and Vattenfall, and it is presently constructing its pilot plant. Essentially, this involves the direct reduction of iron into steel with hydrogen and renewable energy using EAF, which generates water as a by-product instead of carbon dioxide. If the preferred technologies for the decarbonisation of steel changes with the ownership of the IJmuiden plant, then the need for negative emissions could, in turn, also change.
- Lastly, Berenschot assumes a growth of 1% in demand for all metallurgical products until 2050 – with no differentiation between carbon content. However, recent policy developments suggest that greater differentiation between products may emerge over the next few decades. For example, the Border Carbon Adjustment under consideration in the EU would differentiate between the carbon content of products under the EU Emission Trading System (ETS), for example, for steel and cement. Therefore, the demand for metallurgical products may not be evenly distributed, which could, in turn, influence preferences and opportunities for technologies to decarbonise.

3.5. A zero-emission food processing sector

The Dutch food-processing industry (excluding agriculture) is diverse: vegetables; coffee, tea and cacao; fish and shellfish; potatoes; meat; livestock feed; tobacco; dairy; beverages and grain products. Despite this diversity, the processes can be *broadly* grouped into: 1) heating; and 2) mechanical processes. The former includes pasteurisation, distilling, melting, evaporating, baking and cooling, most of which require temperatures between 60 to 250°C, provided by natural gas and electricity. The latter includes mixing, filtering, packaging, or grinding, typically driven by electric motors.

Approximately 2 500 companies operate in the Dutch food processing industry, and it employs 127 000 people and represents 2.3% of GDP in 2018[14]. The total output is EUR 72 billion, and around 50% of products are consumed in the Netherlands. The industry has EUR 32 billion value in exports, mainly to Belgium, France, Germany and the United Kingdom. The sector is relatively scattered throughout the Netherlands (when compared to chemicals, metallurgy and refineries) as shown below in Figure 3.18.

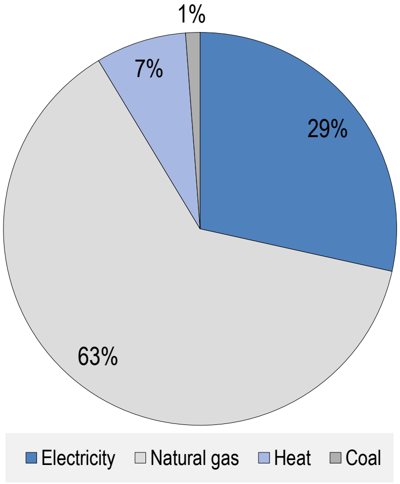
Figure 3.18. CO₂ emissions of the Dutch food-processing sector by community



Source: www.emmissieregistratie.nl, Berenschot calculations.

Figure 3.19. Main energy carriers for food industry

As a share of total primary energy use



Source: Based on Berenschot (2020[1]).

3.5.1. Description of the sector and the main processes

The food processing industry is responsible for approximately 6.5 $MtCO_2$, approximately 4.0 Mt are Scope 1 and 2.5 Mt are Scope 2 in 2018. Therefore, the bulk of emissions are Scope 1, meaning from the production process itself. The main energy source used in the food industry is natural gas. Other important sources include electricity and heat, whereas coal is marginal (Figure 3.19).

The plausible scenario for the Dutch food industry to reach net-zero is based on dairy, sugar and potato, and then expanded to the rest of the food industry (since these are fairly representative of the challenges for decarbonisation and technological options in the sector). The Dairy industry accounts for about 10% of the annual turnover (around EUR 7.5 billion), potatoes approximately 2.5% of annual turnover (EUR 2 billion), and sugar approximately 1% of the annual turnover (around EUR 0.7 billion):

- The energy consuming processes in the dairy industry include heat treatments, evaporation, spray drying and membrane processing. All of which need temperatures of less than 100°C, with the exception of evaporation, where some processes exceed 250°C. Most of these processes are heated with a central steam network that uses gas boilers.
- The typical processing of potatoes is to sort, wash, peel, wash, cut, blanch, fry, cool, freeze and then package. Frying is the most energy-intensive portion of potato processing, which traditionally uses gas boilers. For peeling and blanching, pressurised steam is used, which is reached with temperatures of less than 100°C. All other steps in potato processing use electricity. The final energy consumption is approximately 3.3 gigajoule (GJ) per tonne today.
- There are two large sugar factories in Netherlands that process beets. The process includes juice production (uses water at 75°C), juice purification (90°C), juice evaporation (130°C), and crystallisation (at 80°C). Each of these steps uses steam or electricity provided by a combined heat and power installation, which uses a natural gas boiler.

3.5.2. Main technologies to be implemented for emission reductions

Since most of the processes take place at a relatively low temperature, heat pumps are a viable option to replace gas boilers in all three subsectors, which could then use available waste heat as an input. For example, in dairy processing, the waste heat from spray drying (60 to 90°C) could be reused as an input to heat pumps to provide temperatures of up to 140°C.

However, heat pumps are not the only option to replace gas boilers, other options exist in each of the subsectors:

- In the dairy industry, using a sustainable boiler in the central steam network would greatly reduce emissions – e.g. electric, green gas,[15] or hydrogen. Each of the three has its advantages and disadvantages. An electric boiler is a relatively simple device compared to a gas boiler (since they do not use complicated heat exchanges). However, electric boilers require a substantial amount of electricity; therefore, generating the power to run the electric boiler could also increase Scope 2 emissions depending on the emission intensity of the power supply. Hydrogen is still very expensive and its future distribution, transmission and storage still need to be resolved, especially for scattered production facilities as in the case of the dairy industry. The advantage of green gas is that it can already be used in current boilers, but its future availability is unsure. The central steam network used by the dairy industry could likewise switch to the use of geothermal energy, where possible.
- For the frying stage in the potato industry, green gas is a viable option. A large part of the potato is unused in processing, and this waste could be used for biogas or green gas (meaning it does not face the same hurdles as the dairy industry). Green gas has the same characteristics as natural gas, so could be used directly in the boiler, whilst biogas currently does not fit. Other substitutes include electric boiler (which is already commercially available) and hydrogen.
- Sugar processing is similar to frying. Sugar processing produces a lot of waste, which could be used to create biogas or green gas that could then replace natural gas in the combined heat power installation.

Mechanical Vapour Recompression is a viable option for higher temperatures, for example, in the evaporation stages in the dairy and sugar processing. A MVR reduces steam consumption. It makes use of the evaporator's outlet steam and increases its pressure and temperature by compressing it, thereby making it suitable for evaporation of moisture from the incoming feed. This lowers the steam consumption significantly, thereby saving energy.

3.5.3. Zero-emission scenario: Sectoral assumptions (energy efficiency, demand growth)

The plausible scenario assumes 1% annual growth for all product groups from 2020 to 2050 and energy efficiency gains of 1.2% per year. The plausible scenario applies to the entire food industry, not only dairy, potatoes and sugar.

In the plausible scenario, low-temperature processes are substituted with either electrification or heat pumps, and the high temperature processes are substituted by boilers on green gas or hydrogen. The exact choice of technology depends on local circumstance, e.g. a large supply of waste as seen in the potato and sugar industries enhances the viability of green gas. Modelling by Berenschot projects a mix of technologies in the food industry by 2050: geothermal (10%), electrification (40%), green gas/bio gas (25%) and hydrogen (25%).

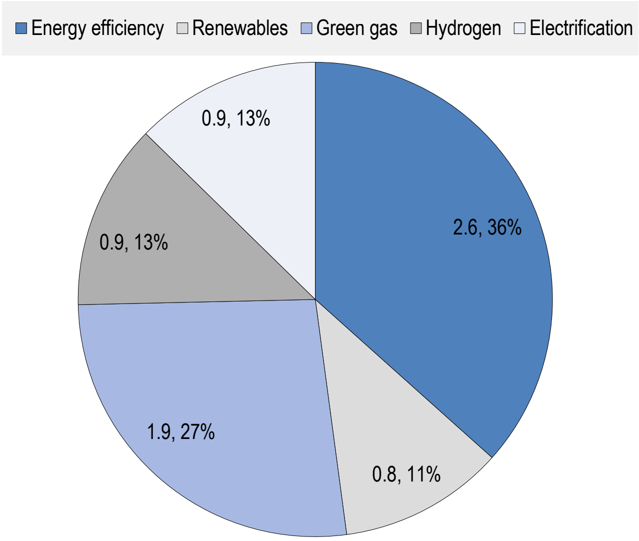
3.5.4. Zero-emission scenario: Impact on emissions and energy usage

Under BAU, Scope 1 and 2 emissions would increase to 7.5 $MtCO_2$ by 2050. To reach net-zero, energy efficiency improvements account for nearly 36% of reductions (2.6 $MtCO_2$) followed by the uptake of green gas, which leads to further reductions of 27% (1.9 $MtCO_2$), as shown in Figure 3.20. The remainder of reductions are accounted for via the uptake of hydrogen, electrification, and renewables.

The uptake of these technologies eliminates the use of coal and natural gas as energy carriers by 2050, as shown in Figure 3.21, whilst substantially increasing electricity usage from 23 PJ to 42 PJ. In addition, the use of hydrogen, heat and biomass, which were not being used at all in 2015, also become key in 2050.

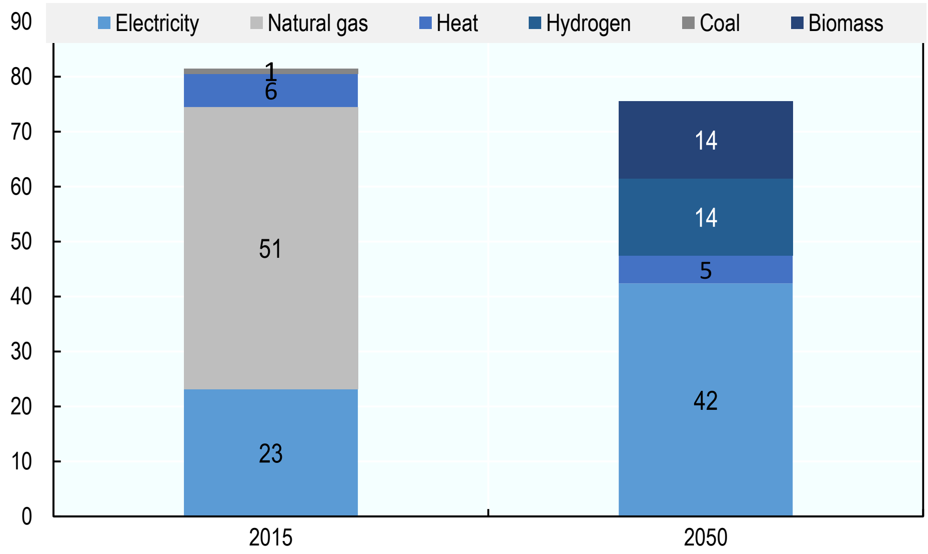
Figure 3.20. Emission reductions in the Dutch food industry by technology in 2050 compared to BAU under zero-emissions scenario

Emission reductions (in $MtCO_2$ and as a share of total emissions reductions) achieved with a given technology



Note: The contribution of "Renewables" corresponds to the abatement of the 2015 Scope 2 emissions, which would be overturned by completely shifting to renewable electricity sources by 2050. The contribution of "Electrification" corresponds to additional electricity needed to reach the carbon neutrality objective in 2050, assuming that this additional electricity is also renewable and carbon-neutral.
Source: Based on Berenschot (2020[1]).

Figure 3.21. Energy carriers for Dutch food industry in 2015 and 2015



Source: Based on Berenschot (2020[1]).

3.5.5. Major uncertainties in the zero emission scenario

The food processing industry is very heterogeneous, with different processes used from product to product. Therefore, the decarbonisation pathway will vary from company to company. The zero emission scenario above provides a sketch of what could happen, but reality will likely deviate for any particular company.

3.6. The zero-emission scenario for the industry

This section presents the aggregated scenario, by combining the scenarios for the four above-mentioned subsectors. It does not correspond to the whole Dutch manufacturing sector, but accounts for more than 85% of emissions, and 37% of value-added.

3.6.1. Role of the different technologies for the zero-emission scenarios over time

Hydrogen is the technology that contributes the most to the transition, accounting for more than 25% of emission reductions (Figure 3.22). It plays a role in the four subsectors but is of major importance in the chemical sector and refineries.

Five other technologies are of prime importance for the transition of the Dutch industry, each of them accounting for 10-16% of emission reductions:

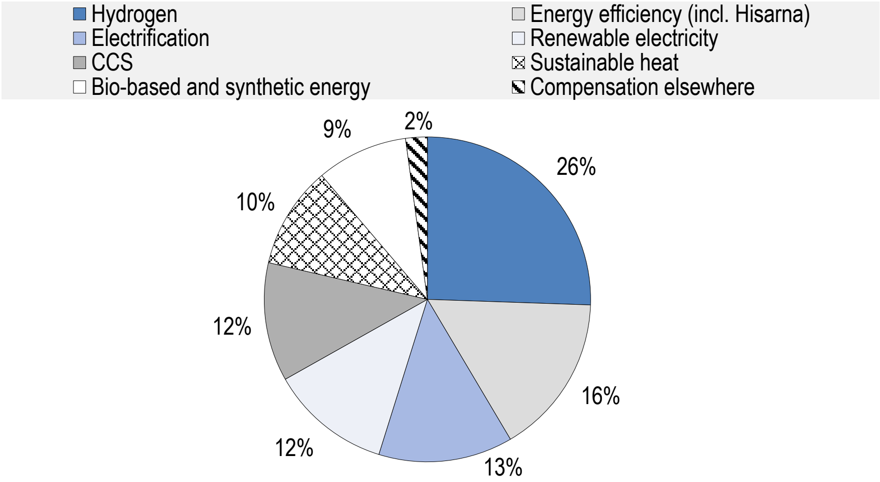
- Energy efficiency, mainly in the chemical and food processing sectors.
- Electrification of industrial processes. This is an important solution for the provision of heat, except for processes requiring a high temperature, such as in refineries.
- CCS is required in the chemical and metallurgical industry because these sectors will remain partly reliant on fossil fuels in 2050. Because reaching a capture rate of 100% would imply extreme costs, the capture rate is assumed to be 85% and the remaining emissions will need to be compensated elsewhere.

- Renewable electricity. Assuming that the energy production (out of the scope of this report) shifts to renewable sources (wind and solar for instance), the Scope 2 emissions of the industry will be abated.
- Sustainable heat plays an important role in the chemical sector.

Even though energy efficiency leads to a reduction of 15% in the use of energy, the technology analysis shows that carbon neutrality is achieved through very significant changes in the **energy sources** (Figure 3.23):

- Hydrogen, which is barely used today, becomes one of the main energy carriers (119 PJ in 2050).
- The electricity demand almost doubles to reach 177 PJ in 2050, without including the electricity needed to produce hydrogen. In 2050, this electricity is assumed to be carbon neutral, avoiding Scope 2 emissions.
- Other sustainable energy sources (pyrolysis oil, green gas, biomass and sustainable heat) amount to 148 PJ in 2050.
- Finally, 36 PJ of fossil fuels are needed in 2050, combined with CCS and carbon compensation. Although the consumption of fossil fuels is reduced by 91% and natural gas is completely eliminated, oil and coal remain necessary in the chemical and metallurgical industries respectively.

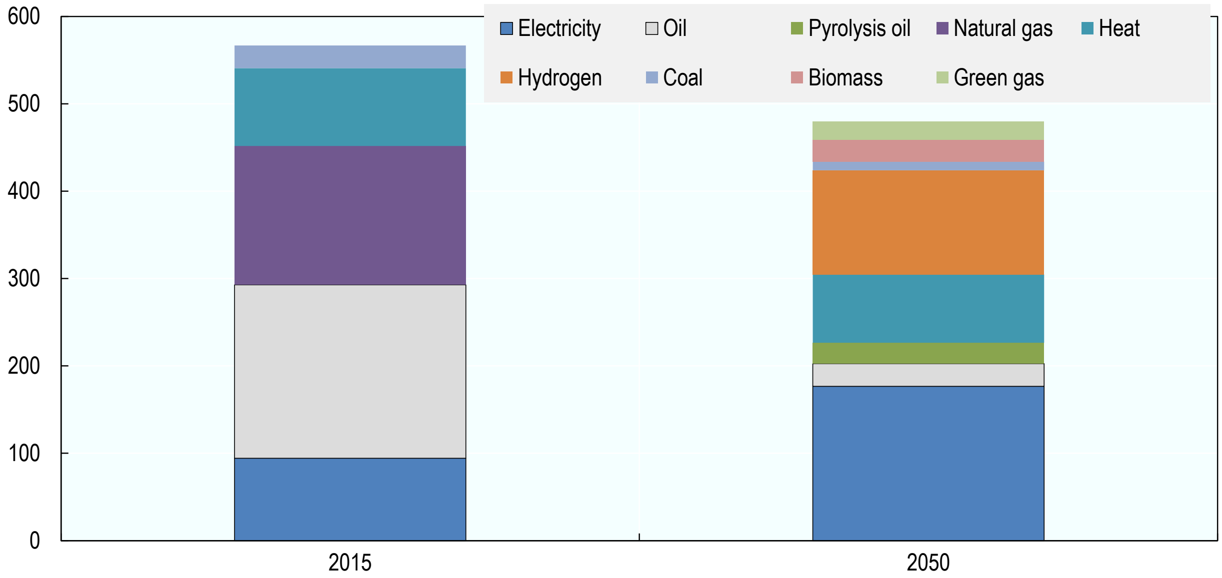
Figure 3.22. Role of different technologies in emission reductions, 2015-50



Note: Four manufacturing sectors: chemical, metallurgy, refineries and food-processing. The contribution of “Renewable electricity” corresponds to the abatement of the 2015 Scope 2 emissions, which would be overturned by completely shifting to renewable electricity sources by 2050. The contribution of “Electrification” corresponds to additional electricity needed to reach the carbon neutrality objective in 2050, assuming that this additional electricity is also renewable and carbon-neutral.
Source: Based on Berenschot (2020[1]).

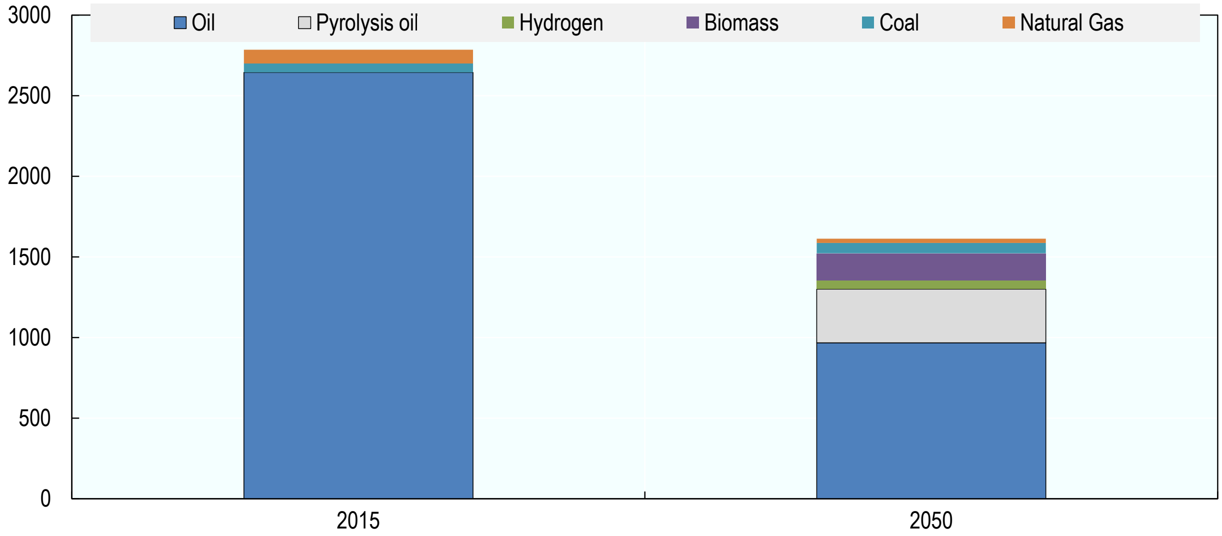
The use of energy carriers as feedstock also drastically changes (Figure 3.24). Whereas the energy content of feedstock is reduced by more than 40%, fossil feedstock experiences a 60% decrease. Crude oil is still used in refineries and part of the refined products are then used as a feedstock for petrochemicals. In addition, coal is still needed as a source of carbon atoms for the production of steel. Sustainable feedstock (pyrolysis oil, hydrogen and biomass) represents close to 35% of the energy carriers used as feedstock in 2050.

Figure 3.23. Energy carriers used as an energy source in 2050 (PJ)



Note: Four manufacturing sectors: chemical, metallurgy, refineries and food-processing.
Source: Based on Berenschot (2020[1]).

Figure 3.24. Energy carriers used as feedstock in 2050 (PJ)



Note: Three sectors of the industry: chemical, metallurgy and refineries. The use of energy carriers as feedstock in the food-processing sector is negligible (0.3 PJ in 2015). This graph is not the sum of the graph of the three subsectors. 150 PJ of biomass used as feedstock in the chemical industry is green naphtha produced by the refineries using biomass, and should not be counted twice. The same is true for the use of oil and pyrolysis oil in the chemical sector.
Source: Based on Berenschot (2020[1]).

3.6.2. Reaching net-zero by 2050: The implications of industry's decarbonisation on the energy system

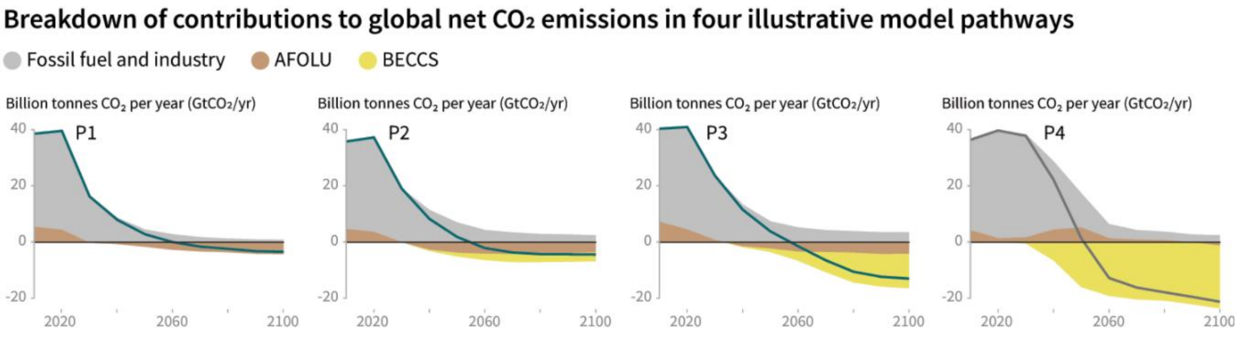
This scenario points to four main challenges facing the Dutch energy and industry sectors for the decade to come.

The first challenge is the **production and transport of carbon-neutral hydrogen**. This scenario relies on the use of 175 PJ of hydrogen (energy source and feedstock). If it were 100% domestic green hydrogen, it would require around 265 PJ of renewable electricity, more than doubling the projected requirement in the scenario, in which the direct use of electricity amounts to 177 PJ. If it were 100% domestic blue hydrogen, it would still require 45 PJ of renewable electricity and 174 PJ of natural gas. In addition, if the capture rate remain below 100%, reaching carbon neutrality in blue hydrogen production would require a significant amount of negative emissions to compensate. The last option is to rely, at least partly, on imported hydrogen. It would of course only shift the question of hydrogen availability to neighbouring countries. Finally, even if the scenario assumes the use of hydrogen for clustered sectors, it requires the construction of a large infrastructure to deliver the hydrogen, especially if it is imported.

Second, the scenario presented above relies heavily on increasing the use of **electricity** as an energy carrier (Figure 3.23, particularly if a significant production of green hydrogen is required). Increasing use of electricity could place a strain on other sectoral pathways to net-zero and the ability of the power system. In general, the greater demand for electricity (during peak hours and months) in industry and other end-use sectors, the lower flexibility given to the power system to decarbonise, since the power system may need to rely on fossil fuels to ensure the reliability of supply (if sufficient storage is absent). This, in turn, could mean greater reliance on carbon dioxide removal (CDR) technologies later in the century. Moreover, high-energy demand scenarios can be more costly, because of the need to build an electricity infrastructure to cover a few hours in the days of winter, to satisfy peak demand from end-use sectors.

Lowering the rate of growth in energy demand in the Netherlands would reduce the necessity to scale up the electricity system (generation, networks) substantially, translating into lower system costs and lower electricity prices (IEA, 2019[13]) as well as benefits to biodiversity, requiring less land, water and materials consumption (von Stechow et al., 2015[14]). Figure 3.25 illustrates this trade-off at the global level and is extracted from the IPCC Special Report on 1.5°C. The figure proposes four scenarios to achieve the goal of limiting warming to 1.5°C by 2100 under different levels of energy demand. Scenarios with higher levels of future energy demand will need to rely more heavily on the use of CDR later in the century. This is assumed to be bioenergy with carbon and capture storage in this scenario, in line with the "P4" scenario, than those with lesser demand (in line with the "P1" scenario) (IPCC, 2018[15]). Therefore, it is important not to forget that industry is embedded in the larger Dutch energy system and its decarbonisation should be evaluated in relation to other sectors.

Figure 3.25. Different illustrative global emissions pathways to 1.5°C by 2100



P1: A scenario in which social, business and technological innovations result in lower energy demand up to 2050 while living standards rise, especially in the global South. A downsized energy system enables rapid decarbonization of energy supply. Afforestation is the only CDR option considered; neither fossil fuels with CCS nor BECCS are used.

P2: A scenario with a broad focus on sustainability including energy intensity, human development, economic convergence and international cooperation, as well as shifts towards sustainable and healthy consumption patterns, low-carbon technology innovation, and well-managed land systems with limited societal acceptability for BECCS.

P3: A middle-of-the-road scenario in which societal as well as technological development follows historical patterns. Emissions reductions are mainly achieved by changing the way in which energy and products are produced, and to a lesser degree by reductions in demand.

P4: A resource- and energy-intensive scenario in which economic growth and globalization lead to widespread adoption of greenhouse-gas-intensive lifestyles, including high demand for transportation fuels and livestock products. Emissions reductions are mainly achieved through technological means, making strong use of CDR through the deployment of BECCS.

Note: AFOLU stands for Agriculture, Forestry, and other Land Use. BECSS stands for Bioenergy with Carbon Capture Storage.
Source: IPCC (2018[15]).

In addition, the potential for negative emissions in 2050 in the present scenario remains to be seen. Depending on the decarbonisation of other industrial subsectors and sectors, there could be more or less wiggle room for industry to rely on negative emissions to reach its targets. The interlinkages between sectors are not modelled in this report; therefore, whether the potential for negative emissions in 2050 is equivalent to what would be needed is unknown.

Third, the scenario also relies on a significant use of **biomass**. Some biomass will presumably be imported from abroad, to meet the total domestic demand. The biomass requirements (around 220 PJ in 2050, including green gas) is close to the domestic potential for yearly biomass production, estimated to be about 250 PJ in 2050 (Table 3.2). In 2050, there is a possibility to be able to import more biomass from abroad. In 2050 the Netherlands' import of biomass could roughly double the biomass availability to about 500 PJ (CE Delft, 2020[16]). Globally, about a third of this biomass could come from forestry and two thirds from agricultural origins. In the Netherlands, agricultural products make up a larger part of the biomass potential (75%), and an efficient use of all waste streams is foreseen. Forest sources could provide the other 25% in 2050.

Table 3.2. Maximum potential of biomass in the Netherlands

	Current yearly production (PJ)	2050 production potential (PJ)
Domestic biomass	121	230
Seaweed (North Sea)	0	18
Total	121	248

Source: PBL (2018[17]).

Finally, the net-zero scenario proposed requires **large investments**, from both the public and private sector, in low-carbon technologies and infrastructure (notably carbon and hydrogen pipelines). Unfortunately, COVID-19 could stall such investments by Dutch industry (OECD, 2020[18]). Great economic uncertainty could lead firms to reduce or postpone investment in innovative activities. In addition, the collapse of oil prices weakens incentives for low-carbon and energy efficiency investments. Moreover, young and small firms (rather than large incumbents) tend to develop radical innovations needed to decarbonise industry, but these are also the firms that have been disproportionately impacted by the crisis. Lastly, a dip in the addition of renewable energy capacity is expected globally because of supply chain disruptions from COVID-19. It is within this context that Dutch industry is making its way to net-zero. Because of this, the Dutch government will need to step up, maintain governmental support for innovation, and take risks to finance businesses working on emerging technologies further from the market.

3.7. Comparison with other decarbonisation scenarios

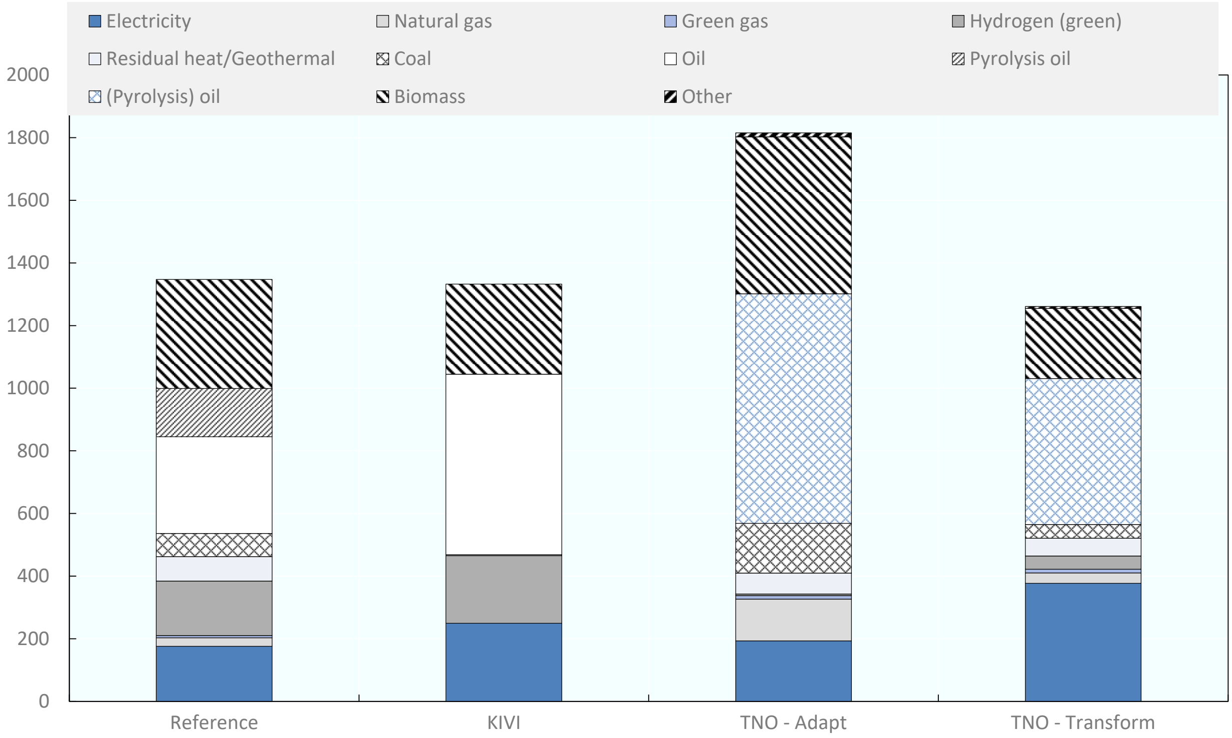
3.7.1. Scenarios available at the 2050 horizon

A thorough comparison of the above-mentioned scenario has been carried out by Berenschot et al. (2021[19]). Overall, the scenario is consistent with the other available scenarios (Figure 3.26), such as total energy use in industry, electricity, oil and biomass consumption. Available scenarios however differ significantly in terms of hydrogen consumption and CCS. The main results from the comparison of these scenarios are as follows.

Production volume growth and energy efficiency improvements are key scenario parameters. These parameters can have a dramatic effect on the scenario energy mix and energy demand. The reference scenario assumes relatively large production volume growth rates. In the TNO scenarios, some industrial subsectors feature declining production volumes. The assumptions in the reference scenario are more in line with the (general) assumption of the Koninklijk Instituut van Ingenieurs (KIVI) scenario.

Large differences in the size of the refinery sector. In the reference scenario, production of fuels for export is included, while other scenarios exclude this type of production. Given that the Netherlands has one of the most advanced refining industries in the world, Berenschot (2020[1]) assumes that part of the refinery industry will produce oil-based fuels for export, even if the domestic demand is significantly reduced. Therefore, the reference scenario assumes a much larger refinery sector in the Netherlands in 2050 than all other scenarios. This has major consequences for the energy consumption. To compare all scenarios, Figure 3.26 makes adjustments for this difference in assumptions.

Figure 3.26. Final energy consumption of Dutch industry in 2050 according to various scenarios (PJ)



Note: The total energy demand for the 'OECD' scenario differs from the previous subsection. Indeed energy used to produce exported fuels for ships and airplanes is not included in this graph, in order to make the scope comparable with the three other scenarios. An extensive discussion of the models and assumptions underlying these projections is available in Berenschot, Kalavasta and E3M (2021[19]).
Source: Berenschot, Kalavasta and E3M (2021[19]).

No consensus on (green) hydrogen use in industry. The (green) hydrogen demand differs per scenario. Hydrogen does not appear, or seems to play only a marginal role in the energy consumption of Dutch industry at the 2050 horizon according to TNO's scenarios. In fact, TNO assumes that hydrogen is produced onsite and is not considered as an input in their simulation, but part of the industry indeed relies on hydrogen as a carbon-free energy source. The TNO Transform scenario also features a limited use of hydrogen in industry due to an extremely low demand for fertilisers. Consequently, the (green) hydrogen demand of the reference scenario, which can only be compared with one of the KIVI scenarios, seems realistic. Actual demand for (green) hydrogen in 2050 will depend on availability of required infrastructure (international), market development and technological breakthroughs (affecting competitiveness).

Biomass remains a very important energy carrier in 2050. Biomass demand increases in all 2050 scenarios. In the TNO Adapt scenario, biomass demand from industry increases to ~500 PJ and is used for energetic purposes as opposed to the reference and KIVI scenarios. This is because TNO assumes that the combination of biomass combustion and CCS, in principle leading to negative emissions, is a viable option. However, the use of biomass for energy purposes is no longer being considered in the Netherlands after the SER Advice and its assessment by the Government.

The use of CCS is heterogeneous across scenarios and linked to the underlying narrative. The reference scenario includes CCS in steel, refinery and fertiliser industries. TNO Adapt also includes CCS. In this scenario, in combination with biomass (bioenergy with carbon capture and storage [BECCS]), negative emissions can be created to compensate for emissions in other sectors this is necessary to meet the carbon reduction goal. KIVI and TNO Transform do not contain CCS, since CCS is not in line with the scenario narratives.

3.7.2. The shift to alternative sources of energy does not start before 2030

This survey of available scenarios was also the opportunity to compare the projections for the 2030 horizon (Figure 3.27). When compared to the current situation, total final energy demand, and in particular the use of fossil fuels, does not necessarily decrease in the industry. This relative stability predominantly comes from the demand for energy carriers as a feedstock.

The introduction of new technologies remains very limited at the 2030 horizon. This affects energy demand and energy mix. The usage of new technologies varies across the scenarios. KIVI assumes the use of DRI in the steel industry, while in the TNO Adapt scenario the steel sector strongly relies on CCS. The mix of technologies determines the energy mix. Considering that the technology mix in the 2050 scenarios will differ more from the current situation than the technology mix in the 2030 scenarios, the heterogeneity in energy carriers among 2050 scenarios is larger than in 2030 scenarios.

The use of green hydrogen in industry is almost non-existent in 2030. When compared to other sectors, adoption of new technologies within the industry requires some time, because adjusting continuous industrial processes requires long-term planning, result in high CAPEX investment and as such have long lead times. In case hydrogen is produced on-site by Steam Methane Reforming (SMR) or Auto-Thermal Reforming (ATR) in combination with CCS, this will still result in an increase in natural gas demand.

Most scenarios expect an increase in overall electrification in 2030. However, the PBL cost-optimal and TNO adapt scenario show none, to limited electrification growth when CCS is allowed. Electrification trends in other scenarios are in line with the reference scenario for 2050. Energy efficiency improvements are one of the reasons to introduce electric technologies, in particular heat pumps and electric boilers for the production of low-temperature heat.

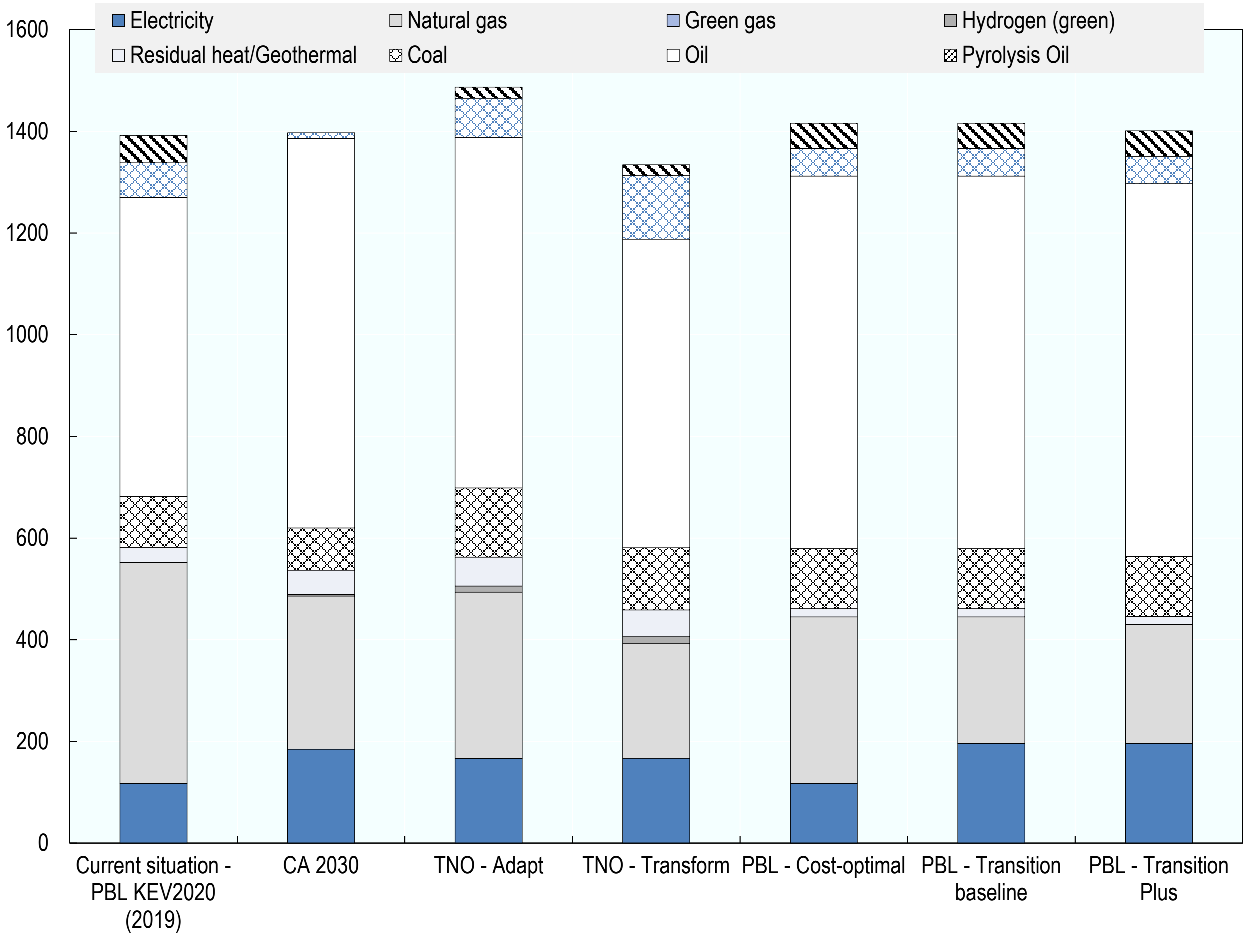
Geothermal and residual heat are scarce. They are key energy carriers in an energy-efficient scenario, although only useful in specific industrial subsectors as they provide low-temperature heat rather than high-temperature heat. In 2030 the amount of geothermal heat is deemed limited.

All mid-term scenarios show a capacity increase of wind energy and solar energy in particular. Some scenarios project more renewables than others; this can mainly be explained by the underlying scenario narratives. Furthermore, the projection of the 2030 scenarios are more or less in line with the 2050 scenarios. When comparing the 2050 scenarios with the 2030 scenarios the installed capacity almost triples.

3.7.1. EU and international scenarios also underline that carbon neutrality will hinge on a diverse portfolio of technologies

Berenschot, Kalavasta and E3M (2021[19]) also show that, at the EU or international level, a diverse portfolio of technologies is needed to support emission reductions in the energy-intensive industries, both in the short term (2030) and in the longer term (2050).[16] Short-term emission reduction in industries are primarily based on accelerating progress in low-hanging fruits such as energy efficiency achieved through the implementation of best available technologies (BAT), heat recovery, horizontal energy management, electrification of industrial processes and reduced oil and coal consumption through fuel switching. However, pursuing the carbon neutrality by mid-century would imply transformative changes along with disruption in value chains and business models. This is a big challenge for European industries, considering the inertia of the sector, the high investment amounts required and the 1-3 investment cycles in most industries by 2050.

Figure 3.27. Final energy demand (energetic and non-energetic use) in the Dutch industry according to various scenarios in 2030, compared to 2019 (PJ)



Note: An extensive discussion of the models and assumptions underlying these projections is available in Berenschot, Kalavasta and E3M (2021[19]).
Source: Berenschot, Kalavasta and E3M (2021[19]).

The emergence of breakthrough technologies is vital for achieving deep decarbonisation. The novel mitigation options include the deep electrification of industrial processes (e.g. through the uptake of high-temperature heat pumps), the switching to renewable energy carriers (e.g. green hydrogen, advanced biofuels, clean synthetic fuels), the emergence of carbon capture, utilisation and storage (CCUS) options and the accelerated improvements in energy and material efficiency embedding industrial processes in the circular economy. In order to avoid both direct and indirect emissions, the decarbonisation of European industries crucially depends on the provision of carbon free electricity and hydrogen from energy supply sectors.

The full decarbonisation of some industrial sectors may not be achievable without the implementation of CCUS technologies. The technology pathways in the European iron and steel sector are largely based on two novel options: 1) increased use of secondary steel, coming from steel scrap and electricity (assuming that power generation has been decarbonised); 2) hydrogen-based steelmaking by shifting away from blast furnace.

More generally, the road towards climate neutrality by mid-century can be achieved through: 1) the significant upscaling of current mitigation efforts (i.e. energy efficiency, fuel switch); 2) the deployment of innovative options, including: green hydrogen, e-gas, deep electrification, circular economy, CCS, embedding CO_2 in products and industrial symbiosis. Strong electrification of industrial processes should be combined with clean-gas and green hydrogen (H_2) solutions to decarbonise hard-to-abate energy intensive industries, while CCS is also required to eliminate remaining emissions in some industrial sub-sectors. Each technological mitigation option has pros and cons, but their combined development (together with the circular economy) is a cost-efficient way towards ensuring carbon neutrality of European industries by mid-century.

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Notes

[1] In this respect, this exercise is close to the MIDDEN project (Manufacturing Industry Decarbonisation Data Exchange Network: https://www.pbl.nl/en/middenweb).

[2] STAN database, OECD.

[3] This section partly relies on previous analysis by Berenschot (Ecofys and Berenschot, 2018[3]).

[4] Although they are some distance apart, Delfzijl and Emmen co-operate closely and are regarded as one cluster in the Netherlands.

[5] This process is often referred to as grey hydrogen, or blue hydrogen if combined with carbon capture, (Box 1.2).

[6] The coefficient of performance is defined as the ratio between the heat supplied by a system and the energy provided to this system.

[7] In theory, using feed to make energy is just about accelerating the cycle of carbon, but it is hard to ensure that the process is completely carbon neutral. First, the use of fertiliser would imply (more or less, depending on the process) some release of nitrous oxide (not carbon, but still a GHG). Second, it could generate some land-use change.

[8] Biobased methanol could also be produced, but the limited availability of biomass could affect the attractiveness of this option (Khandelwal and van Dril, 2020[20]).

[9] Wong and van Dril (2020[4]), Block, Gamboa Palacios and van Dril (2020[25]) and Advani and van Dril (2020[21]).

[10] CBS Statline.

[11] STAN database, OECD. ISIC sector 19.

[12] https://www.world-aluminium.org/statistics/#map; https://www.statista.com/statistics/748414/secondary-unwrought-aluminum-production-worldwide/.

[13] The assumed CCS capture rate is 85%, as in other sectors. However, the capture rate for HIsarna might be higher as the concentration of CO_2 is very high in the flue gas (Keys, van Hout and Daniëls, 2019[24]).

[14] Source: OECD STructural ANalysis Database (STAN), 2020.

[15] Green gas is upgraded biogas in the form of biomethane (with same quality as natural gas, which is why it can use the same infrastructure).

[16] This section is based on the analysis of the PRIMES European Commission Reference 2016 scenario, Sensfuss and Pfluger (2014[22]), the IEA World Energy Outlook 2020, the IRENA REmap Case scenario and Tsiropoulos et al. (2020[23]).

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