8. Emerging technologies: cross-country experience

This chapter discusses policy options to accelerate the development and adoption of five technologies that are critical for the decarbonisation of Dutch industry: carbon capture, storage and utilisation (CCUS), electrification of heating, hydrogen, recycling of plastics and metals, and bio-based materials. It assesses their Technology Readiness Levels (TRL) and analyses the main challenges for their diffusion. A patent analysis provides empirical evidence on the performance of inventors based in the Netherlands with respect to these key technologies.

To reach net-zero by mid-century, Dutch industry will need to quickly deploy an array of emerging low-carbon technologies, as shown by Berenschot's modelling exercise. The objective of this chapter is to understand the current level of technological readiness of these various technologies, analyse the policy support that they benefit from in the Netherlands, and assess how other countries are advancing the development and adoption of these technologies in comparison to the Netherlands.

This chapter focuses on five technologies that the previous chapters have identified as critical for the decarbonisation of Dutch industry: CCUS, electrification of heating, hydrogen, recycling of plastics and metals, as well as bio-based materials. It is important to recognise that these technologies are not mutually exclusive. Even though this chapter is organised by technology, interventions in support of one technology could ultimately advance another.

Beyond the assessment of the Technology Readiness Levels (TRL) of the different techniques, this chapter analyses the main challenges for these technologies to thrive and the core policies needed to overcome them and accelerate the diffusion of these key technologies for the green transition. Some of the challenges relate to supply side problems, others to the demand side. Some technologies need more support for capital expenditures, others for operational expenses, while for some other support could come in the form of R&D subsidies, risk sharing or changes in the legal framework.

An important contribution of this chapter is the comparison of the Dutch strategies for the adoption of these emerging technologies with those of other countries, notably Germany. The aim is to show in which areas the Dutch policies differ from those in other countries, and what the Netherlands can potentially learn from these.

Of note, given the large amount of information in this chapter, key messages related to each technology are provided at the beginning of each section.

Finally, this chapter includes a patent analysis, the objective of which is to provide empirical evidence on the performance of inventors based in the Netherlands and how it stands with respect to these core technologies.

In Brief

CCUS and carbon capture and storage

The technological challenge of CCUS and carbon capture and storage (CCS) in industry, as compared to technologies like solar photovoltaics or wind, is that it is not a modular technology and needs to be tailored to each installation. The challenges to its deployment are not only technical. Industry faces performance risks, capital and operational risks, as well as political and legal risks. Overcoming these requires government involvement. Historically, the United States has been the biggest player with respect to CCUS – with the greatest number of existing installations. However, the United Kingdom is stepping up its ambition with respect to CCUS, as evident in Prime Minister Johnson's Ten Point Plan (announced at the end of November 2020). To date, the United Kingdom has the greatest number of planned or operating installations within Europe. Both of these countries have taken great lengths to work with industry to overcome capital and operational risks as well as political and legal risks through different instruments discussed above. The Netherlands provides funding to cover capital costs of CCUS. However, the discussion in Chapter 5 shows that for a blue hydrogen project in the port of Rotterdam, OPEX can mount to EUR 1.2-2.2 million per year which is substantial compared to the EUR 3.4-4.6 million CAPEX. Funding to cover operational costs has only recently become available in the Netherlands, when the Sustainable Energy Transition Incentive Scheme (SDE++) subsidy opened for CCUS and CCS in 2020. In addition, the legal framework is still largely undefined in the Dutch context, for example, the companies' liability with respect to the risk of leakage. These could make it challenging to deploy this technology in Dutch industry at a large scale in the future. Interest from business exists, as the data about applications for the SDE++ 2020 round shows. There seems to be a business case for CCS: seven applicants requested a total of EUR 2.1 billion subsidies for the capture and storage of 2.3 Mt CO_2.

Electrification of heating

Dutch industry has a large potential for the electrification of heating, which refers to an assortment of technologies depending on what the heat is being used for in a given industrial process (i.e. chemical conversion, melting, casting, baking, distilling, separating, drying or hot water). The technology readiness of the electrification of heating depends on the temperature that needs to be reached. The utility of electrifying heat for decarbonisation, however, requires access to low-carbon electricity. It therefore, requires a significant amount of clean electricity available for the Netherlands. The financial attractiveness of electrifying heat (and replacing a functional piece of equipment) rests heavily on the ongoing costs of energy to run the electrical equipment compared to conventional fuel equipment and the differences in fuel prices. The Netherlands offers incentives to cover the capital expenditures for investing in the deployment of these technologies, but it has not yet overcome one of the key barriers to electrification of heating, which is the relative price of fuels. Electricity (net of taxes and fees) is too expensive compared to fossil-based alternatives to make the electrification of heating viable for most technologies in most industries. In addition, the existing electricity tax and surcharge on electricity increase the price of electricity even further without differentiating the carbon content of the fuels used to produce electricity. This is also the case in other European countries, such as Germany. In order to deploy this technology, the relative price of electricity compared to other fuels would need to decrease in the future. While the carbon levy, and the exemption from energy tax on the use of self-produced electricity, are unlikely to be sufficient for most technologies in most sectors at the current time, the combination with SDE++ subsidies could make the business case for some electrification of low-temperature heating. This also follows from the SDE++ subsidy applications for electric boilers and heat pumps for low temperature heating by the paper and food processing industry.

Hydrogen

Hydrogen has a large potential in end-use sectors like industry. For hydrogen to be viable, there needs to be concerted efforts to develop infrastructure, standards (on the origin of hydrogen and its transport for instance), increased research and development on green production, transport and storage, along with international co-operation. The Netherlands Hydrogen Strategy elucidates similar goals and priorities to that of Germany and the European Union. All three hydrogen strategies set targets from now until 2030 for the installation of gigawatt (GW) for electrolysers, prioritise how to integrate hydrogen production with gas and the electricity grid, recognise the importance of standards (e.g. guarantees of origin), and the importance of international co-operation with neighbours in defining these standards and building infrastructure. The key difference between the three strategies is the explicit mention of carbon contracts for difference (CCfD) for hydrogen in the German and European Hydrogen Strategies. This could be because the Dutch carbon levy in combination with the SDE++ subsidy scheme acts in a similar way. However, the costs for green hydrogen per tonne of CO_2 emission reduction are high compared to competing technologies such as CCS or electrification of heating. As SDE++ subsidies are awarded to applicants who reduce CO_2 in the most cost-effective way, little or no SDE++ subsidy is expected to go to hydrogen. Given the high cost of producing hydrogen, it is unlikely that the carbon levy on its own will be sufficient to make green hydrogen profitable in the short term, which is confirmed in our case study on green hydrogen (Chapter 5). The case study shows that the cost for the construction of a demonstration plant and its subsequent operations are estimated to be EUR 70-75 million for CAPEX and EUR 22-31 million for OPEX. The case study shows that the combination of the carbon levy and the available subsidies through SDE++ are not enough to make green hydrogen cost-effective. To bridge this gap, the Netherlands does mention, in its hydrogen strategy, the desire to create a separate fund to help firms cover operational costs, which could have the same utility as CCfD in German and European contexts if designed appropriately.

The circular economy: recycling of plastics and metals

Recycling of plastics is essential to achieve a circular economy and reap the associated benefits for decarbonisation. Mechanical recycling of plastics is preferred to chemical recycling for environmental reasons. Where mechanical recycling is not possible, chemical recycling reaches better environmental outcomes to incineration of waste for heat or electricity production. Recycling of plastics is critical to the uptake of synthetic feedstock by the chemicals subsector, which is expected to rely heavily on advancements in chemical recycling. This is still a rather nascent technology, which is why further research and innovation is necessary to develop better and more cost-effective ways of chemical recycling. This could be a challenge given that the policy landscaping exercise of the Netherlands found that it is much more focused on deployment rather than on these initial stages. Other challenges are contradictory legislation at the EU-level with the Recycling Directive and the need to improve the traceability and accountability of recycled material, so that its use can be counted towards recycled content targets, e.g. through a mass-balance approach. Policy instruments such as taxes or subsidies should compensate for the price difference between cheaper fossil-based plastics and the more expensive recycled plastics. The main reason for the low uptake of recycled plastics is that there is no separate market for recycled plastics and virgin plastics are generally cheaper and of higher quality. Policies such as minimum recycled content standards, public procurement and public awareness campaigns are needed to create the required (separate) market for recycled plastics. Unlike plastics, the technological processes for the recycling of (major) metals is rather well established, but what remains a challenge for Dutch industry is access to scrap. More co-ordination at the EU level is needed to reclassify scrap and output of steel production, such as slag and fly ash, from ‘waste’ to ‘product’ in order to reduce the administrative burden for companies. This goes hand in hand with increasing possibilities to import scrap from other countries. While the collection and recycling rates for major metals are already high, the collection and recycling rates for minor metals are still low and therefore there is a great potential for improvement here.

Bio-based materials

The large refinery and chemical sectors in the Netherlands offer an enormous opportunity to accelerate the transition to a bio-based economy. Replacing fossil-based materials by bio-based materials, like bioplastics and biofuels, is technologically feasible, but the production of bio-based materials is generally still less cost-effective compared to their fossil counterparts. Additional steps by the Dutch government are therefore needed if the Netherlands wants to achieve its ambition to become one of the most important bio-based hubs in Europe. Subsidies for fossil fuels should be phased out and subsidies for bioenergy and biofuel should apply in the same way to bio-based materials and chemicals. This is necessary to create a level playing field and thus give the bioeconomy a fair chance to thrive. Risks to private sector investments in biofoundries should be reduced to scale up investments. Priority should be given to investments related to conversion technologies. The risk sharing can be achieved through public-private initiatives. One of the most important issues for the development of the bioeconomy is that the demand for bio-based products is lagging behind, which not only hinders investments in production, but also the necessary R&D in bio-based products. Therefore, policies should be implemented to increase demand, for example through quotas, mandates, standards, public procurement and public awareness campaigns.

8.1. Carbon capture utilisation and storage

Key messages

- The Dutch Climate Agreement foresees a significant role for CCS until 2030 and carbon capture utilisation and storage (CCUS) beyond.
- CCUS, however, is still a relatively immature technology with high costs of deployment. In addition, it is not a modular technology, and technological and performance risks, economic risks, and political and legal risks inhibit its greater deployment.
- The United States and the United Kingdom have sought to overcome barriers to CCS and CCUS deployment and share these risks with industry, e.g. by ensuring revenue streams and clearly defining liabilities for leakage.
- The Netherlands has only recently started to overcome these barriers, in particular by introducing a carbon levy and by opening SDE++ to CCS and CCUS in 2020. SDE++ provides funding to overcome the additional costs of reducing carbon emissions by covering part of the operational costs.
- Further improvements are possible by better defining responsibilities and liabilities, for example in the case of carbon leakage and for monitoring the storage sites.

CCUS is one of many technologies that can be used to decrease emissions from industry. Modelling by Berenschot suggests that it will feature prominently in the Dutch industrial transition to net-zero by 2050, particularly for refineries, chemicals, and iron and steel (Berenschot, 2020[1]). Likewise, the Dutch Government views CCS as critical to achieving its 2030 target in the Dutch Climate Agreement (Government of the Netherlands, 2019[2]). Yet, the Agreement emphasises, “CCS should not impede the structural development of alternative climate-neutral technologies or activities for carbon emission reduction” (Government of the Netherlands, 2019[2]). Beyond 2030, CCUS is envisaged, e.g. in the development of synthetic raw materials.

CCS and CCUS are not modular technologies and the scope of CCS and CCUS projects varies widely, as shown in Figure 8.2. For example, since 2004, the K12-B-project has stored a total of only 60 000 tonnes under the North Sea, while the Porthos[1] project is expected to store 2.5 Mt per year.[2] Although the size varies widely, larger CCS projects are generally more cost-effective due to economies of scale (Eccles and Pratson, 2014[3]). In 2020, seven CCS applicants applied for a total of EUR 2.1 billion subsidies from SDE++ for a requested capacity equal to 329 MW, which gives an idea of the size of CCS projects. For the Porthos project alone, approximately EUR 500 million in subsidies will come from the EU and more may come from SDE++. If the cost for Porthos is EUR 53 per tonne (Xodus Advisory, 2020[4]), this would imply that 2.5 Mt emission reduction would cost about EUR 130 million a year.

This section starts with a brief overview of technological readiness of these technologies in industry, followed by an analysis of the current costs associated with their deployment. It then presents the policies in place in the Netherlands to support CCUS, before reviewing instruments implemented in other countries, including tax incentives to facilitate capital investments, options for ensuring revenue streams for CCUS, and public funding incentives to facilitate upfront capital investments. It then overviews a number of other challenges facing CCUS, e.g. lack of clarity on liability for leakage and regulation that holds back the transportation of carbon.

8.1.1. Technological Readiness Levels of CCUS

To date, CCUS globally has mainly been deployed in natural gas processing and ammonia (i.e. capturing via chemical absorption) (IEA, 2020[5]; IEA, 2019[6]). Other large-scale industrial applications are less mature – e.g. for iron and steel as well as hydrogen. Figure 8.1 summarises the Technological Readiness Levels across the chain of CCUS. In terms of usage, CO_2 is typically used in urea production (for nitrogen-based fertilisers) and carbonated drinks. Either of which stores the CO_2 only briefly before releasing it later into the atmosphere. Other promising uses are opening, such as advancements in using CO_2 in building materials and synthetic feedstocks, which are in the demonstration and large prototype phases, respectively as shown on Figure 8.1 (IEA, 2020[5]).

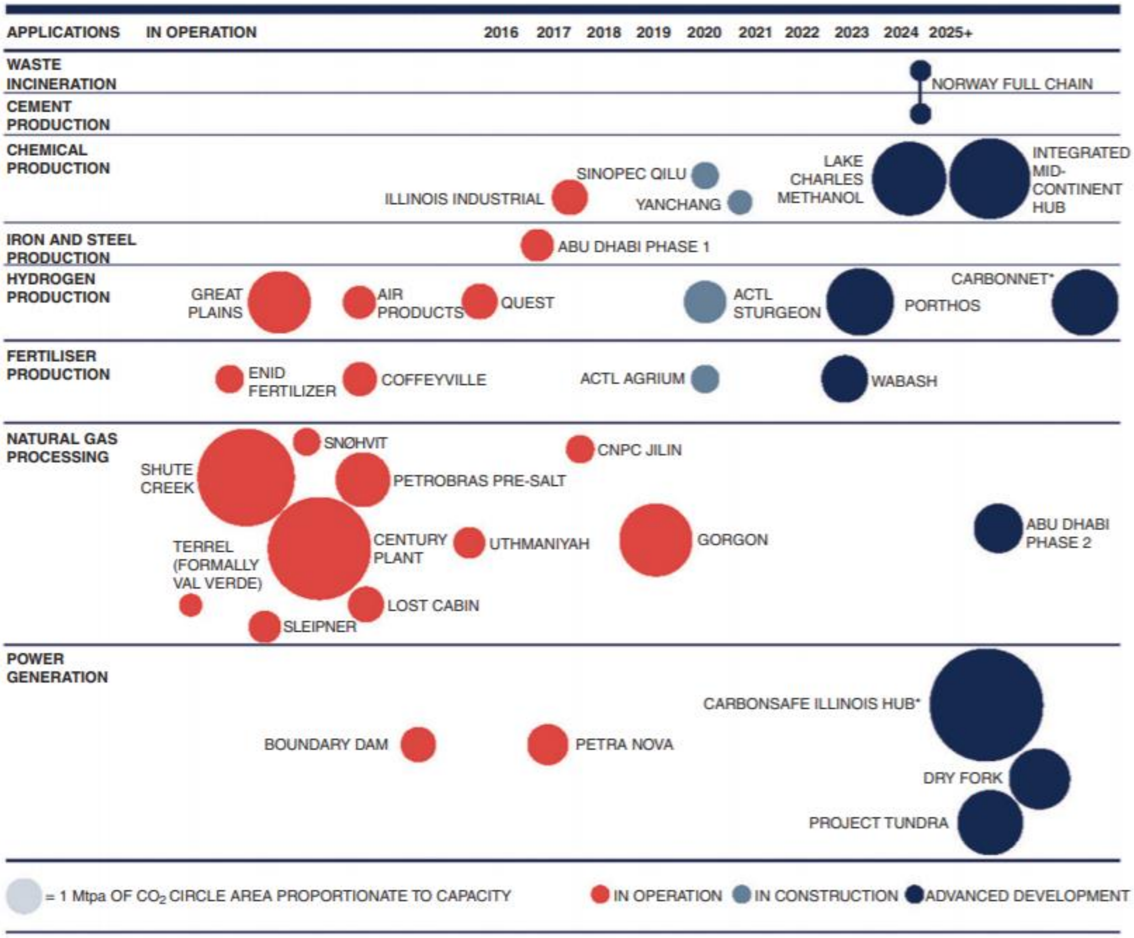
Figure 8.1. Technological readiness across the CO_2 value chain

Source: IEA (2020[5]).

Enhanced oil recovery (EOR) has dominated CO_2 storage for the last five decades (IEA, 2020[5]). EOR is the extraction of crude oil from an oil field using the injection of carbon dioxide and water. EOR has provided a value on CO_2, roughly estimated at USD 15 per tonne of CO_2 in the United States, where the bulk of industrial CCUS projects are located (Friedmann, Ochu and Brown, 2020[7]; Beck, 2020[8]). Geological storage is starting to become a viable alternative, with five large-scale sites operating globally (Figure 8.1) (IEA, 2020[5]). Figure 8.2 summarises all industrial applications of CCUS by company, sector, and capacity as of 2020, according to the Global CCS Institute (Beck, 2020[8]).

Direct Air Capture (DAC) is more and more attractive since, in contrast to other CCS methods, it can be a modular technology. DAC technologies capture CO_2 directly from the atmosphere using chemicals (that either bind or stick to it), which can be stored and re-used (Global CCS Institute, 2019[9]). On the one hand, there is large-scale infrastructure for DAC using water that contains hydroxides that capture CO_2 from the air, but this requires temperatures above 800°C, which is typically provided with natural gas (Global CCS Institute, 2019[9]). On the other hand, DAC is a modular technology based on amine materials (which requires lower temperatures) that has the potential for future cost reductions through mass production (Global CCS Institute, 2019[9]).

Figure 8.2. Large-scale CCS projects by industry



Source: Beck (2020[8]).

8.1.2. Costs of CCUS and regulatory risks

Costs remain a prohibitive factor for many industrial applications of CCUS. Capture, transport and storage, combined with a low valorisation of CO_2, make it a challenge to ensure a viable revenue stream (International Association of Oil and Gas Producers, 2020[10]).

Capture costs

Natural gas processing and ammonia production have the lowest costs (Table 8.1) – which is driven partly by the concentration of CO_2 from the point source and the capture technology (IEA, 2019[6]). On top of this, natural gas processing facilities have frequently used EOR storage, which places a value on CO_2 (making the projects economically viable). Iron and steel still has some of the highest costs (the range reflects the varying capture technologies) (IEA, 2019[6]).

Table 8.1. CCUS, capture cost ranges

Industry	CO_2 Concentration	Average capture cost (USD per tCO_2)
Natural gas processing	96 to 100%	15 to 25
Ammonia	98 to 100%	25 to 35
Ethylene oxide	98 to 100%	25 to 35
Hydrogen (Steam Methane Reforming)	30 to 100%	15 to 60
Iron and steel	21 to 27%	60 to 100

Note: Based on typical CCUS projects in the USA.
Source: IEA (2019[6]).

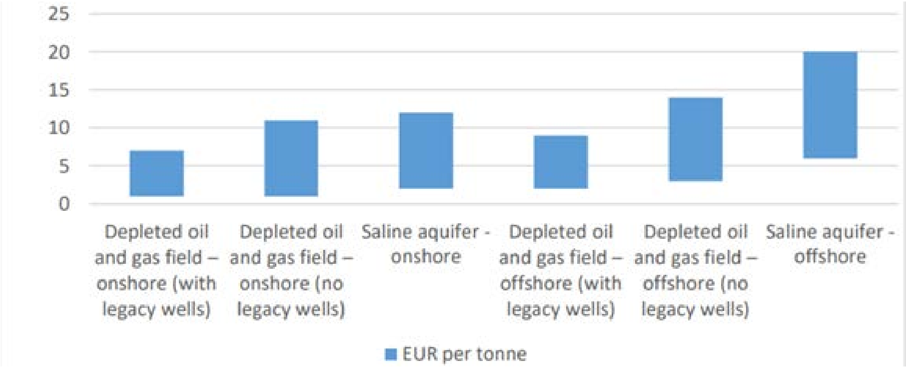
Transport costs

In Europe, reusing offshore oil and gas pipelines to transport CO_2 is estimated to be 1-10% of the cost of building a new CO_2 pipeline (International Association of Oil and Gas Producers, 2020[10]).Offshore CO_2 pipelines costs are estimated to be between EUR 2-29 per tonne of CO_2 in Europe (International Association of Oil and Gas Producers, 2020[10]). Transport costs by ships typically range from between EUR 10-20 per tonne of CO_2, which is preferable for small volumes over longer distances in Europe. The great uncertainty about the costs of CCS is reiterated by the PBL report on the SDE++ 2020 subsidy, in which the transport costs for Porthos are estimated at approximately EUR 45 per tonne of CO_2, but in which, it also states that previous estimates were only EUR 10 per tonne (EBN and Gasunie, 2017[11]) and EUR 30 per tonne in the PBL draft advice (PBL, 2020[12])..

Storage costs

The cost of CO_2 storage varies between locations, but in general, offshore deep saline aquifers have the highest costs in Europe and depleted oil and gas fields have the lowest costs because of pre-existing infrastructure that can be reused (Figure 8.3). However, the storage capacity in deep saline aquifers is much greater compared to onshore basins or offshore depleted oil and gas fields (International Association of Oil and Gas Producers, 2020[10]), which allows for better prospects for scaling-up and cost reduction (International Association of Oil and Gas Producers, 2020[10]). Economies of scale can be achieved for both transportation and storage costs, making larger CCS facilities more cost effective (Eccles and Pratson, 2014[3]). A cost of EUR 10-15 per tonne of CO_2 is also in line with the estimate of EUR 15 per tonne of CO_2 for Porthos (PBL, 2020[12]).

Figure 8.3. Storage costs in Europe per formation type

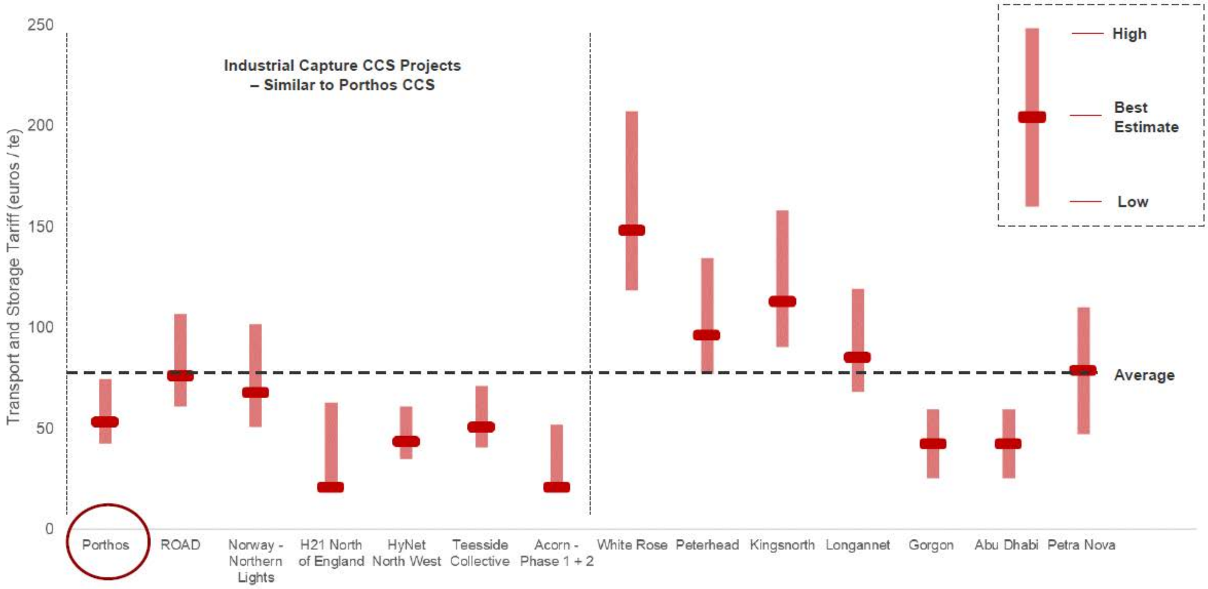


Source: International Association of Oil and Gas Producers (2020[10]).

Projected Costs for Porthos and other CCS projects

Porthos is the most advanced CCS project in the EU. Porthos stands for Port of Rotterdam CO_2 Transport Hub and Offshore Storage. For a period of 15 years, Porthos will store approximately 2.5 Mt CO_2 per year under the North Sea, supplied by Air Liquide, Air Products, ExxonMobil and Shell locations in Rotterdam. This corresponds to 10% of the total emissions produced by Rotterdam's industrial sector, making an important contribution to achieving the climate goals of the Netherlands.

Figure 8.4. Transport and Storage Tariffs of CCS projects



Source: Xodus Advisory (2020[4])

Xodus Advisory (2020[4]) estimate that a transport and storage tariff of EUR 53 per tonne would be enough to make the Porthos Transport and Storage project profitable. They calculate this tariff by comparing Porthos with other CCS projects yielding an average tariff of EUR 47 per tonne. However, this average is calculated based on a wide range of tariffs between EUR 20-100 per tonne for other projects, and by comparing different characteristics of CCS projects they arrive at EUR 53 per tonne for Porthos. Another approach, called the bottom-up analysis, is more like a cost-price approach recreating the Porthos design, and yields an average transport and storage tariff of EUR 51 per tonne with a range between EUR 45-60 per tonne. Both the figures from the Porthos project and the calculations for Porthos conducted by Xodus show that the share of the cost relating to CAPEX (EUR 24 per tonne) is about the same as the share of the cost relating to OPEX (EUR 22 per tonne).

Figure 8.4 shows the transport and storage tariffs of other CCS projects. It shows that Industrial CCS projects generally have lower transportation and storage costs compared to non-industrial CCS projects. On average, EUR 50 seems sufficient to cover the costs of CCS. Of the Industrial Capture CCS projects, the cost for Porthos appears to be average compared with the costs for the other Industrial Capture CCS projects.

Liabilities for CCS leakage

A continual hurdle for CCUS is the question of who can store what and where, the liability and the permanence of CO_2 storage, which challenges traditional risk and liability models. Modelling indicates that the risk of leakage rises throughout a project's first injection phase, then reduces substantially until the site is closed and the maximum storage potential is reached (however, a small risk does remain) (Havercroft, 2020[13]). To make CCS projects viable, regulators and policymakers must allocate responsibilities for CCS operations within a project's lifecycle. Tension can arise between regulators (who represent society's interests) and parties (who would like to invest and deploy the technology).

These questions remain unanswered for Dutch industry. The EU's CCS Directive on the Geological Storage of Carbon Dioxide created some harmonisation between EU Member States and started to answer these questions in June 2009. This Directive has been transposed into Dutch legislation in the Dutch Mining Act (Lako et al., 2011[14]). In September 2011, the Mining Act and subordinate legislation were amended in order to implement the CCS-Directive (2009/31/EC) and the OSPAR Decision 2007/2 (CMS, 2020[15]). This includes, among others, requirements in relation to the contents of the permit (application) and regulations pertaining to the transfer to the State of the responsibility for stored CO_2 after it has been established that this substance has been safely and permanently stored. However, the monitoring plan, the termination plan and the provision of financial security is supposed to be part of the CO_2 storage permit. The final decision on the permit application is taken by the Minister of Economic Affairs and Climate. The Dutch Climate Agreement states that it will address these outstanding issues related to monitoring and liability but has yet to do so.

The European Union amended the Environmentally Liability Directive, which enables national regulators to impose obligations on operators to undertake remedial or preventive measures, when damage has occurred or is threatened. Yet, this is still unclear in the Netherlands. A common element of many CCS-specific legal and regulatory frameworks is the inclusion of detailed requirements regarding site selection, monitoring and verification. Most regimes front-load requirements on operators (Havercroft, 2020[13]).

Transfer of stewardship remains an open question in the Netherlands. Operators also need assurance that storage operations are not liable in perpetuity. Some frameworks, therefore, transfer this liability to the state's relevant authority (e.g. Canada, United States, European Union). The EU instituted the European Commission Storage Directive to transfer liabilities, which many Member States have transferred directly into national legislation. However, those who want to foster the uptake of this technology have gone several steps further. For example, the United Kingdom's extensive transfer provisions encompass any potential civil claim or administrative liability arising from a leakage, *whether the leakage occurred before or after the transfer* (Havercroft, 2020[13]).

Regulation related to the transport of carbon

Two international agreements further hinder the deployment of the CCUS – i.e. the London Protocol and the ETS. The Dutch Government committed in the National Climate Agreement to try to amend these rules to ease the deployment of the technology for Dutch Industry (Government of the Netherlands, 2019[2]).

Article 6 of the London Protocol governs Parties' export of wastes for dumping in the marine environment (IEA, 2011[16]; Global CCS Institute, 2019[9]). An unintended consequence of this Protocol is that it effectively bans transboundary transportation of CO_2 for geological storage, i.e. parties interpret the legislation as prohibiting the export of CO_2 from a contracting party to other countries for injection into sub-seabed geological formations. The signatories to the London Protocol passed an amendment to resolve this issue in 2009; however, two thirds of the Protocol's contracting parties must ratify the amendment for it to come into force (Global CCS Institute, 2019[9]). So far, only Norway, United Kingdom, Netherlands, Finland, Estonia and Iran have done so (Global CCS Institute, 2019[9]).

The status of some forms of CO_2 transportation under European legislation also remains uncertain. Under the EU ETS, covered installations are not required to surrender emissions allowances for the CO_2 they have successfully captured for subsequent transportation by pipelines and geological storage, and they can benefit from the EU ETS carbon price by selling the corresponding allowances (Global CCS Institute, 2019[9]). The scope of the Directive, however, applies narrowly to CO_2 transport by pipelines and those installations that plan to transport CO_2 by other means, e.g. by ships or trucks, would still need to pay for these emissions (Global CCS Institute, 2019[9]).

Risk of CCS translating in more fossil fuel consumption

In addition to the technical costs and risks associated with the feasibility of CCS, there may also be unintended negative effects of CCS on fossil fuel consumption. The risk is that CCS is used as an excuse to avoid further reductions in fossil fuel consumption. Budinis et al. (2018[17]) shows that in a scenario without CCS, 26% of worldwide fossil fuel reserves would be consumed in 2050, against 37% consumed when CCS is available. This difference becomes even larger in 2100. If CCS is the most cost-effective way of reducing CO_2, it will become less attractive for companies to invest more in in the necessary R&D and use of other sustainable alternatives. This may slow down the development of sustainable alternatives such as renewable energy.

While CCS can reduce CO_2 emissions in heavy industry due to economies of scale, CCS could have unintended consequences for the decarbonisation of other sectors. If heavy industry can continue to use and process fossil fuels on a large scale, this would undoubtedly make fossil fuels cheaper elsewhere in the supply chain. As a result, lower emissions in industry risk to be partly offset in the future by increases in CO_2 emissions elsewhere in the supply chain.

Another problem with relying on CCS is that not 100% of CO_2 can be captured (as mentioned in relation to the different costs and varying concentration of CO_2 streams). Budinis et al. (2018[17]) show that these residual CO_2 emissions are the main factor limiting the long-term uptake, more than the costs of CCS.

The strategy of the Dutch government to limit the eligibility of CCS for the main subsidy scheme SDE++ to 2035 may strike the right balance between relying on CCS in the short-run, while maintaining the incentives for the development of sustainable alternatives required in the long-term.

8.1.3. Instruments to increase the uptake of CCS in the Netherlands

National policies

The greatest support for CCS and CCUS comes from **SDE++,** a subsidy for applying CO_2 reducing techniques (Chapter 5). This subsidy is intended for companies and organisations in sectors such as industry, mobility, electricity, agriculture and the built environment. The SDE++ builds on the former SDE+ scheme and extends the scope beyond technologies for sustainable energy production towards technologies that reduce CO_2 emissions such as CCS. In this way, the government wants to ensure that the zero-carbon transition in the Netherlands remains feasible and affordable. A total budget of EUR 5 billion is available in SDE++, of which a significant share is expected to go to CCS and/or CCUS. Indeed, in the first SDE++ call for tender, seven CCS projects were received, totalling around 2.3 million tonnes of captured CO_2 annually over 15 years, and requesting EUR 2.1 billion of total subsidies over the same period.

Since 2020, **Demonstration of Energy and Climate Innovation (DEI+)** subsidies are also open to support pilot and demonstration projects for CCS. The DEI+ transformed the DEI to become a vehicle for development of new and innovative technologies for CO_2-reduction from industry. However, the subsidy percentage depends on the type of project. For DEI+, the maximum budget is EUR 15 million per project.

In addition to support for CSS projects, EUR 10 million of public funding is also available for CCS-related R&D.

The **Dutch carbon levy**, which is discussed in detail in other chapters, is another way in which the Dutch government can make the use or storage of CO_2 more attractive compared to emitting CO_2 and paying a higher price for these emissions. Such a commitment to carbon pricing trajectories can render CCUS investments more viable. For example, the American Recovery and Reinvestment Act of 2009 provided USD 2 billion to develop CCS technologies for coal-fired power plants. Similarly, in 2009 the European Energy Programme for Recovery dedicated EUR 1 billion to co-finance CCS projects.

EU policies

As a member of the European Union, the Netherlands is also eligible for European funds, such as the EU's Innovation Fund and Horizon 2020. Since the Netherlands is a small open economy, it could be more efficient to invest in CCS, and particularly in the R&D component of CCS, at the EU level.

Innovation Fund (Replacement of NER 300)

The EU's Innovation Fund is the largest for financing CCUS in Europe at EUR 10 billion between 2020 and 2030. It finances innovative low-carbon technologies and processes in energy intensive industries, CCUS, renewable energy and energy storage projects. Innovation Fund grants can be combined with other funding sources; for example, with EU instruments like Horizon Europe or Connecting Europe Facility, with national programmes, or with private capital. Up to 40% of grant payments will be given in the project preparation phase, based on pre-defined milestones. The remaining 60%, linked to innovation, are based on verified emissions avoidance outcomes and can continue for up to ten years. The fund's simplicity, flexibility, increased synergies and streamlined governance are a result of lessons learned from its predecessor, the NER300 programme. The first call for proposals was made in 2020, with regular calls expected thereafter.

Horizon 2020

There are a few CCUS projects presently funded under H2020 (IEA, 2020[18]):

- LEILAC (Low Emissions Intensity Lime and Cement), which will pilot a breakthrough technology that has the potential to enable both Europe's cement and lime industries to reduce their emissions dramatically and cost-effectively. LEILAC is based on an innovative carbon capture and storage technology that enables capture of the process emissions in cement production. The EUR 21 million project has received EUR 12 million via the H2020 programme.
- STRATEGY CCUS, a three year programme (2019-22), which supports the development of low-carbon energy and industry in the Southern and Eastern regions of Europe. The programme aims

to identify potential CO_2 transport corridors in relation to industry clusters that can connect them with North Sea CCUS infrastructure is planned. The EU contribution for this project amounts to almost EUR 3 million.

- STEMM-CCS (Strategies for Environmental Monitoring of Marine Carbon Capture and Storage), a project that aims to address gaps in knowledge and capability needed for monitoring offshore carbon capture and storage sites. The EU contribution for this project amounts to over EUR 15 million.

8.1.4. Advancing the uptake of CCUS and CCS: an international comparison

Carbon capture and storage policies in Germany

Unlike the United States and the United Kingdom, which are covered in the next subsection, Germany is not much ahead of the Netherlands in terms of CCUS and CCS.

CCS (for power plants) has experienced strong public opposition and storage of CO_2 is even forbidden in several states. Still, the government realises the need for CCS (or CCU) to decarbonise the large cement industry. As explained in Chapter 6, an innovation funding programme for CCS and CCU is currently being prepared to support large-scale demonstration projects.

The main support for CCS and CCUS comes from a programme on CO_2 avoidance and use in basic industry, which is part of the Climate Protection Program 2030. The focus of this program is on the reduction of process-related greenhouse gas (GHG) emissions in the basic materials industry. The main objective is to further develop central components of the process chain in the field of CO_2 CCS and CCU towards market maturity and thus to create the necessary technical prerequisites for a permanent reduction of process-related greenhouse gas emissions. This involves the entire value chain covering CO_2 capture, transport and storage. This programme provides a total of EUR 500 million subsidies for CAPEX for the years 2021-25. Given the high cost of CCS, this is expected to cover only a few CCS projects.

For investments in R&D, the Hightech-Strategy 2025 and FONA 3 provide EUR 80 million in grants for research on carbon direct avoidance, CCU and CCS.

Compared to the Netherlands, CCS is not widely supported in Germany, but support for CCS is increasing. There are some subsidies to cover CAPEX for CCS, but there is hardly any support to cover OPEX for CCS in Germany as is the case in the Netherlands through SDE++.

Overcoming barriers to capital and operational costs via tax incentives in the United States

To date, the United States has the majority of CCUS installations globally, mainly for Enhanced Oil Recovery (IEA, 2019[6]). The United States has relied primarily on tax incentives to incentivise the use of CCUS, such as the 45Q tax credit (which can be combined with California's Low Carbon Fuel Standard) or accelerated depreciation rates targeted at CCUS projects; and a new incentive may apply within the next few years, such as Master Limited Partnerships. All of these help to create viable revenue streams for CCUS, helping industry to cover the capital and operational costs of CCUS. The Netherlands also offers a tax incentive under the energy investment allowance (EIA) tax, which is allows deductions from taxable income that relate to capital expenditures of specific investments. On average the effective allowance rate has varied over the years covering between 10-15% of capital expenditures (CE Delft, 2021[19]). This said, understanding how the corporate income tax framework works, as a whole, is crucial to understand any underlying technological biases that may exist. For example, with respect to electricity generation, current corporate income tax frameworks can create a technological bias away from generation technologies with high capital costs (Dressler, Hanappi and van Dender, 2018[20]).

The United States recently revised its 45Q Tax Credit (in the Budget Act of 2018), which offers *up to* USD 50 per tonne of CO_2 captured for CCUS operations brought online by 2026 (Krupnick and Bartlett, 2019[21]). This is a steep increase from the 2008 version that offered a maximum of USD 20 per tonne of CO_2 captured (Nagabhushan and Thompson, 2019[22]). The compensation depends on the type of storage: storage through EOR is between USD 10-35 per tonne of CO_2, while storage in saline reservoirs starts at USD 20 ramping up to USD 50 per tonne of CO_2 over ten years (Krupnick and Bartlett, 2019[21]). In its present formulation, the tax credit does not apply to carbon that is captured for re-use, e.g. for urea production or carbonated beverages, since this is not permanent storage (Krupnick and Bartlett, 2019[21]). Moreover, the latest revision eliminates any cap on credits (Nagabhushan and Thompson, 2019[22]). While the 45Q is administratively straightforward, and a fixed price incentivises the most efficient projects, the drawback of a fixed tax credit is the potential overcompensation of some emitters and failure to incentivise others (BEIS, 2018[23]). The Department of Business, Industry and Energy in the United Kingdom is investigating whether tax credits, similar to that of 45Q, could be used strategically to focus the development of CCUS infrastructure in strategic cluster locations to create efficient supply chains for CO_2 (BEIS, 2018[23]), and by consequence, minimise chain risks related to transportation and storage.

In addition, California modified its Low Carbon Fuel Standard (LCFS) on 1 January 2019 to include Direct Air Capture. What this means, in practice, is that any entity that captures and sequesters a tonne of CO_2 from the air can claim a tax credit (at an average price of USD 160 per tonne of CO_2) (Rathi, 2019[24]). In the LCFS, there is no specification of *where* the CO_2 is captured and stored. Therefore, oil and gas facilities with CCS, refineries with CCS, and other CCS projects (e.g. Ethanol with CCS) located anywhere can claim a credit, *if* the fuel is sold for transportation in California, whilst DAC located anywhere can claim the credit (Beck, 2020[8]). This combined with the 45Q means that a company can be compensated close to USD 200 per tonne of CO_2 for storage underground (Rathi, 2019[24]; Beck, 2020[8]). The largest DAC plant in the world is presently under construction in California and the company, Carbon Engineering, claims that this is only feasible because of the combined tax credits that make the project economically viable (Rathi, 2019[24]). States like Montana, Louisiana, Texas and North Dakota also provide tax incentives for CCS deployment, while others like Wyoming, are aiming to substantially progress CCS (Global CCS Institute, 2019[9]).

Accelerated depreciation rates specifically targeting CCUS infrastructure occurs under certain conditions in the United States, which lowers the net present value of taxes paid over the life of a project. In 1986, the US Government introduced the modified accelerated cost recovery system (MACRS), which is a depreciation method that allows tangible investment by firms to be recovered for tax purposes. This takes place over a specified time period through annual deductions for energy projects, in a very favourable five-year MACRS depreciation category (without this it would have depreciated over 20 years) (Friedmann, Ochu and Brown, 2020[7]). Presently, a carbon capture project that *earns the bulk of its revenue from the sale of captured* CO_2*,* is allowed to depreciate the carbon capture equipment over a five-year MACRS cost-recovery period by virtue of the CO_2 falling into Asset Class #28, "Manufacture of Chemicals and Allied Products," (Friedmann, Ochu and Brown, 2020[7]). An MACRS-like mechanism could be extended to CCUS that is permanently stored rather than sold. Beck (2020[8]) argues that this should be extended to all types of CCUS infrastructure to enable investment in CCUS.

Master Limited Partnerships (MLP) Tax Advantages is yet another option, which has been used to fund over USD 500 billion worth of American oil and gas pipelines as well as some coal-related infrastructure. This is presently under review by Congress in the United States to deepen investment in new energy technologies like CCUS (Financing Our Energy Future Act of 2019/2020) (Friedmann, Ochu and Brown, 2020[7]). An MLP is a pass-through entity for tax purposes, which means that taxable profits earned by a project are only taxed once — at the investor level. Otherwise, profits earned by a corporation that files under Subchapter "C" of the tax code may be taxed twice depending on their structure: first, at the level of the corporation via the corporate income tax, and second, at the shareholder level on dividends received (Friedmann, Ochu and Brown, 2020[7]).

There is further discussion on whether tax-exempt Private Activity Bonds (PAB) could be used to expand CCUS infrastructure in the United States, which is drawing on the success of creating solid waste, hazardous waste, and sewage facilities (Friedmann, Ochu and Brown, 2020[7]; Beck, 2020[8]). PAB lowers the costs of capital for projects by providing debt financing at interest rates that are more favourable, functioning like a public guarantee. Bonds are actually issued by the governmental body on behalf of the private party that will use the capital equipment when it is expected to benefit the public. However, *this private party is obligated to make the payments on the principal and interest*. Benefits of accessing tax-exempt bond market are lower interest rates and more favourable and flexible borrowing terms (Friedmann, Ochu and Brown, 2020[7]; Beck, 2020[8]).

Facilitating investment in CCUS in the United Kingdom

In Europe, the United Kingdom has the most CCUS projects, with six projects planned and existing (International Association of Oil and Gas Producers, 2020[10]). The United Kingdom, however, stepped up its commitment to CCUS even further, as part of its COVID-19 recovery package at the end of 2020. Prime Minister Johnson announced his Ten Point Plan (TPP) in late November 2020, doubling previously announced funding to CCUS in March 2020 (HM Government, 2020[25]). The new commitments under the TPP include: invest GBP 1 billion to support CCUS in four industrial clusters, creating "Super Places" (defined as hubs where renewable energy, CCUS and hydrogen congregate) in the North East, the Humber, North West, Scotland and Wales; establish CCUS in two industrial clusters by the mid-2020s (committing to an additional GBP 200 million); and aim for four of these sites to be completed by 2030 (if possible) (HM Government, 2020[25]). This step-up in ambition will help the United Kingdom meet its target to capture 10 $MtCO_2$ annually by 2030.

Ensuring revenue streams

As explained in Section 8.1.2, the costs of CCUS can still be prohibitively high and great uncertainty surrounds the valorisation of CO_2. The UK Department of Business, Energy and Industrial Strategy (BEIS) will release a plan in 2021 on how to guarantee a revenue stream for industry, which was affirmed in the Prime Minister's Ten Point Plan (HM Government, 2020[25]). This will build on prior work in the UK Government, *Industrial Carbon Capture Business Models*. One of the likely proposals is the creation of a Contracts-for-Difference.

A contract-for-differences (CfD) is a potential avenue for the deployment of the CCUS – presently, under consideration in the United Kingdom (BEIS, 2018[23]) as well as proposed by IDDRI[3] (Sartor and Bataille, 2019[26]). A CfD is between two parties, where the buyer guarantees a price (known as the "strike" price), in this case for CO_2 over a given period. The Buyer agrees to pay the difference between the Strike price and the market price of CO_2. The United Kingdom is drawing on its experience with CfDs in the power sector. An electricity generator receives a strike price from the government-owned Low Carbon Contracts Company – which pays the generator the difference between the strike price and the market price of electricity (BEIS, 2018[23]). The Low Carbon Contracts Company is a private limited company owned by the Secretary of State for Business, Energy and Industrial Strategy (BEIS), with the primary role to manage the CfDs as well as the Supplier Obligation Levy that funds CfD payments. Sartor and Bataille (2019[26]) estimate, for example, that for iron and steel with Steam Methane Reforming of Hydrogen with CCS the strike price would need to be around USD 50 per tonne of CO_2.

The CfD would provide the private sector with certainty about returns from capturing CO_2; the risks of bringing the project online will stay with the private sector. This makes incentives cost-effective, while preventing moral hazard. If the costs of capture are higher than expected, then the government could offer liability caps for unexpected OPEX and CAPEX.

CfD is not expected to be a necessary policy instrument in the Netherlands, as the revenue streams from SDE++ subsidies, lower amounts of paid carbon levy and the selling of dispensation rights are expected to already fully cover the cost of CCS.

RD&D in CCUS

Prime Minister Johnson committed GBP 1 billion to a CCUS Infrastructure Fund in his Ten Point Plan by 2025; the details of which will be released in 2021 (HM Government, 2020[25]). The Ten Point Plan states, “Our GBP 1 billion CCUS Infrastructure Fund will provide industry with the certainty required to deploy CCUS at pace and at scale”. The ambition is to capture and store 10 Mt of CO_2 per year by facilitating the deployment of CCUS in four clusters by 2030. These clusters will be the starting point for a new carbon capture industry, which could support up to 50 000 jobs in the United Kingdom by 2030, including a sizeable potential to export their technologies. This commitment has come on top of already existing innovation programmes in the United Kingdom that seek to advance technologies for CCUS even further: CCUS Innovation Programme and the CCU Demonstration Programme.

Research: CCUS Innovation Programme (2018-21)

The UK CCUS Innovation Programme offers grant funding for projects that develop novel technology and processes to reduce the cost of deploying CCUS (BEIS, 2020[27]). The programme started in July 2018 and runs until the end of 2021. GBP 24 million has been allocated for feasibility studies, industrial research, experimental development projects, and infrastructure projects. Below is a list of projects funded under the scheme (as of 2020):

- **Negative CO_2 emissions from full scale BECCS utilising non-amine CCS chemistry**: C-Capture designs chemical processes for carbon dioxide removal. In collaboration with the Drax Group, carbon capture will progress its bioenergy and carbon capture and storage (BECCS) project at Drax Power Station in North Yorkshire in which CO_2 is captured in a plant producing power from biomass. The work includes: an extension of carbon capture’s existing pilot facilities at Drax, plant performance and optimisation trials, a chemistry validation and testing programme, and process design development to move towards commercial scale deployment, including re-purposing the existing Drax infrastructure.
- **ACORN CCS – Front end engineering design (FEED) Programme:** Acorn is a full chain CCS project in north east Scotland. The goal of the project is to develop infrastructure and storage using the UK’s built (offshore gas pipelines) and natural assets (at lowest cost). The CCUS funding is progressing the detailed engineering for this project towards a final investment decision in 2021.
- **Integration of CCUS technology to a 200 MW Open Cycle Gas Turbine TiGRE Project located in the UK Southern North Sea:** TiGRE™ projects under development by the TiGRE Group assess the feasibility of integrating conventional best-practice CCS technology into a real-life production facility.
- **Translational Energy Research Centre (PACT-2):** Funded by BEIS and the European Regional Development Fund, it establishes a scale of world class research infrastructure that supports the long-term competitiveness and international reputation of the United Kingdom in CCUS. The centre’s state-of-the-art facilities will enable UK companies to develop, de-risk, and accelerate their innovations under realistic operating conditions. It will bridge the gap between fundamental research and pilot-scale demonstrations, whilst providing a training ground for the next generation of researchers.
- **HyNet Phase 1:** HyNet is an integrated blue Hydrogen / CCUS project to decarbonise the North West industrial cluster. Phase 1 of this ambitious but deliverable project is to develop the CCUS infrastructure to capture CO_2 emissions from industry and store them in the Liverpool Bay depleted gas fields.

- **Clean Gas Project & Tees Valley cluster Development Select Phase**: OGCI Climate Investments has entered a strategic partnership with BP, ENI, Equinor, Occidental Petroleum, Shell and Total to progress the Clean Gas Project, the United Kingdom's first commercial full-chain CCUS project in Teesside. This feasibility study is an important milestone to build the world's first commercial CCUS project for a gas-fired power plant. The Clean Gas Project will use natural gas to generate power, with CO_2 then captured and transported by pipeline for storage in a geological formation deep under the southern North Sea. The infrastructure created would enable industrial emitters in Teesside and elsewhere to capture and store CO_2 from their processes.
- **Allam-Fetvedt Cycle Power Plant for UK Deployment**: 8 Rivers Capital is conducting a feasibility study for the deployment of the Allam-Fetvedt power cycle. The Allam-Fetvedt Cycle or Allam Cycle is a process for converting gaseous fuels into thermal energy, while capturing the generated carbon dioxide and water. This technology achieves highly efficient and low cost electricity generation with zero emissions through use of a novel supercritical carbon dioxide as the primary process fluid. This technology has been successfully demonstrated at 50 MW scale in La Porte, Texas, and is now being commercialised by NET Power LLC, with 8 Rivers leading development of full-scale commercial projects.

Deployment: CCU Demonstration Innovation Programme (Phase 3)

This programme was designed to encourage industrial sites to capture carbon dioxide which could then be used in industrial applications. The goal of the programme is to demonstrate CCU at a number of key industrial sites in the United Kingdom; to demonstrate and accelerate cost reductions of about 20-45% in carbon capture technology, or about GBP 10-20 per MWh; to encourage a project pipeline of follow-on CCU projects that will help less mature, but more novel technology to be demonstrated at scale; to improve understanding of the cost and performance of carbon capture technology and to de-risk the capture technology (BEIS, 2019[28])

The programme is now in Phase 3: Funding for construction and demonstration**.** Phase 3 offered GBP 14 million grant funding for a number of construction and demonstration projects. The projects provide: learning opportunities about the best way to configure plants and crucial operational data and experience on performance and degradation of the plants. The funding for projects is up to 24 months; all of which finished before 31 March 2021 (BEIS, 2019[28]).

Phase 2 called for FEED studies for five projects for GBP 5 million (BEIS, 2019[28]). The studies produced cost estimates for the construction and operation of demonstration CCU at the host site. The costs estimates were expected to be within an accuracy of 15% to allow the BEIS Developer to make a final investment decision. The funding for this phase was 6 to 9 months and completed by November 2019.

Phase 1 focused on an initial scoping study for an engineering supplier to work on BEIS' behalf with potential host sites, carbon dioxide users and technology suppliers to produce site-specific cost estimates for deploying CCU at UK industrial sites.

8.1.5. The policies needed to further encourage CCUS

The technological challenge of CCUS in industry, as compared to technologies like solar photovoltaics or wind, is that it is not a modular technology. With a modular technology, investors are more flexible and can more easily reduce costs via learning-by-doing, as well as easily replicate. Chemical absorption (for capture), for example, needs to be tailored and designed for each company. Nevertheless, if more companies use CCUS at the global level, then the costs may go down, and there are still significant cost reductions to be reaped.

However, it is not only technical challenges that hold back CCUS deployment. Greater de-risking may help companies that presently face a number of risks (BEIS, 2018[29]; IEA, 2019[6]; Global CCS Institute, 2019[9]):

- **Technology and performance risks**: those associated with the integration of capture technology into existing facilities (e.g. a temporary shutdown of operations), challenge of space restrictions of existing sites, or performance (e.g. lower capture rates than expected).
- **Economic and market risks**: capital and operational costs, uncertainties about markets for lower-carbon materials through CCS, competitiveness, and valorisation of CO_2.
- **Political and legal risks:** associated with policy, regulation, as well as liabilities.
- **Cross-chain risks**: associated with the integration and co-ordination across parts of the CCUS chain – e.g. transportation and storage.

Overcoming these requires government involvement to bring regulatory clarity, share the ownership of these risks and financially contribute in order to create some revenue certainty and incentivise investments.

The Netherlands has dedicated innovation funding to overcome the technological barriers in CCUS. DEI+ subsidy supports pilot and demonstration projects for cost-effective CO_2 reductions in 2030. CATO is the Dutch national R&D programme for CO_2 capture, transport and storage in which nearly 40 partners co-operate. However, the economic, legal risks and cross-chain risks remain:

- The primary funding mechanism for CCS/CCUS in the Netherlands is the SDE++ Scheme, but the restrictions for the use of the scheme for CCS causes great uncertainty for industry (Government of the Netherlands, 2019[2]). SDE++ can only be used at sites for CCS where there is no demonstrably cost-effective alternative available at the time of the application (which will be determined each year based on independent advice) (Government of the Netherlands, 2019[2]). In addition, there is a cap on the level of emission reductions via CCS that SDE++ scheme will fund: in total, a maximum of 7.2 Mt CO_2 by 2030 will be funded. Lastly, after 2035, no CCS applications will be funded under SDE++, which underlines the temporary nature of this subsidy to encourage cost savings and the development of alternatives (Government of the Netherlands, 2019[2]).
- Under the Climate Agreement, Dutch industry can only store CO_2 under the sea. In other words, no onshore storage is permitted, which is common practice in other European countries (Government of the Netherlands, 2019[2]). For example, five federal states in Germany ban storage of CO_2, which is why the large potential for CO_2 in Northern Germany is untapped (due largely to public opposition). Similar bans exist in Austria, Croatia, Czech Republic, Latvia, Slovenia, Sweden, the United Kingdom, and Norway (International Association of Oil and Gas Producers, 2020[10]). The Dutch Climate Agreement leaves scope for storage of CO_2 in other countries (that are part of the EU ETS), but this would require, on the one hand, changes to international agreements to enable the transportation of CO_2 (e.g. London Protocol), and on the other, a willing counterpart. For the time being at least, the only two options for Dutch industry are to store the CO_2 in the North Sea or to use it.
- The legal framework for CCUS in the Netherlands could be improved. The specific monitoring requirements per storage site have yet to be identified. In principle, the government will embed the statutory periods of liability and responsibility into the storage permit, but this is yet to be determined (Government of the Netherlands, 2019[2]).

8.2. Electrification of heating

Key messages

- There is a large potential for the electrification of industrial heating in the Netherlands of approximately 177 PJ (Chapter 3).
- The financial attractiveness of electrifying heat (and replacing a functional piece of equipment) rests heavily on the energy costs of running the electrical equipment compared to conventional fuel equipment, which depends on differences in fuel prices including taxation.
- So far, the relative fuel prices between electricity and others, e.g. natural gas, have not incentivised industry to electrify heat in the Netherlands like in many other European countries.
- The Netherlands has a number of incentives in place to bring down capital costs of new equipment, but the relative fuel price disadvantage needs to be resolved in order to address the issue of operational costs.
- The numerous SDE++ subsidy applications for electric boilers and heat pumps indicates that the carbon levy in combination with the SDE++ subsidies start to make the business case for the electrification of heating.
- Higher temperature heat pumps need further innovation for applications in industry, and the Netherlands appears to be at the forefront of research and innovation in this respect, with TNO's Heat Pump Programme for 2020 to 2025.

Electrification of heating will play a key role in transitioning Dutch industry to net-zero, particularly for the food and chemicals sectors (according to Berenschot projections). Electrification is the process through which heating that is currently powered by solid, liquid, or gaseous fossil fuels (e.g. natural gas or fuel oil) is instead powered by electricity (Deason et al., 2018[30]). "Electrification of heating", therefore, refers to an assortment of technologies depending on what the heat is being used for in a given industrial process – i.e. chemical conversion, melting, casting, baking, distilling, separating, drying or hot water.

The rest of this section outlines the technological readiness of these different technologies, the business case for electrifying heat, summarises various initiatives to further electrify heat in industry and ends with a discussion of a few other barriers that make it challenging to electrify heat.

8.2.1. Technological readiness of various technologies to electrify heat

Different strategies for the electrification of heat

There are two distinct strategies for electrifying heat in Dutch industry, whose potential varies based on the electrification technology, the energy system, and the industrial production process: 1) flexible electrification; and 2) baseload electrification (Den Ouden et al., 2017[31]).

Flexible electrification can be ramped up and down and could even switch between electricity and another mode (for example, to accommodate fluctuations in the renewable electricity supply). Flexible electrification is promising in industries that use batch processes, especially if the process is relatively OPEX- rather than CAPEX-intensive and there is some overcapacity. This allows to run production processes when the costs of electricity are low, which is when renewable electricity is available.

Baseload is relatively constant and not easily adjustable to accommodate large fluctuations in a future electricity system. Baseload electrification becomes attractive when the electrification technologies offer co-benefits compared to a reference technology, for example a higher efficiency in generating heat (high

Coefficient of Performance), environmental benefits through lower emissions, higher selectivity or otherwise lower production costs or induced product/process (quality) improvements.

A number of technologies exist to electrify the uses of heat outlined above, which can be broadly classified as Power to Heat, Power to Chemicals, Power for Separation, and Power for Sterilisation. Table 8.2 lists these specific technologies.

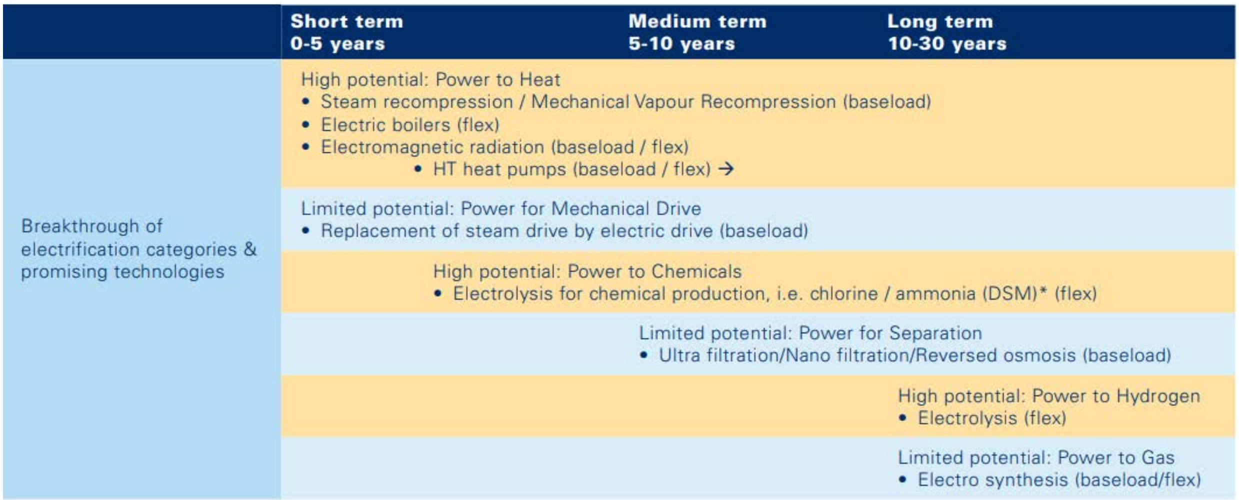
Table 8.2. Electrification technologies by use

	Technologies	Category
Process heat – steam and hot water, thermal oil	Heat pumps Electric boiler/ electrode boiler Steam recompression/vapour recompression	Power to heat Power to pressure
Process heat – baking, melting and casting	Induction furnace Microwave heating Electric melting Electric arc furnace Plasma heating/plasma recycling Infrared heating	Power to heat
Drying	Infrared drying Impulse drying Impingement drying Microwave drying Vapour recompression Heat pumps with low temperature drying	Power to heat
Distilling and separation	Mechanical Vapour Recompression Filtration Mechanical techniques e.g. centrifugation	Power to heat Power for separation
Sterilisation and pasteurisation	Infrared sterilisation UV Microwave pasteurisation and sterilisation Microwave blanching of vegetables Heat pumps HP sterilisation	Power to heat Power for sterilisation
Direct process input: electrolysis/ electrochemical conversion	Electro synthesis Electro catalysis Plasma chemistry	Power to chemicals Power to specialities

Source: Den Ouden et al. (2017[31]).

Den Ouden et al. (2017[31]) discuss the potential applications of these technologies in the Netherlands (Figure 8.5). Power-to-Heat technologies can be applied for a number of uses. High temperature heat pumps, in particular, appear to be a highly promising technology for electrification in the Dutch context, however, technological readiness is a limiting factor. In contrast, Mechanical Vapour Recompression (MVR) and Steam Recompression are already available although CAPEX support is needed for MVR and heat pumps. Electric boilers are commercially available, but these can be unviable in the current Dutch context due to grid connection costs, capacity tariffs, and relatively high power prices. Power for Separation likely has only limited potential and is mainly focused on the food industry. In this context, there are interesting, current initiatives in the Netherlands to develop existing technologies (ultra filtration, nano filtration, reverse osmoses). Power-to-hydrogen is both relevant in core processes (for instance in producing ammonia) and in utility processes. For Power to Chemicals, flexible production of chlorine seems most promising. This does not lead to an increase of electrification, but rather to a more flexible power consumption (demand side management). Power-to-Hydrogen and Power-to-Chemicals will be discussed in greater detail in forthcoming sections.

Figure 8.5. Timescale for technologies in the Netherlands



	Short term 0-5 years	Medium term 5-10 years	Long term 10-30 years
Breakthrough of electrification categories & promising technologies	High potential: Power to Heat • Steam recompression / Mechanical Vapour Recompression (baseload) • Electric boilers (flex) • Electromagnetic radiation (baseload / flex) • HT heat pumps (baseload / flex) →		
	Limited potential: Power for Mechanical Drive • Replacement of steam drive by electric drive (baseload)		
	High potential: Power to Chemicals • Electrolysis for chemical production, i.e. chlorine / ammonia (DSM)* (flex)		
		Limited potential: Power for Separation • Ultra filtration/Nano filtration/Reversed osmosis (baseload)	
			High potential: Power to Hydrogen • Electrolysis (flex)
			Limited potential: Power to Gas • Electro synthesis (baseload/flex)

Source: Den Ouden et al. (2017[31]).

Main barriers to electrification of heating

As a rule of thumb, the fuel costs over the lifetime of a piece of equipment, e.g. industrial boiler, are typically ten times the initial capital investment (Roelofsen et al., 2020[32]). Therefore, the financial attractiveness of electrifying heat (and replacing a functional piece of equipment) rests heavily on the ongoing costs of energy to run the electrical equipment compared to conventional fuel equipment and the differences in fuel prices (Roelofsen et al., 2020[32]; Deason et al., 2018[30]). The *biggest* barriers to electrification of heating are typically economic, not technical. These include:

- **Fuel and other operational costs**: Where commercially available electric and non-electric alternatives exist for a given end use, relative fuel prices often explain adoption decisions.
- **Capital costs of fuel switching**: Generally, in order to electrify, direct fuel equipment needs to be replaced with electrically powered alternatives. The relative upfront costs vary, and if the switch occurs before the end of useful life of the existing direct fuel equipment, this effectively raises the costs per unit of output.
- **Heterogeneity of industrial sectors**: Each industry sub-sector and product has its own process heating requirements and product specifications that require specific designs and performance requirements for electrified processing (Chapter 3, the 2050 scenario).
- **Risk aversion**: Electric equipment and appliances are not identical to their fuel counterparts, which means industry may avoid them even if it is financially viable. For example, the speed of heat provision is often slower (e.g. heat pumps). Therefore, electrification may introduce financial and operational risks for firms. The impact of this is even more pronounced in low margin, commodity type industries like food processing. To limit this risk, natural gas boilers can be used with biogas or hydrogen.
- **Electricity delivery infrastructure:** Extensive changes in large industrial facilities could require distribution system upgrades and in the long run, transmission system upgrades.
- **Heating temperatures are low:** Using electricity for heating becomes less efficient for higher temperatures.

Electrification is most viable in processes, therefore, “with relatively low energy costs; where the degree of process complexity and process integration is more limited and extensive process re-engineering would not be required; where combined heat and power is not used; and where process heating temperatures are lower," (Deason et al., 2018[30]).

Another potential barrier could be electricity storage, as the production of batteries must increase from 320 GWh of batteries per year worldwide to 1 000 GWh in 2025 (IEA, 2020[33]). Fortunately, battery production has become much cheaper over the past decade, therefore, scaling up the production and use of batteries should not be a problem if investments are made on time. However, building a large-scale battery factory can take two to five years, suggesting investments are needed now.

Research and development on heat pumps for industry

Of the potential technologies for Power-to-Heat, heat pumps are the least technologically ready, especially for high temperatures. Currently, the development of heat pumps for the process industry is driven by scattered national initiatives targeted towards local industry sectors, some of which are taking place in the Netherlands. The main motivation for these development projects is typically focused towards saving operational costs, which result from the energy savings. In Europe, the low priority of industrial heat pumps on the research agenda means that only a limited number of projects containing heat pump developments have been undertaken in recent years.

The following projects have received support from national governments:

- SkaleUp (SINTEF): Heat pump solution for combined process cooling (0°C to 4°C) and process heating (90°C to 110°C) with a combined coefficient of performance of 2.8, resulting in the reduction of CO_2 emissions to near-zero.
- LowCapex and FUSE (TNO, Netherlands): Demonstration of heat pump technology on an industrial scale (2 MW), producing process steam at temperatures between 120°C to 150°C from waste heat at 60°C to 90°C with efficiencies above 50% of the theoretical maximum. The heat pumps developed within these projects have the potential to reduce emissions between 20% and 35% compared to the reference scenario.
- Efficiency in Industrial Processes (Swiss Competence Center for Energy Research [SCCER]): The goal is to create energy efficient technologies and components which can be applied in many different processes such as steam and heat generation and applied to numerous industries, allowing for energy savings between 20-50% with respect to common technologies.
- SuPrHeat (DTI/DTU): Development and demonstration of three pilot scale (500 kW) high temperature heat pump technologies based on natural refrigerants, for supplying process heat up to 200°C. The project also develops methods for heat pump integration in existing plants and new process equipment for dairies, slaughterhouses, breweries and other industry sectors.
- SteamHP (Steam-based heat pump systems [DTI]): Development, demonstration and long-term testing of a highly efficient evaporator using a turbo-compressor, which is based on an automobile turbo-charger.

Other projects have been supported by the European Union:

- BAMBOO (AIT): Development and demonstration of a heat pump steam generator for low pressure steam up to 150°C.
- DryFiciency (AIT): Demonstration and integration of three high temperature heat pump technologies in the production plants of starch, brick and waste treatment processes. The heat pump technology can produce heat at temperatures up to 160°C, reducing CO_2 emissions by up to 75%.
- CHESTER (TECNALIA): Assessment of the possibility of storing low price electricity as heat at a high temperature with a heat pump, and then producing electricity at the highest price periods, by employing the stored heat to produce electricity by means of an Organic Rankine Cycle (ORC)

generator. The CHESTER high temperature heat pump must reach temperatures around 140°C in order to charge the phase change material of the thermal energy store, which stores heat at 133°C.

8.2.2. Electrification of heating in the Netherlands

The potential to electrify heat in the Netherlands

The potential to electrify heat in Dutch industrial processes is vast. Table 8.3 breaks down the heat demand in Dutch industry by use, which adds up to more than 400 PJ of heat. However, not all of these can be electrified, for example because required temperatures are too high. Also, significant energy saving is expected to take place before 2050. As shown by estimates in Chapter 3, about 177 PJ of fossil fuel can be replaced by electrification in the four most emitting sectors. Table 8.3 shows how the currently used 400 PJ of heat is distributed across different industries and used for different purposes. Approximately 185 PJ of energy is used for chemical conversion, melting, casting and baking, of which 42 PJ is for melting, casting and baking (Den Ouden et al., 2017[31]). Nearly 150 PJ for distilling and separating, 60 PJ for distilling and separation, along with the approximately 20 PJ for hot water (Den Ouden et al., 2017[31]).

In practice, the potential and the appeal of electrification depends on the plant. The appeal of electrifying heat in a plant wanes if it already uses integrated industrial processes – e.g. use of waste heat generated from fuel combustion or own-use fuel combustion (Box 8.1).

Table 8.3. Dutch industry heat demand by use

In PJ, Estimates for 2017

	Total energy demand	Total heat demand	Breakdown of heat demand by use			
			Chemical conversion, melting, casting, baking	Distilling, separation	Drying	Hot water
Chemicals	279	240	>110	85	>15	
Refining	132	111	n.a.	65		
Base metal ferrous	40	30	30			
Base metal non-ferrous	11.3	3	3			
Metal products	21	12	12			
Food and beverage	85	55	7	2.5	26	16
Pulp and paper, board	23	18	2		4	1
Textile	3.7	3			3	
Construction materials	24	19	19			
Other	53	12				

Source: Den Ouden et al. (2017[31]).

The value of electrifying heat for decarbonisation, however, relies on access to low-carbon electricity. Whether or not this is available for Dutch industry in the future remains to be seen. The projections for electricity production from renewable sources in the Netherlands would not meet industrial heat demand in 2030, for example, if all heat-related processes that are technically possible were electrified (Den Ouden et al., 2017[31]). In other words, electricity production from renewable sources should reach about 375 PJ in 2030 in the Netherlands given present commitments in the 2030 Climate Agreement (Berenschot, 2020[34]), whilst the technical potential for electrifying heat is 400 PJ in the industry sector. This, of course, overlooks the needs of other sectors like transport or buildings. Alternatives for the Netherlands would be to import renewable electricity, slow down the electrification of heating, or rely on a diverse portfolio of carbon-neutral technologies for heat production (including hydrogen, biomass and electrification).

Box 8.1. Lack of appeal of electrifying heat with integrated industrial processes

The refineries and chemicals subsectors may be less likely to electrify heat than foundries or the food processing industry if the facilities already use **integrated industrial processes** – namely, the use of waste heat generated from fuel combustion or own-use fuel consumption. Chemicals and refineries often have fully developed combined heat and power systems (Table 8.4). Electrically powered heating would *not* generate nearly as much as waste heat at the current stage. Further, the oil refining industry has extensive "own-use" fuel consumption where by-products of the oil refining process (e.g. refinery or still gases obtained during the distillation of crude oil) are used as fuel in upstream or downstream processes. Attempting to electrify these processes would complicate the design and increase the energy cost over and above a sector that does not have this type of extensive process integration and own-use energy consumption.

Table 8.4. Industrial subsector breakdown of onsite fuel consumption for heating

	Boiler system	Combined Heat Power (CHP)	Process heating	Facility Heat, Ventilation and Air-conditioning (HVAC)
	Percentage on-site fuel consumption			
Iron and steel mills			87%	4.1%
Food and beverages	25%	40.3%	24.9%	4.2%
Chemical manufacturing	16.8%	43%	32%	1.3%
Refineries (Petroleum and coal products manufacturing)	11.4%	22.0%	57.9%	0.4%

Note: Data are based on the United States. Please note that the percentage of on-site fuel consumption is based on a literature review by Deason et al., (2018[30]). It should be treated as an estimate.
Source: Deason et al. (2018[30]).

Policies to accelerate the electrification of heat in the Netherlands

The Netherlands offers incentives to cover the capital investments necessary to deploy these technologies, but this does not overcome one of the key barriers to electrification of heating, which is the relative prices of energy carriers. Carbon pricing instruments discussed in Chapter 5 may reduce the relative price disadvantage of electricity compared to fossil fuels, under the assumption that electricity decarbonises. However, the current design of the electricity tax and the surcharge on electricity use risks slowing down electrification of industrial processes by increasing the relative price of electricity (Section 5.8.2). In addition, the SDE++ (Stimulering Duurzame Energieproductie) provides significant support for electrification through a subsidy to cover the additional operational costs of CO_2-reducing techniques (Chapter 5). A total of EUR 5 billion is available in SDE++ of which a significant part is expected to go to electric boilers and heat pumps. In the first SDE++ tender in 2020, 27 electric boiler projects applied for a subsidy of EUR 618 million for a capacity of 563 MW, and 38 heat pump projects request a subsidy of EUR 240 million subsidy for a capacity of 192 MW.

On top of this, the capital investments of these technologies "could" qualify for tax allowances and grants under the following schemes:

- EIA (*Energie-InvesteringsAftrek):* Tax allowance for energy-saving investments, which allows deducting up to 45% of eligible investment expenditures from taxable income in addition to the standard depreciation allowance. In past years, the EIA tax rebate lies between 10-15%. Qualifying investments must be in assets new to the firm, amount to at least EUR 2,500 and up to EUR 2.4 million per year, and be part of RVO's energy list (Energielijst).

- VEKI (*Versnelde Klimaatinvesteringen Industrie):* VEKI is an investment subsidy of minimum EUR 125 000 of which the rate depends on the underlying asset.
- MIA (*Milieu-InvesteringsAftrek* - environmental investment deduction): Tax allowance for environmentally-friendly investments, which allows deducting a fraction of the investment expenditures from taxable income. It comes on top of the standard depreciation allowance.
- Vamil is a one-off accelerated depreciation of 75% of the investment expenditures that is targeted specifically to environmental investments.
- ISDE (InvesteringsSubsidie Duurzame Energie) is a subsidy available to firms and business owners for the purchase and installation of heat pumps or solar water heaters (cannot be used with EIA).
- TNO Agenda on Heat Pumps for 2020-25 (Netherlands).

8.2.3. Electrification policies in Germany

National Decarbonisation program

An important German programme for the electrification of heat is the National Decarbonisation program.

The National Decarbonisation Program addresses technology development, demonstration and market uptake. The program particularly aims for the reduction of process-related emissions in hard-to-abate sectors and thus addresses key production facilities in these sectors. For this purpose, Chapter 6 projects in the area of emission-intensive industries with process-related emissions, are supported via grants of total EUR 2 billion for 2020-24 and probably EUR 0.5 billion a year afterwards.

The projects under scope range from application-oriented R&D and industrial-scale testing to the broad market introduction of mature or emerging technologies. The program will provide grants to finance a share of the upfront costs of the investments in new plants, development of climate-neutral processes, switch from fossil to electricity-based fuels, innovative combinations of processes, development of climate-neutral product substitutes as well as bridge technologies. Applications are evaluated technically and economically. Current program design focuses on capital expenditures only and does not foresee financing of operational costs.

8.2.4. Making the business case for the electrification of heating in the Netherlands

The missing business case for electrification of heat

The decision to invest in a given technology to electrify heat is generally assessed by the trade-off between the capital expenditure (investment) needed to purchase and install the technology versus the reduced operational costs (including energy or carbon costs) resulting from the investment. According to TNO, a simple payback period is commonly used to assess this trade-off, and the payback period demanded by industry is typically in the range of one to two years, although this can be extended to the range of two to five years under certain circumstances. This short payback period contrasts with other investments, where returns of about 10% per year are considered sufficient, and questions the idea whether energy savings are really considered as a priority by industry. A plausible explanation for this relatively short payback period for electrification could be that heavy industry is reluctant to take technological risks. The optimised large-scale processes often run continuously and failure in production could be disastrous (ECN, 2015[35]).

The relatively high price of electricity compared to alternative fuels - often three to four times higher than that of natural gas over the last decade in the Netherlands - has likely acted as a disincentive to electrify heat. The ratio of electricity to gas prices in European countries for small scale industrial end-users, which varies from less than 2 in the case of Norway, Finland and Sweden to over 4 in the case of Belgium, the United Kingdom, Italy and Germany, can be a significant barrier to electrification of heating uptake in some countries (de Boer et al., 2020[36]).

Even though, emissions in the industry sector are subject to fuel-specific energy taxes, a surcharge on natural gas and the EU emissions trading system (ETS) (which are included, for example, in the figure above), these may not have tipped the balance in favour of electrifying. This may be partly due to compensation of indirect costs for ETS and exemptions from paying the fuel tax and surcharge. Electricity taxation and the surcharge on electricity use are policy instruments in place that may further slowdown electrification by raising their costs as discussed more in detail in Section 5.8.2.

Will the carbon levy and SDE++ make the business case for the electrification of heating?

While the carbon levy makes a better business case for the electrification of heating, the taxation of energy is not done in the most efficient way, as discussed in the section on energy taxation in Chapter 5. Table 8.5 and Table 8.6 show again the gas and electricity prices and energy tax rates in Dutch industry in EUR per gigajoule (GJ), which were already presented in Section 5.8.2 on the effective price on electricity use (Chapter 5). Table 8.5 shows that the unit price per GJ is almost four times as high for electricity compared to natural gas. Table 8.6 shows that energy taxes are only exacerbating this price difference as electricity is taxed at substantially higher rates for all bands, except for the highest (band 4).

While the carbon levy will reduce the price differential between gas and electricity, the question remains whether this will be sufficient to make the business case for the electrification of heating. Table 8.5 shows that the unit price for electricity (excluding taxes) is approximately EUR 12.5 per GJ higher than the unit price of natural gas. Table 8.6 shows that energy tax rates are likely to increase this price difference substantially in the lower consumption bands. A relatively low electricity tax rate applies to the most energy-intensive consumers in consumption band 4.[4]

Table 8.5. Gas and electricity prices net of tax in Dutch industry, Q2/2020

	Natural gas	Electricity
Unit price, excluding taxes [in EUR/GJ]	4.69	17.22

Note: For natural gas, prices refer to the Eurostat consumption band I4 for industry (annual consumption: 100 000-1 000 000 GJ). For electricity, prices refer to the Eurostat consumption band ID for industry (annual consumption: 2 000-20 000 MWh).
Source: Based on IEA *Energy Prices*.

Table 8.6. Energy tax rates in EUR per GJ for natural gas and electricity in 2021

	Band 1	Band 2	Band 3	Band 4
Natural gas	13.31	2.50	0.91	0.49
Electricity	26.19	14.34	3.82	0.16

In 2020, pre-tax prices in Dutch industry are EUR 4.7 per GJ for natural gas and EUR 17.2 per GJ for electricity for the typical industrial producer. The carbon levy of EUR 125 per tonne of CO_2 applying to the entire emissions base would translate into a EUR 7 rate per GJ for natural gas, thereby reducing the differential to some extent. This increase of EUR 7 per GJ constitutes an upper bound estimate, as it is based on the assumption that everyone would pay the same levy in 2030 and that no dispensation rights would be distributed. While the policy chapter shows that only about half of the users are expected to pay the carbon levy and that half of them receive dispensation rights, i.e. pollution permits under the levy, for free (Chapter 5).

A caveat for this comparison of electricity and gas is that a GJ of energy from electricity is not the same as a GJ of energy from gas, as there are different upstream and downstream conversion efficiencies that may narrow the price differential in favour of electricity, as explained in Section 5.8.2 of Chapter 5 The carbon levy may therefore close the necessary price difference for the electrification of some technologies in some industries, like low temperature heating through electric boilers and heat pumps in the food and paper industry that pay relatively high energy taxes compared to the heavy industry. It is unlikely that the carbon levy alone is sufficient to make the business case for the electrification of high temperature heating in the chemical, refineries and metal industries. (More details on electricity pricing and the carbon levy are described in the section analysing the policy package and the Dutch effective carbon rate and electricity price signal (Chapter 5).

In addition to the carbon levy, SDE++ subsidies may narrow the price differential between natural gas and electricity. The relatively large number of SDE++ subsidy applications for electric boilers (27) and heat pump projects (38) may be an indication that technology support can bridge the gap for low temperature heating in some industries, especially the paper industry and food processing industry. The subsidy requests for electric boilers amount to EUR 618 million for a total capacity of 563 MW and the applications for heat pump projects relate to another EUR 240 million for a capacity of 192MW. However, under the current policies, there does not seem to be a business case yet for breakthrough technologies that could be developed and deployed for high-temperature heating in the chemical, metallurgical and refineries sectors. It is uncertain, when and if their costs will come down, to take advantage of the policy package combining technology support, carbon levy and the tax exemption for auto-generated electricity.

8.3. Hydrogen

Key messages

- Hydrogen is a promising technology with great potential to decarbonise not only industry, but transport, buildings, and power. However, technological maturity along the hydrogen value chain varies.
- The Netherlands Hydrogen Strategy elucidates similar goals and priorities to that of Germany and the European Union. All three hydrogen strategies set targets from now until 2030 for the installation of GW for electrolysers, prioritise how to integrate hydrogen production with gas and electricity grid, recognise the importance of standards (e.g. guarantees of origin), and the importance of international co-operation with neighbours in defining these standards, building infrastructure, and so on.
- The key difference between the three strategies is the explicit mentioning of Contracts for Difference for hydrogen in the German and European Hydrogen Strategies in order to help industry cover operating costs. It remains to be seen if such a mechanism would be needed in addition to the existing toolkit in the Netherlands, because alternative instruments like the carbon levy, SDE++ and the Hydrogen Strategy provide support in this respect.
- The costs for green hydrogen per tonne of CO_2 emission reduction are, however, high compared to other technologies that compete for the SDE++ subsidy. Therefore, and due to the design of SDE++, it is unlikely that much of the subsidy will be awarded to the production of green hydrogen. It is also unlikely that the carbon levy alone is sufficient for the necessary increase in investments in the development and use of green hydrogen. Reserving part of SDE++ subsidies for green hydrogen may be a possible solution.

- Fully realising the potential of hydrogen requires a high-level commitment from government and dedicated attention to mitigate risks, strategic R&D and demonstration, work to harmonise standards and remove barriers, and above all, policies to stimulate demand.
- International standardisation will be crucial in this value chain, including guarantees of origin, hydrogen purity, the design of liquefaction/conversion and regasification/reconversion facilities, for equipment specifications and for blending hydrogen into the gas grid.
- Research and demonstration support should focus on CCUS, underground storage of hydrogen, higher-risk demonstration projects for localised grid conversions, carriers for shipping and the scale-up of liquefaction and regasification facilities.
- Future demand for hydrogen, the supply of renewable energy to produce hydrogen and the infrastructure for hydrogen transportation must be ensured by the Dutch government before companies are prepared to make significant investments that are required for the production of (green) hydrogen.

Hydrogen is already being used in each of the sectors of interest – refining, chemicals (i.e. ammonia and methanol), and metallurgy (i.e. iron and steel) - as an input into industrial processes. Either to purify oil in refineries (i.e. remove sulphur), as a feedstock in ammonia and methanol production, or to remove oxygen from iron ore to create iron. Virtually all of the existing industrial uses of hydrogen today are supplied using fossil fuels (IEA, 2019[37]),[5] which is known colloquially as grey hydrogen. Two existing low-carbon alternatives are blue and green hydrogen. The former still produces hydrogen from natural gas but removes carbon emissions via CCUS (Figure 8.1), while the latter breaks down water into dihydrogen and dioxygen using renewable energy and thereby does not emit CO_2 through fossil fuel use (IEA, 2020[5]).

The first section starts with the Technological Readiness Levels of these technologies across the hydrogen value chain. The second section explains the Netherlands Hydrogen Strategy and the third section then overviews and compares the policies of other countries in five key areas: high-level commitment, mitigating risks, strategic R&D and demonstration, harmonised standards and removal of barriers, and creating demand. The section concludes with policy recommendations to accelerate the development and use of hydrogen in the industrial sector.

8.3.1. Technological Readiness Levels of Hydrogen

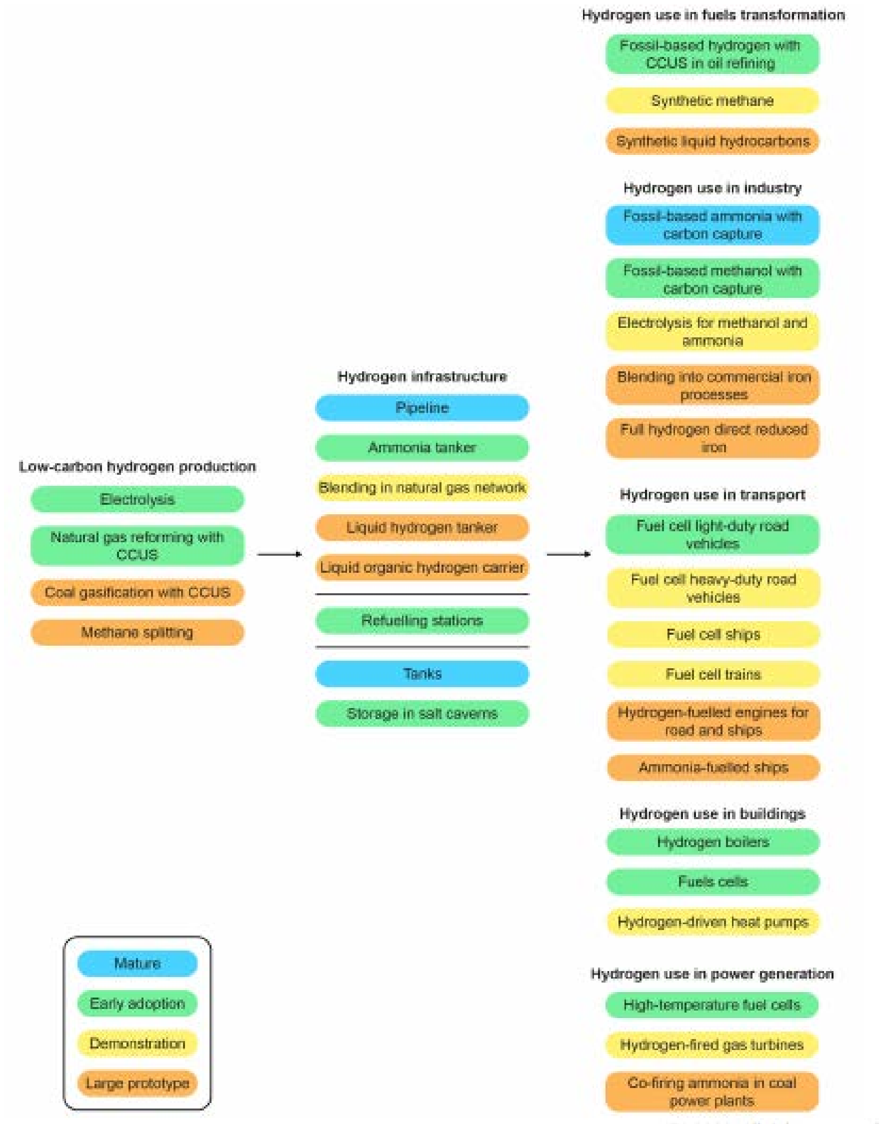
Technological Readiness across the hydrogen value chain

The hydrogen value chain involves varying states of technological maturity. Figure 8.6 classifies technologies into production (left-hand column), infrastructure (middle column) and usage by sector (right-hand column). The rest of this section reviews the technological readiness of relevant technologies for decarbonising Dutch industry by 2050.

Low-carbon hydrogen production (left-side of Figure 8.6) lists technologies that produce hydrogen from water via electrolysis or fossil fuels with CCUS (IEA, 2020[5]). Electrolysis (colloquially known as “green hydrogen”) is in its “early stages of adoption” (IEA, 2020[5]). This encompasses three technologies - alkaline electrolysis, proton exchange membrane (PEM), solid oxide electrolysis cells (SOEC) – which differ in maturity (IEA, 2019[37]). The production of hydrogen through Alkaline electrolysis is a mature technology (Technology Readiness level [TRL] of 9) that has been used since the 1920s and was replaced in the 1970s, with grey hydrogen – natural gas and steam methane reforming (the most common technique for producing hydrogen today) (IEA, 2019[37]). PEM is less mature than Alkaline electrolysis, with a TRL of 8 (demonstration), but was first used in the 1970s and produces *compressed* hydrogen, making it amenable to decentralised production and storage. A key drawback for PEM is the need for expensive materials to acts as catalysts and membranes (IEA, 2019[37]). The least developed of the techniques is SOEC, which uses steam as a heat source to break down the water into hydrogen and oxygen. The disadvantage of this technology is that it requires high temperatures that are more difficult to obtain in a sustainable way and, therefore, typically receives less attention than the other two techniques (IEA, 2019[37]). In principle, these technologies could be modular unlike CCUS – easing its diffusion and uptake by industry. However, this is all still in development but ideas are already emerging, for example, for PEM (Wirkert et al., 2020[38]).

Figure 8.6 shows that blue hydrogen, i.e. natural gas reforming with CCUS and coal gasification with CCUS, is already in "early adoption" phase and a large prototype exists for the latter (TRL 5) (IEA, 2020[5]). Methane splitting (Figure 8.6) is a misfit and not usually labelled blue – as of yet. This technique has existed since the 1990s and produces hydrogen from natural gas, combined with methane as the feedstock and electricity as the energy source – which ultimately, produces hydrogen and solid carbon (the latter of which can be used in rubber, for example) (IEA, 2020[5]). One relevant feature of methane splitting is that it uses *significantly less* electricity than any of the electrolysis techniques – on average, about three times less (and there is presently a large prototype of this technology being used at a chemicals plant) (IEA, 2020[5]).

Figure 8.6. Technological readiness levels across the hydrogen value chain



Source: IEA (2020[5]).

The costs of these different production techniques range considerably in 2030 – and the IEA estimates that at least, in the short term, blue hydrogen will be cheapest at approximately USD 2.50 per kgH_2 (IEA, 2019[37]). Hydrogen produced via electrolysis with grid electricity is by far the most expensive option over the next decade at around USD 5 per kgH_2 – if there was a surplus of electricity, perhaps it could become cheap enough. For electrolysis, a dedicated supply of renewable energy is often needed (to ensure that it is low-carbon hydrogen). This is root to the speculation that green hydrogen production will shift to parts of the globe with ample and cheap renewable electricity – i.e. Morocco or Australia.

On-site production of Hydrogen

Hydrogen can be produced on-site by refineries, chemicals or steel plants or it could be supplied to them. Dutch plants will likely produce some of their blue hydrogen (and maybe green) on-site in 2050. Table 8.7 lists a few plants in the sectors of interest that are already doing this. For plants producing green hydrogen, the amount of renewable capacity needed is included where possible. Nearly all plants using blue hydrogen use the captured CO_2 for EOR, with the exception of Air Liquide selling CO_2, meaning that the captured CO_2 is eventually released into the atmosphere. One ammonia plant in Australia plans to use geological storage.

Table 8.7. On-site production for blue or green hydrogen by relevant industries

	Hydrogen	Project	Status	Capacity	Technology
Refineries	Blue	Product's Port Arthur project (Texas, USA)	Completed demonstration phase	Plans to use the CO_2 for EOR	
		Air Liquide's Port Jerome (France)	Operational	Sells CO_2 to the beverage industry	
		Hokkaido Refinery (Japan)	Pilot		
	Green	WESTKUESTE 100 (Heide, Germany)	Under construction, could be operational by 2030	3 kt of H_2 annually	Alkaline electrolysers
		REFHYNE (Rhineland, Germany)	Under construction, to be completed in second half of 2020	1.3 kt of H_2 annually	PEM Technology
Chemicals	Blue	Three ammonia-based fertiliser plants (USA)	Operational	150ktH_2 annually 2MtCO_2 annually (used in EOR)	
		2 ammonia-based fertiliser plants (USA) 1 ammonia-based fertiliser plants (CAN) 1 ammonia-based fertiliser plants (CHN)	Planned, to be operational by 2022	All plan to use EOR	
		1 ammonia-based fertiliser plants (AUS)	To be operational by 2025	No EOR, only geological storage	
	Green	1 ammonia-based fertiliser (NOR)	Prototype by 2022	5 MW to decarbonise 1% of the plant's output	Alkaline electrolysers
		1 ammonia-based fertiliser at the Kapuni plant (NZE)	Project completion date 2021	16 MW to decarbonise 2% of the plant's output	
Steel	Green	HYBRIT: 1 plant in SSAB site in Luleå, Sweden	Planned for construction in 2021, Goal is to have fossil fuel free steel by 2035		Alkaline electrolysis

Source: IEA (2019[37]).

Box 8.2. On-site production of hydrogen through public private partnerships

Current status of blue hydrogen

- **Air Product's Port Authority** project in Texas (demonstration phase) – Operating since 2013 (1 Mt of CO_2 per year, Source*:* Steam Methane Reformers, Capture type: vacuum swing adsorption technology, Storage: EOR in West Hasting's and Oyster Bayou oil fields in Texas)

In February 2009, the American Recovery and Reinvestment Act (AARA) designated USD 3.4 billion for CCS programs. This funding was broken down into three major sources, one of which was USD 1.52 billion for a competitive bidding for industrial CCS projects. Three demonstration projects were selected (a total of 6.5 million tonnes of CO_2 per year), one of which was Air Product's Port Authority in Texas. The US Department of Energy (DOE) awarded the Port Arthur project USD 900 000 from the American Recovery and Reinvestment Act (ARRA) in October 2009. The project also received an additional USD 253 million from the ARRA as part of the DOE's CCS Program's Phase 2 in June 2010. USD 368 million in private funding matched this money. In June 2016, Air Products announced that it had successfully captured more than 3 million $MtCO_2$ at Port Arthur after three and half years of operation.

The 1 $MtCO_2$ per year, dried and purified to 97% purity of CO_2 at the Port Arthur facility. The CO_2 is then delivered, via a 12-mile connector pipeline, to Denbury's Green Pipeline (Texas). The CO_2 is then piped 101-150 km before injection for EOR in Denbury's onshore operations. The CO_2 then aids in recovering 1.6-3.1 million additional barrels annually of domestic oil.

- **Air Liquide's Port Jerome** project in France already captures and sells CO_2 (Operating since 2015, Source*:* Steam Methane Reformers, Capture Type: Pressure Swing Absorption, Sold not stored).

In 2002, the ExxonMobil group signed a long-term contract with Air Liquide for the supply of around 50 000 Nm^3 per hour of hydrogen for its Esso refinery in Port-Jérôme. Several key features were demonstrated: the integration of the CRYOCAP™ (hydrogen) H_2 unit within the existing H_2 production plant, the increase of H_2 production flow, the operation of the cold box near the triple point, and the production of liquid food grade CO_2 (300 TPD – Temperature Programme Desorption), which is then used by the beverage industry – e.g. sparkling beverages (13 tonne per hour of liquid CO_2 at food grade quality). Air Liquide received funding from ADEME for CRYOCAP™ at Port-Jérôme (Dubettier, 2010[39]).

- **Hokkaido Refinery** in (Tomakomai) Japan (Operating since 2016, Capture Technology: Activated Amine/Pressure Swing Absorption, Stored: Offshore geological storage)

Tomakomai started capture from its pilot plant in March 2016. Tomakomai plans to capture at least 100 000 tonnes of CO_2 per year for three years. The CO_2 will be stored in offshore geological units (Tanaka et al., 2014[40]). About JPY 34 billion (USD 300 million) had been set aside for the project by the Ministry of Economy, Trade and Industry for the four years through the end of this month to build the project site.

A portion of the PSA (Pressure Swing Adsorption) offgas containing approximately 52% CO_2 generated by a hydrogen production unit in the Idemitsu Kosan Co., Ltd. Hokkaido Refinery is transported by a 1.4 km pipeline to the adjacent capture facilities, where CO_2 is captured. The CO_2 is compressed and stored 3-4 km offshore in two sub-seabed reservoirs at different depths.

The project will continue monitoring other efforts, including observing very small oscillations in the areas surrounding the reservoir point, surveying marine environments and checking behaviours of injected CO_2, e.g. displacement and spreading. The project will conduct a demonstration test for carbon recycling, e.g. methanol synthesis, effectively taking advantage of the facilities for the CCS

Demonstration Project, and advance establishing a base for demonstration of CCS and carbon recycling in Tomakomai City.

Current status green hydrogen 2020

- **Shell's Rheinland refinery** (Germany) announced a 10 MW electrolyser project for 2020

The project is funded by the European Commission's Fuel Cells and Hydrogen Joint Undertaking and will install and operate the world's largest hydrogen electrolyser the Shell Rheinland Refinery in Wesseling, Germany. The plant will be operated by Shell and manufactured by ITM Power. The electrolyser has a peak capacity of 10 megawatts (MW) and will be able to produce approximately 1 300 tonnes of hydrogen per year. This decarbonised hydrogen can be fully integrated into refinery processes including the desulphurisation of conventional fuels. The project will use the hydrogen produced for processing and upgrading products at the Wesseling refinery site, and testing the PEM technology at the largest scale achieved to date. The REFHYNE project began in January 2018 and will run for five years to December 2022.

The total investment is EUR 16 million, of which the European Fuel Cell Hydrogen Joint Undertaking contributes EUR 10 million. EUR 6 million will be contributed by the REFHYNE consortium with Shell, ITM Power, SINTEF, thinkstep and Element Energy.

- **Heide** (Germany) announced a 30 MW electrolyser project (alkaline electrolysers) to replace its purchase of 3kt H_2 per year (currently under construction and could be up and running by 2030)

The partners involved in the Heide refinery project, known as WESTKUESTE 100, received approval for EUR 30 million in funding from the German Ministry of Economic Affairs. They are providing EUR 59 million making at total investment of EUR 89 million. The plant will pass electricity from wind turbines through water to extract carbon-free hydrogen that will be used by the Heide refinery to replace fossil fuel-based hydrogen.

The ten partners in the project include the German sections of French utility EDF and cement maker Holcim, gas pipeline operator Open Grid Europe (OGE), Danish wind company Orsted, the Heide refinery, the Heide town's municipal utility, local utility network Thuega and Thyssenkrupp Industrial Solutions. Eight of the partners are companies, which are working with the Heide region's public sector development agency and the Westkueste University of Applied Sciences.

The Alkaline Electrolysers will split water into hydrogen and oxygen. The hydrogen will be used by the gas plant and the oxygen will be sold to the cement plant (for use as oxyfuel), with the waste heat being sold to the district heating system. Some of the green hydrogen will also be used to make synthetic methanol, which could then be refined into carbon neutral kerosene (i.e. aviation fuel).

The Heide refinery happens to have huge salt caverns on its land where up to 10 million tonnes of hydrogen can be stored, as well as a dedicated bidirectional hydrogen pipeline to a Linde grey-hydrogen facility 30 km away — so large amounts of green hydrogen could eventually be stored and transported via a pipeline for use elsewhere, including injection into the natural-gas grid.

- **BP, Nouryon and the Port Rotterdam** assessing the feasibility of 250MW electrolyser project for the BP refinery in Rotterdam

The parties have signed a memorandum of understanding to study the feasibility of a 250 MW water electrolysis facility to produce up to 45 000 tonnes of green hydrogen yearly using renewable energy. Nouryon would build and operate the facility based on its leadership position in sustainable electrochemistry. The Port of Rotterdam would facilitate local infrastructure and investigate options for further development of a green hydrogen hub in the area. The partners intend to take a final investment decision on the project in 2022. In March, BP established a USD 100 million fund for projects. The study will also take into account a possible connection to the heat grid and oxygen pipelines.

- **Uniper and the Port of Rotterdam** are investigating the possibilities for large-scale production of green hydrogen on the Maasvlakte.

The ambition is to realise a hydrogen plant with a capacity of 100 MW on the Uniper site by 2025 and eventually expand that capacity to 500 MW. The feasibility study will be completed this summer. Following the recent successful pre-qualification for the EU IPCEI (Important Projects of Common European Interest) program, the conceptual design and technical dimensions of the hydrogen plant will be under investigation in the coming months.

While this project is about green hydrogen, Box 8.3 gives more information about the production of blue hydrogen in Rotterdam.

- **Ørsted and Yara** want to develop a green ammonia project in the Netherlands aiming at replacing fossil hydrogen with green hydrogen.

Ørsted, the world's leading developer of offshore wind energy, and Yara, the world's leading fertiliser manufacturer, have joined forces to develop a ground-breaking project to replace fossil hydrogen with renewable hydrogen in ammonia production with the potential to reduce CO_2 emissions with more than 100 000 tonnes per year. The renewable hydrogen would generate around 75 000 tonnes of green ammonia per year. If the necessary public co-financing is guaranteed and the appropriate regulatory framework is in place, the project could be operational in 2024/2025.

Hydrogen transport

The alternative to on-site production of hydrogen is to purchase from suppliers, yet this requires infrastructure (IEA, 2020[5]). A key challenge to transport hydrogen is its low density, which makes transport very costly today. Natural gas tends to be liquefied or compressed for transport, but for hydrogen this is not easily done. Liquefying is possible, but the process consumes about 25% of the hydrogen as compared to gas, which only consumes 10% (IEA, 2019[37]). Even when compressed hydrogen is very expensive to transport over long distances because its density will still represent only 15% of the density of gasoline (IEA, 2019[37]). Hydrogen can be transported via dedicated pipelines (similar to natural gas). Today, approximately 5 000 km of hydrogen pipelines exist (compared to the 3 million km of natural gas pipelines) (IEA, 2019[37]). These tend to be found in dense industrialised clusters since it lowers costs, such as in the Rotterdam industrial cluster in the Netherlands. Existing high pressure natural gas transmission lines could be used (if no longer used for natural gas) with slight upgrades, but their suitability needs to be assessed on a case-by-case basis. Also, hydrogen can be blended with natural gas and can then be used by conventional end users of natural gas to generate power and heat. A certain amount of hydrogen can be blended into existing natural gas pipelines (around 2-10% in Europe), which is currently the cheapest option for transport over distances of less than 1 500 km (IEA, 2019[37]).

For long distance transport (more than 1 500 km), the most cost effective option is to store the hydrogen in other larger molecules – either ammonia or liquid organic hydrogen carrier (IEA, 2019[37]). However, such molecules cannot be consumed as final products so the hydrogen will need to be liberated as a final step before consumption. There are experiments with marine tankers, which are either in early adoption or large prototype, respectively (IEA, 2020[5]). The other option is that ammonia can be transported by pipelines, which could be cheaper to build than new pipelines for pure hydrogen.

Box 8.3. H-Vision: Potential for blue hydrogen in Rotterdam (research)

The H-Vision feasibility study investigated the potential for blue hydrogen (Box 8.2) in Rotterdam. The captured CO_2 will be stored either in the depleted gas fields in the North Sea or used for basic chemicals, such as methanol. The H-Vision project includes parties from Rotterdam Region - Deltalinqs, Air Liquide, BP, Gasunie, the Port of Rotterdam Authority, Power Plant Rotterdam, Shell, Uniper, Royal Vopak and ExxonMobil, supported by province of Zuid-Holland and City of Rotterdam, and benefited from funding under DEI+). The hope is that Rotterdam will become the "seed of the new hydrogen economy."

In 2019, a feasibility study found that blue hydrogen would enable local industry of Rotterdam to reduce its emissions significantly before 2030. Estimate savings would increase from 2.2 $MtCO_2$ in 2026 up to 4.3 $MtCO_2$ in 2031. Adopting blue hydrogen as an energy carrier would lead to emission reduction of 16% of total CO_2 emissions of Rotterdam's industrial sector in 2018 (26.4 $MtCO_2$). The goal H-vision to build an annual production capacity of over 700 kt – equivalent to some 3200 MW, which would enable Rotterdam's industrial sector to produce at least 20% of its required heat and power using blue hydrogen. Constructing these installations would require an investment of approximately EUR 1.3 billion. If the technical and infrastructure adaptions required by industrial users is included, estimated investment would be around EUR 2 billion.

H-Vision is now in a phase of conferring with government and other partners about risk hedging, financial support, and regulations.

Source: https://www.deltalinqs.nl/h-vision-en and https://www.portofrotterdam.com/en/news-and-press-releases/h-vision-kicks-off-the-hydrogen-economy-in-rotterdam

8.3.2. Netherlands hydrogen strategy

Research priorities

Basic research takes place in the Electrochemical Conversion & Materials programme, which connects strong knowledge positions in the Netherlands in the fields of chemistry, energy and high-tech manufacturing. Applied research takes place in the Top Sector Energy, as part of the various multi-year mission-driven innovation programmes (MMIPs).

Link hydrogen to offshore wind energy. TNO studies the advantages and disadvantages of linking hydrogen production to offshore wind energy via integrated tenders. There is the possibility for the eventual tendering of a specific amount of electrolysis capacity at landing sites for offshore wind energy. It is the first place in the world where an offshore hydrogen factory is being built, which is expected to reduce the cost of green hydrogen enormously as the transport of hydrogen from offshore wind parks is much cheaper than the transport of electricity from offshore wind parks.

Support schemes

The two main schemes to support the development of green hydrogen is DEI+ and SDE++. The Government plans to implement a new, temporary support scheme for operational costs related to scaling up and cost reduction processes for green hydrogen as mentioned in the Dutch Climate Agreement.

The Dutch plan on using mission-driven research, development and innovation (MOOI) Tenders for applied research and development of hydrogen production. In addition, the DEI+ can subsidise 25% of the eligible costs, and potentially up to 45% under certain conditions. This subsidy is up to a maximum of EUR 15 million per project.

Scaling up will be supported through the Climate Budget funds available for temporary operating cost support as of 2021 (approximately EUR 35 million per year, by rearranging part of the existing funds for hydrogen pilot projects in DEI+).

Through the SDE++, approximately 2 000 load hours are eligible for subsidy, which will result in a subsidy intensity of maximum of EUR 300 per tonne of CO_2; blue hydrogen can apply via the CCS category.

In addition to these direct support schemes, the carbon levy will support closing the price differential between using hydrogen compared to cheaper fossil fuels. However, at the current stage and given the design of SDE++, it is unlikely that the combination of carbon levy with SDE++ will be enough to make green hydrogen production a competitive choice for industry in order for them to step in and start producing at a large scale (Chapter 5).

The Netherlands is still exploring the different possibilities to finance the transition to green hydrogen, as it is aware that the current support for green hydrogen is not yet sufficient to achieve its ambitions (EZK, 2020[41]). Several options for financing the transition to green hydrogen include the European funds and instruments, such as the Recovery and Resilience Facility (RRF), the Just Transition Fund (JTF) and the European Innovation Fund. Also the National Growth Fund gives possible opportunities to finance hydrogen programmes.

8.3.3. Comparison between Dutch, German and EU Hydrogen Strategies

Key elements of European, German and Dutch Hydrogen Strategies

To accelerate the innovation and deployment in hydrogen, several countries have created hydrogen strategies: China, France, Germany, Italy, Japan, Netherlands, Norway, Korea, United Kingdom, and the United States. In addition to subnational governments, e.g. Leeds (UK), London (UK), Northern England (UK), and California, as well as supranational governments like the European Union. Table 8.8 compares the key features of the European Union, German and Dutch hydrogen strategies in terms of targets, key instruments for industry, infrastructure priorities, standards, and international co-operation (Government of the Netherlands, 2020[42]; Federal Ministry for Economic Affairs and Energy, 2020[43]; European Commission, 2020[44]). The three strategies also outline innovation programmes (e.g. basic and applied research, allocated funding mechanisms), however, these will be discussed in detail in the next section. All three hydrogen strategies set targets from now until 2030 for the installation of GW for electrolysers, prioritise how to integrate hydrogen production with the gas and electricity grid, recognise the importance of standards (e.g. guarantees of origin), and the importance of international co-operation with neighbours in defining these standards, building infrastructure, and so on. Each of these is discussed in turn.

As can be seen in Table 8.8, the Dutch's commitment to renewables for electrolysers is comparable to Germany. Germany plans to build 5 GW for electrolysers and the Netherlands 2-4 GW. Neither country specifies a production target.

The Hydrogen Strategies of all three countries nominate or create task forces to discern how to best use the existing gas grid for transportation infrastructure. This is by far the cheapest option at present, since it can avoid significant capital costs. However, hydrogen volumes of more than 2% may result in cracks of steel pipes, may affect the durability and integrity of transmission pipelines. Different countries allow for different levels of blended gas – some as high as 10% (i.e. Germany), whilst the Netherlands only allows 2% blending. However, for blending to happen, it would be considerably easier if these regulations were harmonised across European borders. The reason for different regulations is due to some of the challenges of blending. First, blending hydrogen into the gas grid can reduce the energy content of the delivered gas so end users would need greater gas volumes, so industrial sectors that rely on the carbon contained in natural gas could ultimately use more natural gas. In addition, hydrogen could have an adverse impact on the operation of equipment designed to accommodate only a narrow range of gas structure (could affect the quality of some industrial processes). In addition, the upper limit for hydrogen blending in the grid depends on the equipment connected to it. If these differences persist, hydrogen blended into gas may actually be rejected by other Member States. This could impact the uptake by industry if they need to purchase hydrogen by suppliers.

All strategies also discuss the importance of establishing standards, in particular guarantees of origin (GO). The EU has a pilot scheme, CertifyHY that differentiates between low-carbon or green hydrogen. This could help develop technologies if the scheme is more widely applied. A GO essentially labels the origin of a product and provides information to customers on the source of their products. It operates as a tracking system ensuring the quality of hydrogen. The proposed premium hydrogen GO system, similar to the existing green electricity GO scheme, decouples the green attribute from the physical flow of the product and makes premium hydrogen available EU-wide, regardless of where the specific molecule is ultimately consumed.

Table 8.8. Key elements of European, German and Dutch Hydrogen Strategies

	Europe	Germany	Netherlands
Targets	**2024** • At least 6 GW of renewable hydrogen electrolysers • Production of 1 million tonnes of clean hydrogen **2030** • 40 GW renewable hydrogen electrolysers in Europe • Production of 10 million tonnes of renewable hydrogen in the EU • 40 GW of electrolysers in Europe's neighbourhood with export to Europe	**2030** 5 GW of renewable hydrogen electrolysers **2040** 10 GW of renewable hydrogen electrolysers	**2025** 500 MW of renewable hydrogen electrolysers **2030** 2-4 GW of renewable hydrogen electrolysers
Highlighted Instruments	**Carbon Contracts for Difference** in order to bridge the cost gap - in particular to support the production of low carbon and circular steel, and basic chemicals.	• A new pilot programme entitled Carbon Contracts for Difference, which mostly targets the steel and chemical industries with their process-related emissions. • Rewards for industry for switching from conventional fossil-fuel based technologies and avoiding using CO2 in industries relying on base substances'. • The fund for 'Decarbonising the industrial sector' and the programmes for 'hydrogen use in industrial production' (2020-24) • A demand quota for climate-friendly base substances, e.g. green steel, is being considered. • Efficient use of electricity from renewables, to create greater scope for the production of green hydrogen and exempt electricity used for the production of green hydrogen from taxes, levies, and surcharges.	• Carbon levy • SDE++ subsidy • MOOI Tenders for applied research and development of hydrogen production • DEI+ subsidy
Infrastructure priorities	**Gas Grid** Up to 2030: Review of Trans-European Networks for Energy to review the internal gas market legislation to ensure compatibility with pure hydrogen and cross-border operation rules. Elements of the existing gas infrastructure will be repurposed for the cross-border transport of hydrogen.	**Gas grid** Compile report to use existing structures (dedicated hydrogen infrastructure as well as parts of the natural gas infrastructure that can be adjusted and back-fitted to make it H_2-ready), starting with the supplier to the end consumer. **Electricity grid** • Efforts to better link up the electricity, heat, and gas infrastructure will continue. The aim is to shape the planning, financing, and the regulatory framework in a way that makes it possible to co-ordinate these different parts of the infrastructure.	**Gas grid** Government will review whether and under what conditions part of the gas grid can be used for the distribution of hydrogen (with the aim of developing of North-Western Europe hydrogen market). Gradually increase blending obligation from 2% to 10-20%. **Electricity grid** • Gasunie and TenneT develop and co-ordinate hydrogen and electricity grid

	General: Ten-Year Network Development Plans (TYNDPs) (2021) taking into account also the planning of a network of fuelling stations.	• New business and co-operation models for operators of electrolysers and for the grid and gas network operators (principle of regulatory unbundling)	• Government will co-ordinate the precise locations of electrolysers (Main Energy Infrastructure Programme) The Netherlands sets a target to realise the "Hydrogen Backbone" in Europe – which would be a mix of newly constructed hydrogen pipelines and the conversion of existing natural gas pipelines throughout Europe reaching from Spain to Sweden. The goal is to create an initial 6 800 km pipeline network by 2030, connecting hydrogen valleys. The infrastructure would then further expand by 2035 and stretch into all directions by 2040 with a length almost 23 000 km.
Standards	• Establish common low-carbon threshold/standard for hydrogen production installations (full lifecycle GHG) • Comprehensive terminology and European-wide criteria for the certification of renewable and low-carbon hydrogen • Establish Guarantees of Origin between low-carbon and green hydrogen	• To ensure that a market can develop which contributes to the energy transition and to decarbonisation, as well as boosting export opportunities for German and European companies, there is a need for reliable sustainability standards and for a sophisticated quality infrastructure, proof (of origin) for electricity from renewable energy and for green hydrogen and its downstream products. • Advocacy for an international harmonisation of standards for mobility applications for hydrogen and fuel-cell-based systems (e.g. refuelling standards, hydrogen quality, official calibration, hydrogen-powered car type approval, licencing for ships etc.).	• Guarantees of Origin system is required, Vertogas (Certifies green gas) will be designated to develop this system • Hydrogen Safety Innovation Programme – implemented as PPPs – to adequately address any issues
International co-operation	• Strengthen EU leadership in international fora for technical standards, regulations and definitions on hydrogen. • Develop the hydrogen mission within the next mandate of Mission Innovation (MI2). • Promote co-operation with Southern and Eastern Neighbourhood partners and Energy Community countries, notably Ukraine on renewable electricity and hydrogen. • Set out a co-operation process on renewable hydrogen with the African Union in the framework of the Africa-Europe Green Energy Initiative. • Develop a benchmark for euro-denominated transactions by 2021.	• One option is the creation of a new IPCEI for the field of hydrogen technologies and systems as a joint project with other Member States. The focus here should be on the entire value and use chain for hydrogen (generation, transport, distribution, use). To this end, the Federal Government is proactively approaching the European Commission and EU Member States in order to attract support for such a project (ongoing process). • The establishment of a European hydrogen company to promote and develop joint international production capacities and infrastructure is being explored and will be progressed if there is sufficient European backing. • Strengthening the existing international activities, particularly in the context of the energy partnerships and of multilateral co-operation, such as that of the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE), the International Renewable Energy Agency (IRENA) and the International Energy Agency (IEA), and we will make use of them to progress the supra-regional aspects of hydrogen. • Pilot projects in partner countries of Germany, not least as part of German development co-operation involving German firms, are to show whether and how green hydrogen and its downstream products can be produced and marketed there on a sustainable and competitive basis.	• Direct contact with European Commission at every conceivable level • Pentalateral Forum (Benelux, Germany, France, Austria and Switzerland) – develop standards, market incentives, regulations • Consultations with North Sea countries, North Sea Wind Power Hub Project • Feasibility study – on Dutch/Germany offshore wind energy and the benefits for scaling up green hydrogen, which would then be made available through Dutch gas pipelines (HY3 project) • IPCEI – Netherlands will be focusing on green hydrogen

Source: Dutch, German and EU Hydrogen strategies.

Research priorities

Germany hydrogen strategy

The National Hydrogen Strategy (NWS) of the German Federal Government is supported by the German government's economic stimulus package, in which it massively expands the promotion of hydrogen and fuel cell technology. A total of roughly EUR 2 billion is foreseen for the use of hydrogen to decarbonise industry. This includes the development of a new pilot program for Carbon Contracts for Difference (CCfD) and the examination of demand quota for climate-friendly raw materials (e.g. green steel) and tendering models for the production of green hydrogen to de-carbonise the steel and chemical industry. An important instrument for the implementation of the NWS is IPCEI Hydrogen in which the German government wants to promote integrated projects along the entire hydrogen value chain and offers co-ordination at EU level.

New cross-ministry research campaign entitled ‘hydrogen technologies 2030’ will see a strategic bundling together of research activities into hydrogen-related enabling technologies. (Implementation began in Q2 2020). Key elements of the research campaign include:

- Regulatory sandboxes for the energy transition so as bring up Power-to-X technologies[6] that are close to market to an industrial scale and accelerate the process of innovation transfer.
- Large-scale research projects entitled ‘hydrogen in the steel and chemical industries’ that pave the way for climate neutrality.
- Projects in the transport sector that will use research, development and innovation to further bring down the cost of hydrogen technologies.
- Feasibility studies and atlases of potential to help pinpoint economically suitable global location for a future, green hydrogen industry. This work will take into account future developments of energy needs and of the natural resources available in the various countries.
- International networks and Research and Engineering (R&E) co-operation to prepare new markets for German technology exports.
- The establishment of a new research network on hydrogen technologies to foster networking and an open dialogue between business and science that can inform public funding policy.

European Union Hydrogen Strategy

- Larger size cost-effective electrolysers in a range of gigawatts (a call for 100 MW electrolysers launched in 2020).
- Infrastructure needs further development to distribute, store, and dispense large volumes of hydrogen and repurposing of existing gas infrastructure.
- Large-scale end-use applications (notably in industry).
- Improved and harmonised (safety) standards, assessing the environmental impacts of hydrogen technologies of large scale electrolysers.

Funding Mechanisms

- Clean Hydrogen Partnership – support research, development and demonstration of technologies.
- ETS Innovation Fund – EUR 10 billion between 2020 and 2030.
- Launch of a call for pilot action on interregional innovation under cohesion policy on Hydrogen Technologies in carbon-intensive regions (2020).

Support to help industry cover operational costs in the Netherlands and in Germany

The key difference between the Netherlands, the German and EU hydrogen strategies is that CCfDs are only mentioned in the German and EU strategies. Neither strategy specifies the detail of this mechanism in great length, but both Germany and the European Union mention CCfDs as a way to help cover the operational costs of hydrogen and to catalyse its deployment.

CCfDs are contracts that companies can sign with the government for low-carbon industrial production, and in return the government assures a fixed carbon price, a so-called strike price. As long as the carbon price is lower than the strike price, the difference will be paid to the company by the government. If the carbon price is higher than the strike price, companies must pay back the difference between the two prices. CCfDs are designed to offset the higher operating costs of low-carbon production processes compared to the fossil fuel-based reference process. In the German hydrogen strategy, a pilot program for CCfDs is planned for the steel and chemical industries. CCfDs are selected through tenders. However, this and other issues such as conflicts with European state aid law or the determination of reference costs are still under investigation.

While CCfD policies are well suited to cover the price difference between hydrogen and fossil fuels, the budgets of EUR 250 million in 2022 and EUR 300 million in 2023 are likely not enough to close the OPEX gap to make hydrogen-based technologies cost-competitive with today's fossil fuel-based technologies.

It is possible that the Netherlands does not need a CCfD instrument because of the ambitious carbon levy and the SDE++ subsidies which could be used to close the OPEX gap for hydrogen. However, it is unclear when the carbon levy and SDE++ would actually cover the costs of the hydrogen technology. The carbon levy is not expected to bite in the coming years and the expected allocation of SDE++ to hydrogen is limited per design of the scheme, as it is not one of the most cost-effective ways of reducing emissions. It is not a good sign that of the applications for SDE++ in 2020, only EUR 2 million was requested for hydrogen production for a capacity of only 2 MW. The Netherlands mentions in their hydrogen strategy the desire to create a fund to help firms cover operational costs, which could have the same utility as CCfDs in the German and European contexts if designed appropriately.

Hydrogen targets in other countries

Table 8.9 lists other national commitments (outside of the EU, Germany and the Netherlands) that relate to hydrogen, excluding targets related to fuel cell technology (Hydrogen Policy Database – G20 Japan). The usage of hydrogen in transport is different to that of industry. Fuel cell technologies – whether for buses, trains, planes, ships, or even vehicles – combine hydrogen and oxygen to create electricity and work similar to a conventional battery, except that instead of metals as the reactants it uses gases (i.e. hydrogen provides the electrons). Fuel cell technology, in itself, is not immediately relevant to industry since hydrogen is an input into industrial processes, rather than a means to electricity. Therefore, fuel cell targets – e.g. France's target for 200 hydrogen fuel cell buses by 2023 - are excluded from Table 8.9. Some of the targets in Table 8.9 relate to bringing down the costs of decarbonised hydrogen – i.e. Japan, Korea, California (USA), and Shandong (CHN) – with no bifurcation of green and blue (Hydrogen Policy Database – G20 Japan). Korea and the Netherlands also specify targets for the transmission and distribution of hydrogen – both aim to create pipelines, whilst Korea also set targets for storage of hydrogen.

Table 8.9. Targets related to the uptake of hydrogen by industry

	Target
France	10% of decarbonised H_2 (ca. 90 000 tonnes) used in the industry by 2023 and 20-40% by 2028
Italy	The Government's plan to help boost production of green hydrogen, as stated in the draft document, is to introduce about 5 GW of electrolysing capacity to extract the gas from water over the 2021-30 period.
Japan	Procure 300 000 tonnes of hydrogen/year by 2030. Reduce the cost of hydrogen to USD 3 per kg by 2030 and USD 2 per kg in 2050. Subsidy for R&D, demonstration (national government initiative)
Korea	Establish overseas production base to stabilise hydrogen production, import with demand. By 2040, the annual supply of hydrogen will reach 5 260 000 tonnes, and the price per kg will reach KRW 3 000. Transmission and distribution targets: • Improve efficiency by diversifying storage methods such as high pressure gas, liquid, and solid • Relax regulations on storage of high-pressure gas, and develop liquefaction and liquid-storage technology with excellent safety and economic efficiency. • Use of tube trailer, pipeline. Use Lightweight high-pressure gaseous hydrogen tube trailers and reduce transport costs, and build a long-term hydrogen pipeline that connects the entire country.
California (USA)	Cost Target: USD 4 per kg (produced, delivered, dispensed) ultimately, USD 7 per kg by 2025, to supply early markets
Shandong (CHN)	By 2028, the province's H_2 energy industry output value will strive to exceed CNY 50 billion (USD 7.22 billion).

Source: Hydrogen Policy Database – G20 Japan.

8.3.4. Policies to accelerate the development and use of hydrogen in industry

Hydrogen value chains - from its production, transmission, distribution and storage - are complicated and full of risks. Investors face co-ordination difficulties across the value chain, rapidly changing technological costs and development (of hydrogen and its competitors), in addition to fluctuating regulations when crossing borders. IEA (2019[37]) pinpoints near-term opportunities to start to unravel this complexity in coastal industrial clusters ("as gateways to lower-cost and lower-carbon hydrogen hubs"), existing gas infrastructure (to scale up supply), and the creation of first shipping routes (to kick start international hydrogen trade). Moreover, as hydrogen is a technology featuring large network externalities, standardisation will be key in ensuring complementarity with other policy instruments (Vollebergh and van der Werf, 2014[45]). Fully realising this potential requires a high-level commitment from government and dedicated attention to mitigate risks, strategic R&D and demonstration, work to harmonise standards and remove barriers, and above all – policies to stimulate demand.

Working to harmonise standards and remove barriers will have to be done in close co-operation with other countries, the Netherlands will not be able to resolve these issues alone. International standardisation will be crucial in this value chain, including guarantees of origin, hydrogen purity, the design of liquefaction/conversion and regasification/reconversion facilities, and for equipment specifications. There are a number of risks associated with blending into the gas grid – legal differences between European member states on what amount of hydrogen can be transported in pipelines, ambiguities surrounding third-party access (hydrogen suppliers) to natural gas pipelines, and how to regulate returns for systems operators. As hydrogen in the gas grid, whether blended or 100% hydrogen, will be used in people's homes, ensuring safety is of paramount importance. Public safety concerns or adverse events could seriously impair the speed of deployment or prevent it altogether. Standards will also be important for new appliances and equipment. A key barrier to be addressed is the current low level of blending permitted in many jurisdictions, especially where cross-border pipelines exist.

For R&D, The IEA's Hydrogen Strategy points to the following as being the top research priorities for the immediate future:

- First major applications of CCUS technologies in a given region and large-scale integrated electrolyser demonstrations can help ensure that some of the resulting knowledge is widely shared to accelerate subsequent adoption.
- R&D for underground storage of hydrogen in depleted oil and gas fields and aquifers is likely to be necessary to prove their suitability for use with hydrogen.

- Higher-risk demonstration projects for localised grid conversions are also likely to need public support.
- Uncertainty remains about the most effective type of carrier for shipping hydrogen, with much scope for thorough investigation of the options and improvement of efficiency and capital costs.
- Liquefaction efficiency, boil-off management, scalability and the efficiency of the cooling cycle require improvement. Strategic demonstration projects could target the scale-up of liquefaction and regasification facilities for hydrogen directly or in the form of ammonia.

Finally, the huge amounts of carbon-neutral energy carriers required to produce green hydrogen are not yet available. Important uncertainty exists on when and if such energy carriers will be sufficiently provided at a competitive price. For companies to make investments worth several hundred million euros, the supply of such renewable energy carriers need to be ensured. This also includes the local availability of hydrogen infrastructure for generation/import and transport. Investors in hydrogen applications need to know if there will be access to a hydrogen network at a certain date in the future and if hydrogen is a strategic part of the Netherlands industry decarbonisation strategy. Thus, increase in the development and deployment of hydrogen also links to infrastructure planning.

8.4. The circular economy: Recycling of plastics and metals

Key messages

- For plastics, the technological readiness level for mechanical recycling is high, but chemical recycling of plastics is still very much under development.
- For the recycling of major metals, the technological readiness level is high, but much more improvement is possible for the recycling of minor metals.
- From an environmental point of view, mechanical recycling of plastics is preferred to chemical recycling, but where mechanical recycling is not possible, chemical recycling is preferred to incineration of waste for heat or electricity production.
- In line with the EU Circular Economy Action Plan, the Netherlands has an ambitious circular economy agenda to reduce raw materials consumption by 50% by 2030 and to have a circular economy by 2050.
- The main reason for the low uptake of recycled plastics is that there is no separate market for recycled plastics and virgin plastics are cheaper and often of higher quality. Policies such as minimum recycled content standards, public procurement and public awareness campaigns are needed to create the required market for recycled plastics.
- More investment in R&D is needed to develop better and more cost-effective ways of chemical recycling and the recycling of minor metals.
- For metals, by-products of steel production, such as slag and fly ash, have to be carefully relabelled from 'waste' to 'product' in order to reduce the administrative burdens associated with purchasing scrap for companies. This requires more co-ordination at the EU level. This goes hand in hand with increasing possibilities for import of scrap from other countries.
- Trade policies can help increase recycling of metals by enabling economies of scale, harmonising legal frameworks and by addressing the problem of exports to countries with inadequate recycling facilities.
- For the recycling of metals, the main constraint is the supply of scrap, while for the recycling of plastics the main constraint is on the demand side.

As the circular economy is a very broad concept, we limit ourselves in the rest of the chapter to the role of three of the core materials for industrial production: recycling of plastics and metals in this section, and bio-based materials in the next section.

8.4.1. Technological Readiness Levels across the recycling value chain of plastics

Plastics have different polymer types and different origins (fossil-fuel based, bio-based, as well as CO and CO_2-based, as summarised in Table 8.10), with greater demand in different sectors for different polymers. The steps to recycling these plastics involve: plastic stream preparation, sorting and separation, plastic waste preparation, and finally, recycling – either via mechanical or chemical technologies. The rest of this subsection summarises the key challenges to perform these activities, the relevant polymers, the key technologies to overcome these challenges, and the state of the technology.

Plastic stream preparation

Plastic waste contains solid and liquid contaminants that result from their specific use and history, which can significantly affect the quality of the recycling output and are not easily removable. For example, it is difficult to remove inks – i.e. very costly and energy intensive. As a result, plastic waste with printed inks are often recycled “as is” and used in lower value products such as plastic shopping bags.

Table 8.10. Challenges in plastic stream preparation and technological options

Challenge	Technology	Polymers	2020
Removal of contaminants from plastic articles	Solvating fluid treatment during continuous extrusion to treat flowable polymer masses	All	Pilot/Demonstration
	Use of sensors	PE-LD, PE-LLD, PE-HD, PE-MD	Pilot/Demonstration
Removal of ink	De-inking	PE-LD, PE-HD, PP, PET, PVC	Pilot/Demonstration
Removal of odour	Supercritical fluid extraction	PP, PE-LD, PE-LLD, PE-HD, PE-MD, PVC, PET, PUR, PS, PS-E	Pilot/Demonstration
	Friendly oxidants water-based treatments	PP, PE-LD, PE-LLD, PE-HD, PE-MD, PVC, PET, PUR, PS, PS-E	Pilot/Demonstration

Source: Suschem (2020[46]).

Sorting and separation

Table 8.11 shows the main challenges in sorting and separation of plastics and the main technological options to deal with them. The composition of waste varies from a stream composed solely of bottles (e.g. PET) to streams containing additional trays, pots and films, with a wide range of different polymers. Moreover, rigid plastics are often multi-layered, and therefore, difficult to separate. Bottles can be covered in PVC sleeve labels, or PET grade materials that need to be separated from bottles and trays. Furthermore, applications polymers are often mixed with other materials (e.g. wood, metals, oil, etc.) and can contain legacy additives and also organic additives (e.g. dyes) for which sorting and separation is difficult. In order to recycle these streams efficiently, polymer articles need to be sorted by their constituent materials to minimise waste and ensure a high quality end product. The two main routes currently employed, namely wet and dry sorting, need further technological development and cost reduction to be deployed widely.

Table 8.11. Challenges in sorting/separation and technological options

Sorting	Challenge	Technology	Polymers	Short-term investment needs
Wet	Separation of light or similar plastics	Hydro-cyclone	All	Demonstration/ industrial/first of a kind
		Floatation	All	Demonstration/ industrial/first of a kind
		Polymer tracing	All	Pilot/ demonstration
		Magnetic Density Sorting (MDS)	PP, PE-LD, PE-LLD, PE-HD, PE-MD, PVC, PET, PUR, PS, PS-E	Pilot/demonstration
	Sorting waste while reducing environment impact of consumables	Closed loop process to eliminate contaminants	PP, PE-LD, PE-LLD, PE-HD, PE-MD, PVC, PET, PUR, PS, PS-EI	Pilot/demonstration
Dry	Recovery of black polymers	RAMAN spectroscopy	ABS, PP, PC, PS, PE-HD, PA, PVC, PET	Pilot/demonstration
		XRF, XRT	ABS/HIPS, PP, PC, PS, PE-HD, PA, PMMA, PVC, PET	Demonstration/First of a kind
		Laser Induced Breakdown Spectroscopy (LIBS)	ABS/HIPS, PP, PC, PS, PE-HD, PA, PMMA, PVC, PET	Pilot/demonstration
		Mid-infrared spectroscopy	POs, PVC	Pilot/demonstration
	Sorting of packaging articles	Optical sorting (Near Infrared Technology – NIR, Visible sorting - VIS)	All	Research/Pilot
	Increase recovery of plastics from the construction sector	Optical sorting (NIR, VIS)	All	Research/Pilot
	Identifying additives of very high concern in older (legacy) plastic applications)	LIBS	All	Research
		Laser sorting	All	Pilot/Demonstration
	Heterogeneity of waste streams	Combination of NIR, VIS, and Mid-infrared thermography (MIR-T)	All	Pilot
		Artificial intelligence algorithms	All	Pilot/Demonstration
		Tera Hz	PHA	Research/Pilot

Source: Suschem (2020[46]).

Plastic waste preparation

Table 8.12 shows the main challenges of waste preparation and the technological options. The separation of the various polymers in a stack is often difficult and must be done manually most of the time.

Table 8.12. Challenges for waste preparation and technological options

Challenge	Technology	Polymers	Short-term investment needs
Separation of polymer layers	Integrated solution of grinding machinery with thermal and chemical, and magnetic separation	PU/PE	Research/Pilot
Delamination	Delamination with supercritical CO_2	All	Research/Pilot

Source: Suschem (2020[46]).

Recycling technology: mechanical and chemical

Mechanical

Mechanical recycling aims to recover plastic waste via mechanical processes (i.e. grinding, washing, separating, drying, re-granulating and compounding). In these processes, polymers stay intact, which enables the re-use of polymers in the same or similar products — effectively creating a closed loop. It currently represents the most common form of plastic recycling due to its cheap and simple nature. However, such processes cannot remove additives (e.g. dyes), impurities (e.g. dust), or other organic contaminants meaning the results tends to be impure and low-quality. Another limitation is that some quality is lost with each cycle and is typically limited to five cycles. For this reason, recycled plastics are often mixed with virgin plastics, and are still partly based on fossil fuels.

Advanced mechanical recycling techniques could be enhanced by developing:

- Stable reagents for high temperature processing by means of twin screw extruders/compounding to permit the re-introduction in the value chain of cross-linked polymers that cannot be reprocessed, under normal conditions.
- New mechanical methods to break the chemical bonds by using twin screw extruders with the combination of high shear and high energy sources (radiation).
- New mixers based on extensional flow (specific reactor) to improve dispersion and distribution quality for a wide range of viscosity ratios and avoiding thermal degradation.
- Fibre functionalisation and reactive compatibilisation extrusion.
- Reactive extrusion process to improve adhesion between the recycled fibre and polymer matrix (compatibilisation).

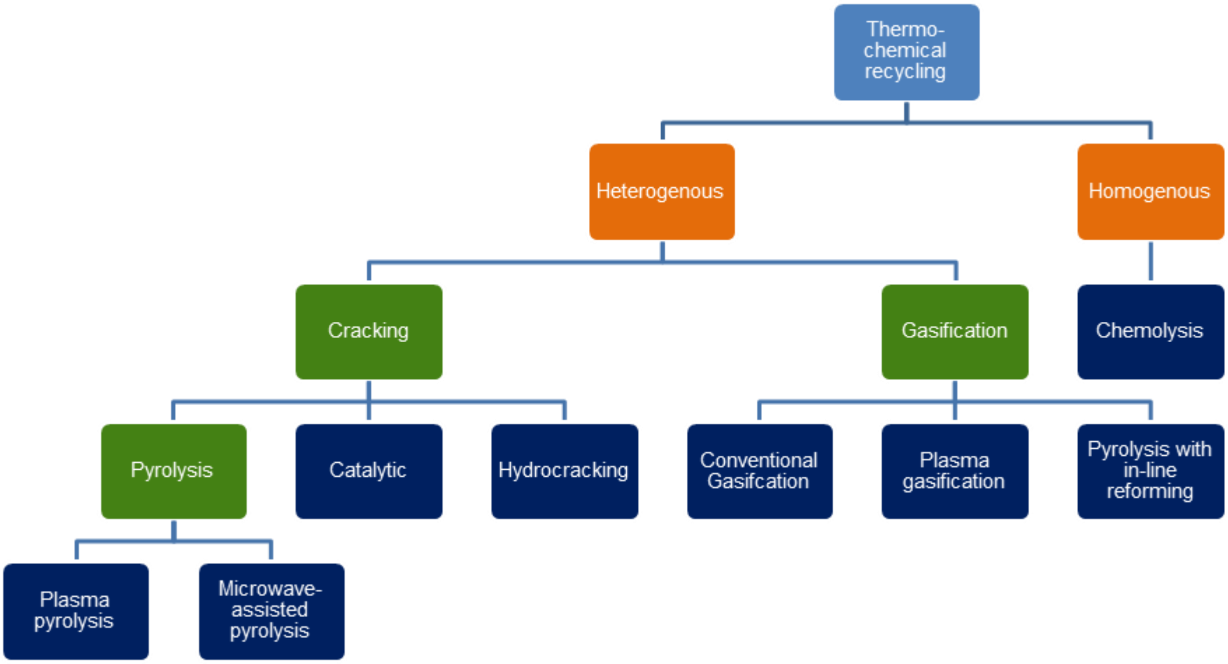
Chemical recycling of plastics

Chemical recycling requires a lot of energy, which has to be renewable to achieve the climate ambitions. As for mechanical recycling, chemical recycling can close the cycle, but the cycle is bigger with chemical recycling because polymers are broken down to produce synthetic feedstock before they are re-processed into polymers again by the chemical industry.

Pyrolysis is a process to chemically decompose organic materials at elevated temperatures in the absence of oxygen. Conventional pyrolysis is called **thermal cracking** which is used to recycle mixed plastics, such as multi-layer plastic packaging, that cannot be recycled mechanically. The process is performed at moderate to high temperatures between 300°C and 700°C and without oxygen. The main problems are the complexity of the reactions and the large amount of energy required in the process. Pyrolysis has a low tolerance for PVC in the raw material, as the chlorinate compounds can then be formed in the pyrolysis oil which make it difficult to use. The products from waste plastics thermal cracking are gas, char and liquid oil. Pyrolysis oil is the most valuable product form of thermal cracking as it can be used for many applications, e.g. in petroleum blends or for the production of new plastics.

This section reviews the technological readiness levels for chemical recycling of heterogeneous plastic waste streams (Figure 8.7, for an overview of these technologies, and Table 8.13 for a summary), and therefore, concentrates on cracking and gasification. This subsection reviews the seven technologies in dark blue that relate to heterogeneous waste and assesses these on process temperature, sensitivity to feedstock contamination and level of polymer breakdown. In general, higher temperatures can more comprehensively breakdown polymers, which can lead to a higher purity in the processed material and a greater portfolio of products that can be regenerated. The lower the process temperature of a technology, the greater sensitivity of the technology to the quality of the waste, which often requires more advanced separation before chemical recycling. Of course, the sensitivity of different technologies to the quality of waste stream, in turn, impacts the needed logistics to separate (and costs).

Figure 8.7. Chemical recycling technologies



Source: Adapted from Solis and Silveira (2020[47]).

Figure 8.7 gives a summary of TRLs of chemical recycling technologies. Two promising technologies include: plasma pyrolysis and micro-wave assisted pyrolysis.

Plasma pyrolysis is promising for gaseous fuels, chemical production, and suitable for electricity generation in turbines or in hydrogen. It transforms plastic waste into syngas (by integrating conventional pyrolysis with the thermochemical properties of plasma). The syngas is composed of CO, H_2, and small amounts of higher hydrocarbons. These process temperatures can be very high from 1730°C to 9730°C and are very fast, typically lasting between 0.01-0.05 seconds (depending on temperature and waste). The advantage of this technology is the production of gas with less toxic compounds (than other methods) since the temperature is high enough to decompose them. Thermal plasma technology is well-established in metallurgy, material synthesis, and destruction of hazardous waste. Plasma pyrolysis of waste plastics has only been investigated at the laboratory scale, since several technological challenges remain before the technology can be deployed at scale.

Microwave-assisted pyrolysis mixes waste plastics with a highly microwave-absorbent dielectric material (i.e. a substance that is a poor conductor of electricity, but an efficient supporter of electrostatic field). The heat absorbed from microwaves is transferred to the plastics by conduction. This process allows for very high temperatures and is very efficient at converting electrical energy into heat. It offers more control over the process than conventional pyrolysis techniques. Plastics have poor dielectric strength, however, and when mixed with an absorbent, the heating efficiency may vary and it may be difficult to use these efficiently at industrial scale. So far, this has only been studied at laboratory and pilot scales.

Catalytic cracking adds a catalyst to the pyrolysis process to reduce the process temperature, which saves energy and reduces costs. Catalytic decomposition of polymers follows the same reaction stems as hydrocarbon catalytic cracking used in refineries, even the catalysts are similar. With a catalyst, the temperature can be lowered to 300-350°C, rather than 450°C for conventional pyrolysis. Moreover, it has a higher oil yield than conventional cracking for most plastics, ranging from 86-92%. Most of the work on this has been performed with pure polymers since this process can be impacted by contaminants present in plastic waste streams. There are several commercial catalytic cracking processes at industrial scale. One of world's largest catalytic cracking projects was Sapporo Plastics Recycling which, together with Toshiba, co-owned the world's largest waste plastic liquefaction facility in Japan. The facility converted 15 000 tonnes of mixed waste plastic into light oil, which was used as feedstock for new plastic products, medium fuel oil equivalent to diesel and heavy oil used for electricity generation. However, Sapporo Plastic Recycling withdrew from the business in 2010 due to financial problems.

Hydrocracking adds hydrogen to the cracking process (which results in higher product quality). The process has a temperature range of 375-500°C and occurs at elevated hydrogen pressures. The waste plastic first goes through a lower temperature pyrolysis, which leads to plastic liquefaction, which is then sent over to the catalyst bed. The catalyst is important in the hydrocracking process since it reduces the temperature and increases the oil yield and quality. The biggest obstacle in implementing this technology is the cost of hydrogen. Hydrocracking of waste plastic feedstock is only available at a pilot scale. Several challenges remain to make it commercially viable.

Conventional gasification of waste plastics leads to a mixture of hydrocarbons and syngas, which can then be used to produce energy, energy carriers such as hydrogen as well as chemicals from syngas. It usually occurs at temperatures between 700-1 200°C depending on the gasifying agent – i.e. air, steam or plasma. The agent, in turn, determines the composition of the syngas produced and possible applications. Two undesirable products – tar and char – can result from the process, the actual amounts depend on the plastic waste characteristics. An operational full-scale plant is owned by Enerkem, and located in Edmonton, Canada. It converts 100 000 tonnes of dried and post-sorted plastic waste annually into 38 million litres of biofuels: methanol, then ethanol and ethylene. The company is part of a consortium planning a waste-to-chemicals plant in Rotterdam, which will have capacity to convert up to 360 000 tonnes of non-recyclable waste plastics and other mixed wastes into 220 000 tonnes (270 million litres) of methanol**.** This is more than the total annual waste from 700 000 households and reduces CO_2 emissions by approximately 300 000 tonnes, compared to incineration.

Table 8.13. Summary table of technology readiness levels (TRLs) of chemical recycling technologies

Technology	Scale of operation	Temperature (in process)	Sensitivity to feedstock quality	Polymer breakdown	TRL
Conventional pyrolysis	Commercial	300 to 700	High	Moderate	9
Plasma pyrolysis	Laboratory	1 800 to 10 000	Low	Very detailed	4
Microwave assisted	Laboratory	Up to 1 000	Medium	Detailed	4
Catalytic cracking	Commercial	450 to 550	High	Moderate	9
Hydrocracking	Pilot	375 to 500	High	Detailed	7
Conventional gasification	Commercial	700 to 1 200	Medium	Detailed	9
Plasma gasification	Commercial (hazardous waste)	1 200 to 15 000	Low	Very detailed	8
Pyrolysis with in-line reforming	Pilot	500 to 900	Medium	Detailed	4

Source: Solis and Silveira (2020[47]).

Plasma gasification is a process where plasma is used to pass an electric current through the gas. The process temperature is very high, up to 15 000°C. However, it has a high tolerance to low quality feedstock. It results in a higher quality gas with lower level of tars. Yet, these have a very high electricity requirement compared to, for example, a plasma gasification plant with around 1 200-2 500 MJ per tonne of waste. Some of the first commercial applications of plasma gasification are located in Japan - a waste-to-energy (WTE) plant owned by Westinghouse Plasma Corporation and Hitachi Metals located in Eco Valley and a WTE plant owned by Hitachi Metals located between cities of Mihama and Mikata. Other operating plants exist in China and India, however, there are none in Europe. There were plans to construct two plants in the United Kingdom (in Tess Valley), but these fell through when the project became economically unfeasible.

Pyrolysis with in-line reforming is carried out in two connected in-line reactors for pyrolysis and reforming steps. The interest in this lies in high hydrogen production from the process and the gas is free of tars. The process temperature varies between 500-900°C depending on the feedstock, reactor configuration and bed material. This is currently only at laboratory scale.

8.4.2. Technological Readiness Levels of recycling of Metals

For the recycling of metals, it is essential to facilitate the uptake of scrap in the metallurgical sector for the production of steel and aluminium. Foundries in the metallurgical sector use mechanical recycling technologies. The present recycling rates for metals varies substantially in the European Union:

- The use of recycled metals saves a lot of energy compared to the production of metals from raw materials. For the recycling of aluminium only 5% of the original energy consumption is used, as aluminium retains energy from its primary production.
- Over 90% End-of-Life (EoL) stainless steel is currently collected and recycled into new products. 70% of the steel produced to-date, however, is still in use (European Recycling Industries' Confederation, 2020[48]).
- Of the total amount of aluminium scrap generated in the EU at EoL (i.e. 4 338 thousand tonnes of aluminium), about 2,986 thousand tonnes of aluminium were collected and recycled, resulting in an EoL recycling rate of 69% (European Recycling Industries' Confederation, 2020[48]).
- With respect to metals, the obstacle is one of access more than technological (as noted in the industry consultations). Mechanical recycling is sufficient for recycling of metals. Metals do not lose quality when melted and recycled, which means that they are infinitely recyclable in principle. Therefore, the key policies needed to incentivise the uptake of scrap are those that facilitate access. In addition to increased collection rates of discarded products, improved design for recycling (e.g. to not use different layers of different metals) and the enhanced deployment of modern recycling methodology can help to create a closed-loop metal material system (Reck and Graedel, 2012[49]).

8.4.3. Recycling in the Netherlands

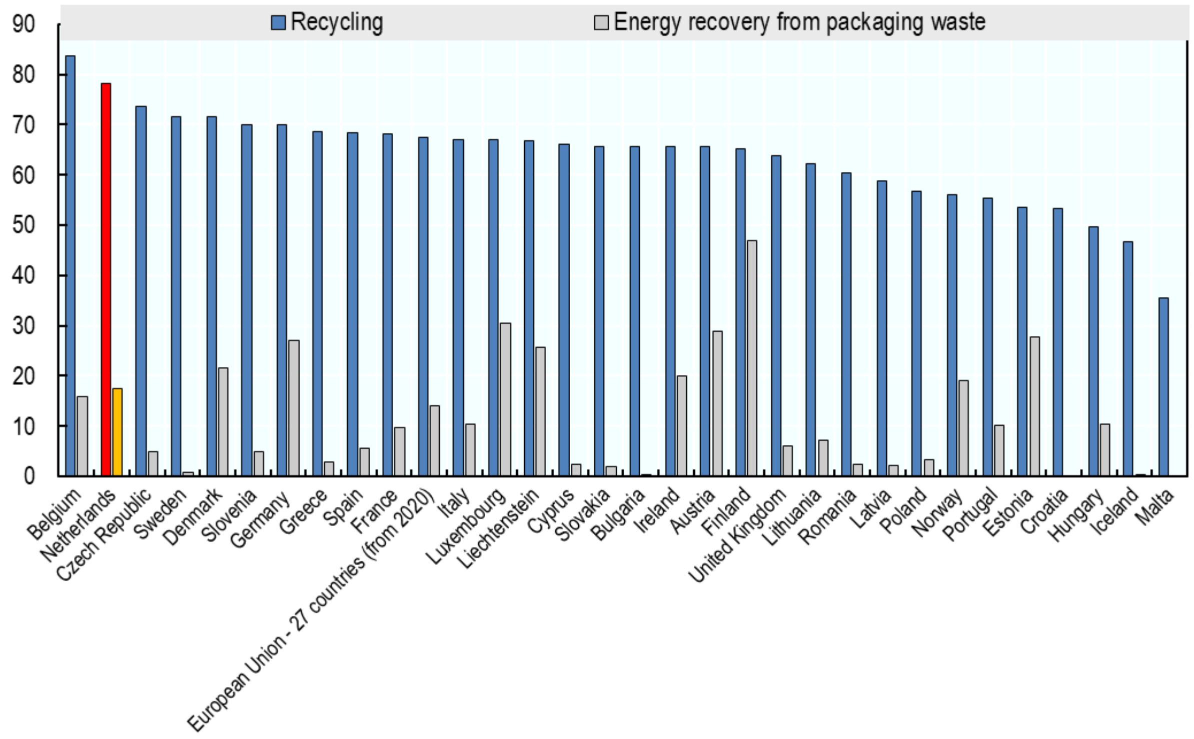
Recycling of plastics will likely play a role in the decarbonisation of the chemicals subsector, for instance through the use of synthetic feedstock (e.g. pyrolysis oil) as a replacement to fossil fuels, which will use chemical recycling technologies. The present recycling rates for plastics varies substantially in the European Union.

Of all plastic waste collected in Europe, 31% was recycled in 2018, with the remainder either incinerated or landfilled (Hesselink and Van Durren, 2019[50]; Plastics Europe, 2019[51]). For plastic packaging specifically, the recycling percentage for collected waste is a bit higher at 41% (Hesselink and Van Durren, 2019[50]; Plastics Europe, 2019[51]).

Figure 8.8 shows that recycling rates for packaging waste reported by the European Environmental Agency are relatively high for the Netherlands and already meet the EU target for recycling 75% of packaging waste by 2030. However, this share also includes non-plastic materials like wood, metal, paper and glass. According to Eurostat, this is estimated to be around 50% for plastics in 2017.

According to the transition agenda for plastics, 250-300 Kt plastics were recycled in the Netherlands in 2018, while 2 000 Kt was produced. More than five times as much plastic (1 313 Kt) is used for incineration plants to produce heat and electricity. The ambition is to reduce the amount that is incinerated by 44% by 2030. This must be achieved through better separation of plastics and better sorting machines.

Figure 8.8. Packaging waste recycling share in percentage of generated packaging waste



Source: Packaging waste by waste operation and waste flow provided by Eurostat, 2017.

There is a push by countries worldwide to ameliorate these recycling rates in order to catalyse the shift from a linear to circular economy. A thorough review of these agendas is beyond the scope of this section. Instead, this chapter focuses on two distinct challenges for the chemicals and metallurgical sector, respectively.

Synthetic feedstocks from plastics is still far from reality. Open questions remain across the plastics value chain that need to be resolved. We have now briefly overviewed the outstanding challenges to recycling plastics for each step in the value chain, presented the key technologies to overcome these barriers, as well as the state of the technology as of 2020, and provided a deep-dive into chemical recycling. The next section reviews how the Netherlands and other countries are advancing chemical recycling compared to the Netherlands and how to enable the policy environment for chemical recycling.

Dutch strategy for a circular economy by 2050

The circular economy is an economy that aims to eliminate waste and to create a closed system, to minimise resource use, waste production, pollution and carbon emissions. This is achieved through reusing, sharing, repairing, refurbishing, remanufacturing and recycling. The ambition of the Dutch government is to reduce raw materials consumption by 50% in 2030 and to have a circular economy run entirely on reusable materials by 2050. However, this still has to be operationalised, as the base year for this 50% has not yet been defined and it is also unclear whether the reduction is measured in kilos or another unit (PBL, 2019[52]).

The Dutch government formulated three objectives to reach a circular economy. First of all, existing production processes have to make more efficient use of raw materials, so that fewer raw materials are needed. Second, when raw materials are needed, sustainably produced, renewable and widely available raw materials, such as biomass, are used as much as possible. Third, new production methods and circular products need to be developed.

The Netherlands follows a timeline for the transition to a circular economy in 2050. This timeline begins with the Government-wide programme for a Circular Dutch Economy by 2050 that was adopted in 2016 (Ministry of Infrastructure and the Environment and Ministry of Economic Affairs, 2016[53]). This programme describes what needs to be done to use raw materials, products and services more intelligently and efficiently.

In 2017 the Raw Materials Agreement was signed by 180 parties from both government and industry. This agreement sets out what needs to be done to ensure that the Dutch economy can run on renewable resources. Partners in this agreement commit themselves to jointly draw up five transition agendas in 2018 for sectors and value chains that have a high environmental impact but are also economically important to the Netherlands. These five transition agendas are for the following sectors: biomass and food, plastics, manufacturing industry, construction and consumer goods.

Biomass is used for animal feed, chemicals, biofuels and energy. Biomass can make many sectors greener and reduce CO_2 emissions. A more extensive overview of the importance of biomass is provided in the next section on bio-based materials.

With the Plastic Pact, government, industry and environmental organisations are fighting against plastic waste. In 2050, plastics need to have a low carbon footprint, be made from recycled or renewable bio-based materials and will no longer be incinerated.

The manufacturing industry processes materials, such as metals, into new products. These processes are often harmful to the environment. A circular design for high-quality sustainable reuse of materials is required. Three important points in the transition agenda for the manufacturing include: 1) Material efficiency, optimising life cycle products and closing raw material chain at the end-of-life; 2) recycling technology to close cycles, optimising not only on quantity but also on quality with the ambition to have no net outflow of critical raw materials; 3) facilitate circular business models: transition from product sales to service models.

The construction sector accounts for 50% of the raw material consumption in the Netherlands. Much waste is demolition waste. In order to organise our living environment in a sustainable way, an acceleration of innovations (circular and modular construction) within the construction sector is necessary.

Consumer goods must be reused to avoid unnecessary waste.

In 2019, the Dutch government presented the Circular Economy implementation programme, which translates the five transition agendas into concrete actions and projects between 2019 and 2023. Examples from this implementation program include: the production of bioasphalt from natural adhesives from trees, the use of components in mattresses that can be easily separated and reused, the reduction of plastic waste through the Plastic Pact, and a circular Central Government Real Estate Agency.

In addition to the Dutch Circular Economy programmes, the European Commission also has a Circular Economy Action Plan, in which 35 actions are formulated for the implementation of the circular economy. With this action plan the EU wants to lead global efforts on the circular economy by introducing legislative and non-legislative measures targeting areas where action at the EU level brings added value. This action plan makes sustainable products the norm in the EU and focuses on the sectors that use most resources and where the potential for circularity is thus the highest, which are electronics and ICT, batteries and vehicles, packaging, plastics, textiles, construction and buildings, food, water and nutrients. Consumers and public buyers are empowered and circularity must work for people regions and cities.

A new Dutch National Platform for chemical recycling should promote knowledge exchange and co-ordinate chemical recycling initiatives. The platform will also identify areas of innovation, so that (development) programs are designed to cover blind spots. The platform was created at the request of the

Top Sector Chemistry and the Dutch ministries of Infrastructure and Water Management and Economic Affairs and Climate (EZK). Chemical recycling is one of the most important subjects in the Dutch Plastics Transition Agenda and is part of the innovation agendas in the context of the Climate and Resources Agreement.

The funding for innovation and demonstration for the circular economy amounted to approximately EUR 180 million in 2018, with the largest budgets coming from DEI+ Circular Economy (EUR 44 million), the EU Horizon 2020 (EUR 43 million to the Netherlands), WBSO (EUR 35.6 million), Top Sector policies (EUR 26.9 million), LIFE (EUR 12 million) and PPS bonus (public-private partnership bonus) (EUR 11.3 million) (RVO, 2020[54]). This is in addition to other budgets for the circular economy, such as the region-envelopes (EUR 90 million in 2019) and national climate envelopes (EUR 22.5 million in 2019), consisting of EUR 10 million for encouraging the recycling of plastics and consumer goods, EUR 5 million for recycling of asphalt, and steel, and EUR 7.5 million for climate neutral procurement. Finally, MIA and Vamil are responsible for another EUR 45 million subsidy for the circular economy in 2019. Hundreds of millions in total are thus targeted at the circular economy (Ministry of Infrastructure and the Environment and Ministry of Economic Affairs, 2019[55]).

Chemical recycling in the Netherlands and climate change impact

Three types of plastic waste streams seem most interesting for chemical recycling: left-overs from mechanical recycling, difficult to recycle mono-streams such as PET trays and expanded polystyrene (EPS) from construction, and mixed plastics. In the Netherlands, this amounts to 230 kton of plastics in 2020. In 2030 this will amount to 260-340 kton a year.

A first analysis of the climate impact of various waste processing techniques, based on life cycle assessment (LCA), shows that chemical recycling is having a climate impact between 0 and -0.5 tCO_2-eq/tonne of inputs (CE Delft, 2019[56]). This is in between the impact of approximately -2.3 tonnes CO_2-eq/tonne input for mechanical recycling and the 1.5 tonnes CO_2-eq/tonne for incineration where production of heat (e.g. for buildings) and electricity has already been taken into account (CE Delft, 2019[56]).

By 2030, 10% of all plastics used in the Netherlands will be chemically recycled according to the Dutch circular economy transition agenda.

A roadmap for chemical recycling of plastics in 2030 has been developed by the employers' organisation VNO-NCW together with the Rebelgroup (VNO NCW and Rebelgroup, 2020[57]). It contains three pillars: the potential of chemical recycling for the Netherlands in 2030, the sourcing of plastics for chemical recycling and support for circular economy policy.

Ambitions from industry show that a strong upscaling of chemical recycling is needed. Shell wants to use 1 Mt of plastic waste a year as feedstock in its production process, Dow 100 Kt a year, Nestle wants to reduce the use of virgin plastics in its packaging by one third and use 100% recycled or reusable packaging by 2025.

The Industry roadmap starts with 50 Kt of recycling capacity in 2020 and scales up to 500 Kt in 2025 and 1-1.5 Mt in 2030. From 2025 onwards, large scale projects should follow the pilot phase. The ambition is to have at least one or two large-scale plants producing 200-400 Kt recycled plastics in 2030. To realise this, it is important to have large-scale investments in sorting capacity and enough supply of used plastics.

Table 8.14 displays an overview of the volume of plastic waste streams that could be used as inputs for chemical recycling in the Netherlands in 2020 and 2030. For 2030, conservative and optimistic scenarios are created, based on assumptions regarding for example the growth in plastics consumption and post-consumer sorting efficiency. In addition, the optimistic scenario assumes that a part of the plastics discarded in Belgium, Germany and the United Kingdom are imported to the Netherlands. The table shows that by 2030, the Netherlands is estimated to produce a plastic waste volume of around 260 to 330 Kt per year that could be treated in chemical recycling technologies.

Table 8.14. Volume of waste

	2020	2030		
		Conservative	Optimistic	
			Netherlands	Imports
Recycling losses	97	107	161	558
PET trays	32	36	40	0
Mixed plastics (DKR-250)	101	112	126	583
Bromine-containing EPS	7	8	9	0
Total	237	263	336	1 141

Note: EPS stands for Expanded PolyStyrene, which is a white foam plastic produced form solid polystyrene beads.
Source: CE Delft (2020[58]).

8.4.4. Some of the countries at the forefront of the circular economy

Regulatory measures in Germany

Germany has a Circular Economy Act since 2021, which is the legal framework for waste management and implements one-to-one the EU Waste Framework Directive. Besides defining waste and by-products, Germany is known for using hierarchy within waste management. Separated collection of waste and recycling quotas are important in Germany.

The German Resource Efficiency Program ProgRess III mentions the relevance of resource efficiency for achieving climate goals and the relevance of digitisation for resource efficiency in particular. The ProgRess III includes 118 measures to improve resource efficiency in Germany. The measures concern: protection of resources in value chains and material cycles, transversal instruments, protection of resources at the international level, national, municipal and regional level and protection of resources in everyday life. ProgRess II is monitored through a set of indicators taking into account total raw material productivity, raw material consumption, secondary raw material use and material stock change. The German Resource Efficiency Program and its current version ProgRess III provide the framework for goals, ideas and approaches to protect natural resources. That is why various policy instruments are based on this program in the field of material efficiency and circular economy.

The German Packaging Act introduces stricter quota requirements and describes how to monitor and further develop recycling of plastics and metals. Plastic bags are banned from 2022 onwards and there is an amendment under discussion on a minimum recycled content for disposable bottles to increase demand for recycled plastics.

The German Commercial Waste Ordinance will impose stricter requirements for separation, sorting and recycling of mixed commercial waste. This will save about 1 million tonnes of CO_2 equivalent. This reduction is supported by waste prevention and resource conservation measures as described in the national Waste Prevention Programme and the German Resource Efficiency Programme. Table 8.15 gives an overview of the ambitious German recycling quotas as well as targets up to 2035.

In addition to recycling, Germany funds the Technology Transfer Programme Lightweight Construction (TTP LB) with a total EUR 300 million. This programme follows from the German Sustainability Strategy and the Industry Strategy 2030. Part of this project is about new design techniques and materials and another part about resource efficiency and substitution.

Table 8.15. Overview of German recycling quotas

	Current	2022	2025	2030	2035
Residential waste	50%	n.a.	55%	60%	65%
Packaging	55%	n.a.	65%	70%	n.a.
Glass	80%	90%	n.a.	n.a.	n.a.
Paper	85%	90%	n.a.	n.a.	n.a.
Ferrous metals	80%	90%	n.a.	n.a.	n.a.
Aluminium	80%	90%	n.a.	n.a.	n.a.
Beverage cartons	75%	80%	n.a.	n.a.	n.a.
Other composite	55%	70%	n.a.	n.a.	n.a.
Commercial waste	30%	n.a.	n.a.	n.a.	n.a.

Source: Fraunhofer ISI (2021).

As in the Netherlands, Germany generally does not implement technology specific tools, but the funding programmes in Germany are typically sector specific (construction or plastics), which is not the case in the Netherlands. Both countries offer measures targeting larger companies, SMEs and knowledge institutions, whereas the Germany policy mix is more focussed on PPP .The emerging technologies chemical recycling and bioeconomy are addressed more specifically in the Netherlands than in Germany. The bioeconomy in particular is of great importance to the refinery and chemical sectors in the Netherlands. For the same structural reason, chemical recycling of plastics is also part of the Dutch policy mix. In the Netherlands, a roadmap for the implementation of chemical recycling of plastics, including quotas, has been established. Based on a comparable legislative policy mix, it seems that the Dutch funding policy mix allows for more targeted actions in the field of material efficiency and the circular economy than Germany. Nevertheless, both countries lack specific product design standards.

R&D support in Germany and other countries

Another important angle through which Germany supports the circular economy is through speeding up the technological possibilities through investments in R&D. The FONA (Forschung für Nachhaltigkeit) research for sustainability includes the “Ressourceneffiziente Kreislaufwirtschaft” (resource-efficient circular economy) which covers the following topics: innovative product cycles, construction and mineral material cycles and plastic recycling technologies. Projects up to five years can get 50% funding for enterprises and up to 100% for higher education and research institutions. The budget available for 2018-23 is EUR 150 million.

Another stream of funding in Germany comes from the "Impulse für industrielle Ressourceneffizienz" (r+Impuls, impetus for industrial resource efficiency), which is supported by the expiring FONA3. Between 2016 and 2021, 26 joint projects are funded with EUR 22.3 million in the field of industrial resource efficiency. The funding only applies to TRL 5-9 and thereby closes the gap between R&D projects and introduction on the market.

Besides important transitions at the EU level, for example in Germany and overall in the European Union through Horizon 2020 funding, also the United States and the United Kingdom have ambitious plans for the transition to a circular economy.

UK Research and Innovation (UKRI) Industrial Strategy Challenge Fund is investing GBP 20 million in four chemical recycling plants. The four projects receiving funding are: ReNew ELP’s Catalytic Hydrothermal Reactor (Cat-HTR™) plant, Recycling Technologies’ chemical recycling plant, Poseidon Plastics’ hard-to-recycle PET chemical recycling plant, a collaboration between Veolia, Unilever, Charpak Ltd and HSSMI to develop the United Kingdom’s first dual PET bottle and tray recycling facility.

The DOE announced over USD 27 million in funding for 12 projects that will support the development of advanced plastics recycling technologies and new plastics that are recyclable-by-design. As part of DOE's Plastics Innovation Challenge, these projects will also help improve existing recycling processes that break plastics into chemical building blocks, which can then be used to make new products.

8.4.5. Addressing the main risks and bottlenecks for the recycling of plastics and metals

Enabling policy environment for recycling of plastics

For plastics, the main reason why the recycling rate is still much too low is that no separate market for recycled plastics exists, as primary and recycled plastics are treated as substitutes (OECD, 2018[59]). This causes the price of recycled plastics to be disconnected from the costs producing them and ultimately be driven by highly fluctuating oil prices. In addition, the average recycled plastics producer is about ten times as small as the average primary plastics producer, making the sector more vulnerable for market shocks such as the recent collapse in oil prices.

In the absence of a separate market, industry prefers to use virgin plastics, as making plastics from oil is very cost efficient, and therefore still easier and cheaper compared to producing recycled plastics, especially if the full environmental costs are not reflected in market prices. Recycled plastics are relatively expensive because of the technological barriers for sorting of plastics and chemical recycling as explained above. Policy interventions to create a market for recycled plastics include (OECD, 2020[60]):

- Setting statutory targets for recycling to drive supply of material, increase economies of scale, reduce costs and increase resilience.
- Using Extended Producer Responsibility (EPR) regulation to drive supply of material and increase economies of scale, reduce costs and increase resilience. Under EPR, a producer's responsibility extends throughout a product's lifespan, from production to the post-consumer stage – in other words producers must collect and recycle packaging after use.
- Green public procurement to create a market for greener products.
- Raising public awareness to create demand for plastics recycling, reduce contamination and to reduce dumping in the environment.
- Regulatory instruments such as recycling targets, product standards, recycled content requirements, lifetime warranties, bans and restrictions and deposit-refund systems.
- Market instruments, such as taxes, subsidies and tradable permit schemes, e.g. virgin material taxes or landfill taxes, cap-and-trade schemes for waste management. The full price difference should be captured by either taxes on virgin plastics or subsidies for recycled plastics.

Chemical recycling

In addition to the policies described to create a separate market for recycled plastics, more is needed if the Netherlands wants to exploit the potential of chemical recycling. Dutch waste policies view chemical recycling as low-value recycling, and therefore Extended Producer Responsibility systems for packaging do not regard chemical recycling as recycling. However, environmental analyses show that chemical recycling can still make a non-negligible contribution to emission reduction (CE Delft, 2019[56]), albeit much less than mechanical recycling. To give chemical recycling technologies the push needed to become commercialised, a level playing field with mechanical recycling could help. This is important for waste treatment policies and permits, for monitoring and reporting of recycling figures and also for producer responsibility schemes which support recycling (CE Delft, 2019[56]).

For chemical recycling the main challenge is the unavailability and inconsistent quality of feedstock, and again the before mentioned inefficient and thereby costly sorting, non-existing markets and unclear regulations for plastic waste management (Qureshi et al., 2020[61]). Solutions include:

- Tight co-operation between feedstock providers and converters to secure steady quantity and quality of feedstock.
- Advanced pre-treatment as basis for cost-effective recycling, classification of pyrolysis liquid as a product instead of waste.
- REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals) registration should be carried out to standardise the liquid oil as product.

Another issue is the traceability and accountability of recycled material, so that its use can be counted towards recycled content targets. Mass-balance can be introduced to create a workable set of rules to ensure the attribution of recycled feedstock into new products, such as naphtha, syngas, oil or monomers. Mass balance can enable a credible and transparent traceability between feedstock input and product output, and along the value chain to the producer of a final article. The European Chemical Industry Council recommends: the adoption of a mass balance approach in the tracing of chemically recycled plastics; Transparent certification by an independent party at each step of the value chain and the development of a standard which includes clear and credible rules on feedstock qualification, mass balance calculation and the use of appropriate product claims.

Chemical recycling installations become more economical with a larger scale. A common European policy on chemical recycling could make import and export for efficient chemical recycling easier. This requires the following policies at the **European level**:

- Ensure a level playing field with mechanical recycling of plastic waste. Chemical recycling falls under the recycling definition in EU Directive 2008/98/EC, except when it leads to reprocessed products in fuel. Therefore, there could be a trade-off between achieving recycling targets and chemical recycling.
- Develop a clear and harmonised recycling-rate and recycled-content rule throughout the EU, building on the common recycling definition in the EU Directive 2008/98/EC.
- Public sector co-funding to accelerate R&D partnerships and address the higher risk areas (e.g. bridging the valley of death, co-ordinating innovation across the whole value chain).
- Ensure an open single market for plastic waste. This can be achieved with a “fit for purpose” and harmonised approach for the shipment of plastic waste for use in recycling facilities within Europe, and potentially also imported into Europe to help other regions in the creation of low carbon circular economy for plastics.

  Create legal acceptance of a mass balance approach for chemical recycling based on a recognised standard and transparency when implementing or amending legislation. A mass balance approach refers to a set of rules on how to allocate the recycled content to different products to be able to claim and market the content as recycled. This is a crucial precondition for creating a separate market for recycled plastics.

Policies to increase the recycling rates of metals

Increase the availability of scrap

An important distinction for the recycling of metals is between major metals, such as aluminium and steel, and minor metals such as magnesium, ruthenium and lithium. For major metals, collection and recycling rates are already high and therefore the potential for further increases is limited. For minor metals collection and recycling, rates are low and therefore a large potential for improvement exists.

Major metals

If the world wants to decrease primary production, then scrap needs to be available for secondary material production. Aluminium can be recycled infinitely and re-melted. Scrap steel can be re-used in electric arc furnaces, in principle, if there is scrap steel without qualitative and quantitative losses. Either of which produces less emissions than primary production.

The availability of scrap is thus the main constraint to the increase in recycled metals. Availability mainly limited because 70% of the steel produced to-date is still in use due to the sustainable nature of steel (European Recycling Industries' Confederation, 2020[48]).

Another reason why the availability is under further pressure is that much scrap is exported to lucrative markets outside the EU (European Aluminium and Aluminium Center Belgium, 2016[62]). However, from a global recycling perspective this may be optimal if developing countries are specialised in low quality steel.

The Netherlands should strive for greater availability of scrap for industry. This calls for innovations in the collection and sorting of scrap, so that every piece of metal is saved. Waste should always be pre-treated to prevent recyclable metal products from ending up as waste.

Policies that can help to increase the supply of scrap include better sorting, pre-treatment of waste, legal reclassification of scrap from 'waste' to 'products', harmonisation of different national regulations at the EU level, a reduction in exported scrap and legislation facilitating the import of scrap.

Minor metals

Many of the 60 metals analysed by UNEP (2011[63]) have a very low end-of-life recycling rate: only eighteen of these metals are above 50% and many of them even below 1%. Reasons for these low recycling rates of minor metals are low efficiency in collection and treatment of most metal-containing discarded products, limitations in recycling processes, and because primary material is often relatively abundant and therefore relatively cheap compared to recycling (UNEP, 2011[63]).

Define waste to facilitate the trade and usage of scrap

First, the demarcation between scrap, waste, and end-of life products changes by country; forcing any exporter of scrap to comply with multiple regulations for the same piece of material, all of which adds costs and impedes trade. For example, member states' interpretations of the waste framework directive in the EU (2008/98/EC) and the end-of-waste criteria (Commission Regulation 333/2011) differ. The outputs from steel production, such as slag and fly ash, are labelled as "product" or "waste" from one region to the next, which results in a situation where the same material must comply with both product and waste legislation.

Classification, restricts what can be done with the material, e.g. whether and where it can be further processed or used leading to further administrative burdens and costs (Technopolis, 2016[64]). Material, which is classified "end-of-waste", is usually more expensive because of the administrative processes involved, and a material can only obtain end of-waste status when the producer possesses the necessary certifications, which do necessarily correspond with any existing standards in the industry. For example, the end-of-waste regulation in the European Union was aimed to increase the recycling of scrap steel, but it was largely unsuccessful. In all but one member state, steel scrap is still classified as a waste, which inhibits its use in secondary production, inadvertently fostering the use of primary materials (Technopolis, 2016[64]). While the waste status is there for environmental and health protection, its limitations on recycling may increase environmental harm. There is still no consensus among EU member states on the criteria and definitions for waste regulations that could lift this waste status.

Harmonisation of terminology is a first step to understanding what the potential uptake of scrap could be within the European Union, but also internationally. A convention, similar to the Basel Conventions for hazardous waste is needed, which can be used to set harmonised standards by the International Standards

Organisation for these kinds of materials. Clarifying this terminological ambiguity is a first step to facilitating its use in production.

Despite this definitional quandary, trade in waste already exists, but import and export bans also exist. These bans partly stem from health and safety, in addition to protecting domestic industry. As of 2018, China no longer imports 24 types of waste and since then 32 other materials have been added to the list – including plastics and some types of scrap metal, such as high-grade copper and aluminium. The rationale for this is partly from the health consequences of the informal recycling sector on humans and the surrounding environment. The traded volumes reached an enormous magnitude, along with efforts to minimise the cost of disposing waste, which led to the increasing use of landfills and incinerators rather than more advance recycling methods. The burning of uncategorised waste also produced toxins contaminating the environment and harming human health.

Trade policies can help increase recycling of metals not only by harmonising legal frameworks but also by enabling economies of scale, and by addressing the problem of exports to countries with inadequate recycling facilities (de Sa and Korinek, 2021[65])

European legislation is needed to further allow and stimulate the import of scrap to increase the recycled share in metal production.

8.5. Bio-based materials

Key messages

- The production of various bio-based materials, like bioplastics and biofuels, is technologically feasible, but generally still less cost-effective and in some cases of lower quality than their fossil counterparts.
- Most emission reductions can be achieved through the use of biofuels in the refinery and petrochemical industry. However, this could require great amounts of land use, raising concerns about unintended negative effects on the environment, such as illegal logging. Therefore, biomass should primarily be used to produce bio-based materials for which no renewable alternatives exist, instead of using biomass to produce energy.
- The large refinery and chemical sectors that are clustered in the Netherlands offers an enormous opportunity to accelerate the transition to a bio-based economy.
- The Dutch government closely monitors developments in the bioeconomy and tries to support them through numerous policy measures. However, additional steps are needed to speed up the process and achieve its ambition to become one of the most important bio-based hubs in Europe.
- Subsidies for fossil fuels should be phased out and subsidies for bioenergy and biofuel should apply in the same way to biomaterials and biochemicals. This is necessary to get a level playing field and thus a fair chance for the bioeconomy to thrive.
- Risks to private sector investments in biofoundries should be reduced to scale up investments. Biofoundries are facilities that provide an integrated infrastructure to enable the rapid design, construction, and testing of genetically reprogrammed organisms for biotechnology applications and research. Biofoundries are biotech infrastructure independent of manufacturing, i.e. biorefineries. Biofoundries can help make the bioeconomy more profitable by creating a bioecosystem of industrial symbiosis. Priority should be given to investments related to conversion technologies. Reducing risks to increase private investments can be achieved through public-private initiatives.

- One of the most important issues for the development of the bioeconomy is that the demand for bio-based products is lagging behind, which not only hinders investments in production, but also the necessary R&D in bio-based materials. For this reason, policies should be implemented to increase demand, for example through quotas, mandates, regulatory standards, public procurement or public awareness campaigns.

The European Commission defines the bioeconomy as using renewable biological resources from land and sea, like crops, forests, fish, animals and micro-organisms to produce food, materials and energy. The aim of a bio-based economy is both to meet climate objectives and to become less dependent on fossil fuels and other scarce raw materials.

There are important synergies between the bioeconomy and the circular economy described in Section 8.4. The circular economy is about sustainable use, reuse and recycling of products, while the bioeconomy tries to reach the same climate objectives through using renewable bio-based materials.

The synergies between the bioeconomy and the circular economy also follow from including ‘biomass and food’ action points in the Dutch transition agenda for the circular economy (Ministry of Infrastructure and the Environment and Ministry of Economic Affairs, 2016[53]). Other commitments to the bioeconomy are about the mobilisation of biomass, innovation, support and the development of market demand for bio-based products (Ministry of Economic Affairs and Climate Policy, 2018[66]).

In 2016, the Netherlands counted around 1 200 companies that are active in the bio-based economy, with an estimated turnover of EUR 21 billion, which is rather average at the European level (Ministry of Economic Affairs and Climate Policy, 2018[66]).

While the Netherlands was one of the first countries with a bioeconomy strategy (Ministry of Economic Affairs, 2015[67]), it is now time for additional steps to bring the bioeconomy to the next level. The Netherlands has a very good starting position for the transition to a bioeconomy, thanks to its well-developed agriculture, refinery and chemical sectors. The refinery and chemical sector require workers with similar skills and knowhow as the bioeconomy, therefore an enormous unutilised potential could be tapped into to accelerate the transition to a bioeconomy. The only disadvantage for the Netherlands is that it has little biomass, but biomass can be imported and the available biomass that is currently used for energy generation must first be used for bio-based materials for which there is no CO_2-neutral alternative.

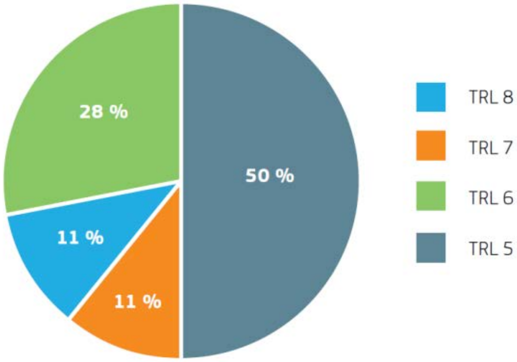
8.5.1. Technological readiness levels (TRL) of bio-based materials

Figure 8.9 shows that most promising bio-based materials still have a relatively low TRL 5 or 6, but that 22% of the bio-based materials studied by Fabbri et al. (2018[68]) already reach a TRL of 7 or 8. This shows that the bioeconomy is still a concept that is under development and that more is expected for the future.

Most bio-based materials relate to platform chemicals, plastics, biofuels and bioenergy. Biofuels and bioenergy have a relatively low added value per tonne of biomass, but because the vast majority of biomass is used for this, they still have the greatest economic and environmental impact.

The rest of this section will focus on bioplastics and biofuels. Other forms of bioenergy, like the use of biomass for electricity production, is beyond the scope of this report and many studies on bioenergy are already available.

Figure 8.9. TRLS Distribution for 20 of the most promising bio-based materials



Source: Fabbri et al. (2018[68]).

Bioplastics

Bioplastics are plastic materials produced from biomass, usually in the form of sugar derivatives, including starch, cellulose and lactic acid. Biodegradable plastics are plastics that can be decomposed by the action of living organism into water, carbon dioxide and biomass. Bioplastics are not necessary biodegradable and biodegradable plastics are not necessarily bio-based.

The production of bioplastics is technologically feasible but generally still more expensive than fossil-fuel based plastics. Therefore, bioplastics account for only less than 1% of all plastics manufactured worldwide (Rujnić-Sokele and Pilipović, 2017[69]). Moreover, when replacing plastics, there is a risk of using arable land that can no longer be used for food production, unless waste industrial gases are used as feedstock. Biodegradable plastics designed to be compostable are often sent to landfills due to a lack of proper composting or waste disposal facilities.

However, to reach a climate neutral economy, fossil-fuel based products should be replaced by sustainable alternatives, meaning that the share of bioplastics is expected to sharply increase in the future, which requires more R&D to increase the quality and cost-effectiveness of bioplastics.

Bioplastics are expected to become a more attractive alternative for fossil-based plastics if in the future it can be made from biomass flows with limited other uses. Bioplastics are currently made from carbohydrates such as corn or sugarcane. In the future, fermentation technologies are expected to enable the utilisation of lingo-cellulosic feedstock sources, for example non-food crops, waste industrial gases, domestic waste, forestry and agricultural residue materials, that have limited other uses. However, these types of bioplastics are still under development. Some of the new bioplastics hold great promise for commercial deployment within the next 5-10 years (Fabbri et al., 2018[68]).

Fabbri et al. (2018[68]) provide an overview of the 20 most promising bio-based materials and their TRL levels. Bio-based innovations relate to plastics in more than half of these 20 materials. Different types of plastics, like thermosets and thermoplastic materials, are being developed. Innovation can take place in the synthesis of completely new polymers (e.g. limonene-based engineering polymers: polyurethanes, polycarbonates, polyamides) or in drop-in substitutes from renewable resources (e.g. biophenolic resins). Polyhydroxalkanoates (PHAs) are being investigated for biodegradable substitutes for polymers as high-density polyethylene, PP and others. PHAs can be obtained through a purely biotechnological route using carbon-rich biomass, including agricultural waste or solid municipal waste and urban wastewater. The development of these PHAs based on renewable oils and fats and urban waste (OFMSW and UWW) is at TRL 6-7, while bioplastics based on sugars are already at TRL 9.

About half of the current bioplastics are not biodegradable (Rahman and Bhoi, 2021[70]). The polymers of some bioplastics, e.g. drop-ins such as PE and PET, have identical molecules as the polymers from fossil-fuel based plastics and both can therefore be recycled together. In contrast, it is more difficult, if not impossible, to recycle plastics when they are mixed with biodegradable plastics. Waste consisting of Bio-PE and bio-PP can also serve as feedstock for gasoline and diesel production. Bio-PET, bio-PA and PLA can be a potential feedstock for the gasification process (Rahman and Bhoi, 2021[70]).

Biofuels

A biofuel is a fuel that is produced from biomass and is usually used for transportation, but can also be used for energy generation and to provide heat, for example in the chemical sector. The two main types of biofuel are bioethanol and biodiesel.

Bioethanol is an alcohol made by fermentation, usually from carbohydrates produced in sugar or starch crops such as corn, sugar cane or sweet sorghum. Cellulosic biomass, from non-food sources such as trees and grasses, is also being developed as a raw material for ethanol production. Ethanol can be used in its pure form as a vehicle fuel (E100), but it is most commonly used as a gasoline additive to increase octane rating and improve vehicle emissions. Bioethanol is widely used in the United States and Brazil.

Biodiesel is produced from oils or fats through transesterification and is the most common biofuel in Europe. It can be used as a fuel for vehicles in its pure form (B100), but it is most commonly used as a diesel additive to reduce particulate matter, carbon monoxide and hydrocarbon content in diesel vehicles.

Technologies for the production of biodiesel and hydro treated vegetable oil (HVO) from animal fats and waste oil are technically mature and account for 8% of all biofuel production in 2018 (IEA, 2020[71]). Production of new advanced biofuels from other technologies is still limited and progress is needed to improve technology readiness levels. These technologies in development are important to make use of more commonly available raw materials which have other limited uses (for example agricultural residues and municipal waste).

The investment landscape for advanced biofuels is challenging, with only a small proportion of announced projects under construction.

8.5.2. Bioeconomy strategy in the Netherlands

The chemical and plastics industry use fossil fuels for the production of a wide range of products (including plastics, coatings, adhesives, detergents) and also use fossil fuels as energy source in their production processes. This fossil fuel based material needs to be replaced as much as possible by bio-based materials to achieve a climate neutral industrial sector.

The government programme “Netherlands circular in 2050” mentions ‘biomass and food’ as one of their top priorities (Ministry of Infrastructure and the Environment and Ministry of Economic Affairs, 2016[53]). Three strategic targets within this top priority are:

- The optimal use of biomass through the closing of cycles. Part of this is using biomass as efficiently as possible through cascading, preventing waste and efficient combustion.
- Reducing and replacing fossil fuels by sustainably produced biomass.
- Development and implementation of new ways of production and consumption.

These strategic goals translate into the operational objectives of replacing fossil resources by biomass and to also base chemical production on biomass (called ‘green chemistry’). Examples are support for biochemical factories and biorefineries for advanced bio-based fuels, chemicals and resources. The Vision Biomass 2030 formulates the ambition to reduce fossil resources by 70% in 2030.

In addition to the circular economy agenda, the Dutch government has also adopted a strategic vision for the use of biomass in 2030 (Ministry of Economic Affairs, 2015[67]). The strategic vision also states that the use of biomass plays an important role to replace fossil fuels by renewables and therefore reduce GHG emissions.

A number of actions are taken to meet the operational objectives. Ecological and social sustainability criteria are used for the sustainable production of biomass. Agricultural and forestry areas can be used more efficiently for biomass generation and more can be done to reduce losses in the biomass chain. For the origin of biomass, it is important that it does not have an unintended effect of increasing emissions elsewhere, e.g. by illegal logging.

Better cascading should take place, meaning that biomass should be used for products that create the most economic value over multiple lifetimes and that energy generation should be the last option only after all higher-value products and services have been exhausted (Keegan et al., 2013[72]). Cascading crosses sectors and applications, which requires measures to stimulate cross-sectoral co-operation.

The Netherlands recognises that in the long term it is important to use biomass primarily for applications where there are (hardly any) alternative cost effective sustainable sources. This concerns high temperature heat for industry, biofuels for aviation and shipping, and raw materials for chemicals and materials. The Dutch government argues that in the short and medium term, there are subsidies and investments in bioenergy to increase the supply of sustainable woody biomass flows. However, it is questionable whether this is the best possible strategy, since similar subsidies for bio-based materials can have a greater impact (OECD, 2018[73]).

The Dutch government expects that the demand for biomass for energy, biofuels, chemicals and materials will be between 432-570 PJ in 2030 (Ministry of Economic Affairs, 2015[67]). It expects that there will be enough supply of biomass to meet the demand, but this depends on the condition that the supply of biomass will increase and be used more efficiently and that additional biomass can be imported.

To support the bioeconomy, the Dutch government uses the following instruments: smart market incentives, stimulating legislation and regulations, innovation, the government as network partner and greening through trade and investments (Ministry of Economic Affairs, 2015[67]).

These instruments are used to: 1) increase the supply of sustainable biomass; 2) encourage the demand for sustainable biomass; 3) increase sustainability of production and use of biomass; 4) use all applications of biomass including materials; 5) focus on innovation and earnings capacity (Ministry of Economic Affairs, 2015[67]).

- The supply of biomass will increase by making better use of residual flows, increase productivity in agriculture and forestry at a European and global scale, produce blue biomass in the North Sea, use degraded land for biomass production and use European agriculture subsidies to support the transition to the bioeconomy.
- Demand for biomass will be increased by promoting product policies at the European level aimed at the phasing out of harmful substances if there is a good bio-based alternative, stimulating bio-based and biodegradable products in applications where products are left behind in nature or when bio-based products score better on sustainability and health than their current alternatives.
- The increase of sustainability of production and use of biomass is reached by developing a sustainable framework for all raw materials, push for the development of a harmonised European sustainability system, and promote cross-sectoral co-operation and cascading.
- To stimulate the use of all applications of biomass including materials, the Netherlands pursues policy integration at the EU level on renewable energy, climate and materials, with a focus on one parameter, CO_2 reduction.

- The focus on innovation and the earnings capacity is achieved by stimulating investments in new production capacity for advanced biofuels, chemicals and materials. The Top consortium for Knowledge and Innovation Biobased Economy (TKI-BBE) is strengthening research and innovations for the long term, such as on refineries of wood and agro residual streams.

The Netherlands wants to transform the Dutch “oil hub of North-West Europe” into the ‘green energy-hydrogen and plastic recycling hub’ of Europe, linked to a climate neutral industry. The refinery sector, together with the chemical sector, invest in renewable separation technology and new techniques for biotic raw materials (bio-based feedstock) (Ministry of Economic Affairs and Climate, 2020[74]). The application of bio-based resources is already taking place on a commercial scale for the production of biofuels. In addition, commercially feasible production of bio-based plastics would be possible in the Netherlands, but the bottleneck is often the demand side and European source policy is required to increase demand (Ministry of Economic Affairs and Climate, 2020[74]).

Another ambition is to have at least one or two installations on a commercial scale for each major GHG reducing technique (CCU, chemical recycling, electrification and bio-based resources). The government wants to realise these flagship-projects to build national experience to attract multinationals. Rotterdam is developing as one of the most important European bio-based clusters, including Neste’s biofuel refinery. In this refinery, they produce renewable biofuels from algae, among other things, in addition to traditional biofuels from waste.

There are a number of policies used to support the transition to a bioeconomy. The TKI Biobased Economy aims to have both the energy and chemical sector replace fossil resources with biomass, and focuses on the development of bio-based innovation throughout the entire biomass value chain, according to the principle of cascading. TKI biobased consists of four programme lines: thermal conversion, chemical catalytic conversion, microbiological conversion and solar capturing and biomass production.

Other policies aimed at the circular economy also apply to bio-based materials. For example, the Mission Oriented Innovation Programme 6 (MMIP 6) is about the closing of industrial cycles and also includes the bioeconomy. The same is true for MOOI subsidies, DEI+ and DEI+ Circular Economy, the MIA and Vamil tax credits and the Green project loan facility. These instruments are explained in more detail in Chapter 5 on the current policy package.

8.5.3. Bioeconomy strategies in other countries.

Germany

Although the Association of German Industry believes that biomass plays an important role as a relatively cheap energy carrier for decarbonising the heating of industrial processes, the government is more cautious and the Ministry of Environment is even against expanding the use of biomass for process heating due to significant competition with other sectors and other applications (Fraunhofer ISI report).

The fourth FONA Research for Sustainability Framework Programme (FONA4) is effective from 2020 to 2024 and has a total budget of EUR 4 billion. It provides grants for a wide range of research projects in the fields of green hydrogen, circular economy, climate protection and the bioeconomy in specific funding guidelines and funding announcements. As part of this FONA4 programme, the funding guidelines "Epigenetik - Chancen für die Pflanzenforschung" (Epigenetics - opportunities for plant research) and "Zukunftstechnologien für die industrielle Bioökonomie" (future technologies for the industrial bioeconomy) are supported. While the first one focuses on food production, the second supports bioeconomy technologies in general. The funding amount is currently not published.

The bioeconomy is addressed more specifically in the Netherlands than in Germany, which may be related to its high relevance for the refinery and the chemical sector in the Netherlands. The German policy mix has a broader sectoral focus and is less dependent on bio-based materials. This is also consistent with finding a relatively large number of patents related to the bioeconomy in the Netherlands, while Germany is underperforming in this area, (Figure 8.12, Figure 8.14).

United Kingdom

The United Kingdom has an ambitious bioeconomy strategy for 2030 (Department for Business, Energy and Industrial Strategy, 2018[75]). The United Kingdom wants to boost their productivity by using their world class bioscience base to: 1) create new forms of clean energy; 2) produce smarter and cheaper materials such as bioplastics; 3) reduce plastic waste and pollution by developing environmentally sustainable biodegradable plastics; 4) provide sustainable healthy affordable and nutritious food; 5) increase sustainability of agriculture and forestry and use microbes instead of chemicals to create medicines and cosmetics (Department for Business, Energy and Industrial Strategy, 2018[75]).

The United Kingdom takes the lead on the transformation to sustainable plastics by investing GBP 60 million through the Industrial Strategy Challenge Fund to make plastics more sustainable, efficient and productive. An additional GBP 20 million is invested in the Plastics Research Innovation Fund, GBP 25 million in the Commonwealth Marine Plastic Research and Innovation Framework and GBP 20 million for research and development into new, smarter more sustainable packaging and boosting recycling.

The bioeconomy strategy for the United Kingdom relies on four main strategic goals: 1) capitalising on world-class research, development and innovation base to grow the bioeconomy; 2) maximising productivity and potential from existing UK bioeconomy assets; 3) delivering real, measurable benefits for the UK economy; 4) creating the right societal and market conditions to allow innovative bio-based products and services to thrive.

The UK Plastics Pact sets out the ambition for all plastics to be reusable, recyclable or compostable by 2050. This should be achieved through a strong innovation-based supply chain.

The Synthetic Biology Leadership Council (SBLC) is installed to set out the details on delivering the strategic actions required to support the development of technology platforms such as synthetic biology and industrial biotechnology; and to provide a regulatory framework to support the bioeconomy.

Global biofoundries alliance

Biofoundries are fundamental for the development of cheaper high-quality bio-based materials. Biofoundries provide an integrated infrastructure that makes it possible to rapidly design, build and test genetically reprogrammed organisms for research and biotechnology. Most biofoundries are in the United Kingdom and United States, with some in China and South Korea, but no biofoundry exists in the Netherlands yet. The Global Biofoundry Alliance (GBA) has recently been established to co-ordinate activities around the world.

The objectives of the GBA are: 1) to develop, promote, and support non-commercial biofoundries established around the world; 2) to intensify collaboration and communication among biofoundries; 3) to collectively develop responses to technological, operational, and other types of common challenges; 4) to enhance visibility, impact and sustainability of non-commercial biofoundries; 5) to explore globally relevant and societally impactful grand challenge collaborative projects (Global Biofoundries Alliance, 2021[76]).

8.5.4. Advancing the uptake of bio-based materials

Level playing field with fossil fuels, but also with biofuels and bio-energy

The Dutch government provides 13 individual subsidies for fossil fuels for a total amount of EUR 4.483 billion government revenue per year (IEA, 2020[77]). Most of these subsidies are related to tax exemptions for international flights and maritime transport. This huge number of fossil fuel subsidies is many times the amount of subsidies for the bio economy. The bioeconomy lacks significant subsidies which prevents scaling up for the more efficient production of bio-based products.

Even without fossil fuel subsidies it is already hard to compete with the fossil fuel industry, given that refineries and the petrochemical industries are very old and large, and therefore already very efficiently organised with perfectly aligned value chains. The bioeconomy is still a very new and upcoming industry and therefore it has not yet reached the most efficient scale, nor perfectly aligned value chains in which each component of biomass is used where it has the highest value added. The removal of fossil fuel subsidies is a necessary but probably not a sufficient condition to give the bioeconomy a fair chance to reach similar levels of efficiency (OECD, 2017[78]).

Competition is not only unfair with fossil fuels, but there is also no level playing field for the input of biomass, between bio-based materials and biochemicals on the one hand, which are hardly supported, and the much more subsidised biofuels and bioenergy (OECD, 2018[73]) on the other hand. Scaling up the bioeconomy requires a holistic approach to understand the complex interactions of value chains in the societal carbon cycle. First of all, to ensure that different components of biomass are used in the most economical and environmental friendly way. Second, because only subsidising bioenergy and biofuels, but not biomaterials, is expected to have a negative impact on the amount of biomass available for the production of bio-based materials and chemicals. This may unintentionally undermine the development of the bioeconomy. Therefore, some have called for the Renewable Energy Directive (RED) to be transformed into a Renewable Energy and Materials Directive (REMD) (Nova Institute, 2014[79]). Bio-based materials use, such as bioethanol and biomethane, could be accounted for in the renewable quota the same way as it counts for the energy use of the same building block, e.g. fuel. A third risk is that subsidies to bioenergy and biofuels can lead to unintended consequences elsewhere in the world, such as illegal logging.

Derisking private sector investments

Large uncertainty exists about the economic returns of biofoundries and biorefineries. Often, bio-based materials do exist, but the production is more expensive than their fossil fuel counterparts. Therefore, additional investments are required to further develop the quality of bio-based alternatives in biofoundries and to help upscale the bio-based materials production to a more economically efficient level.

Systemic business risks exist as suppliers of bio-based materials are dependent on the uptake of bio-based materials further down in the value chain. This means that a holistic approach is needed to reduce risks caused by dependencies between different parts of the value chain (Marvik and Philp, 2020[80]).

Public private initiatives, and other forms of risk sharing such as government venture capital, may help to reduce these risks and increase private investments in bioeconomy. Involvement in public-private partnerships would also give the Dutch government instruments to give a bit more direction to the development of the bioeconomy.

Given the importance of focusing on the development of new materials that are of higher quality and more cost-effective, the focus should be on supporting biofoundries, the place where innovation in the field of bio-based materials is currently taking place. Biofoundries provide integrated experimental and computational infrastructure for designing building and testing of bio-based materials (Kitney et al., 2019[81]). Within these biofoundries, one of the things that should be further invested in are **conversion technologies**, as feedstock is often bio-based, but conversion technologies are often still chemistry based. Engineering biology may provide the breakthrough to cost-effective lignocellulose conversion in bioprocessing. In addition, support should be given to cross-disciplinary research and education to embed computer-aided biology.

Technical barriers for commercialisation of biotechnology can partly be solved by setting standards for reproducibility and reliability (Kitney et al., 2019[81]). Given that small changes in cellular or environmental context are important for bio-based materials, small changes may underpin learning from earlier iterations.

While the construction of bio-based materials is often a formulaic exercise in engineering, it is much more difficult to create an ecosystem of stakeholders, from feedstock owners and producers to customers for bio-based products, to end-of-life recycling (Philp and Winickoff, 2019[82]). The main problem is to get commercially viable value chains. A large industrial refinery and chemical sector in the Netherlands has the potential to exploit this local agglomeration effects. Policies can help to co-ordinate between different stakeholders in the value chain.

Increasing demand through standards, public procurement and awareness campaigns.

As much of the uncertainty for investors comes down to uncertainty about future demand for bio-based products, commitment of the government to the bioeconomy is important. This subsection explains how the increase in demand for bio-based materials can help solve this problem of uncertainty and how policies can increase demand for the bioeconomy.

The risk is being locked into a vicious circle, in which the lack of demand for more expensive bio-based products prevents investments in better and cheaper bio-based materials. Reducing uncertainty, by setting ambitious expectations on future demand, could therefore break this vicious circle, by stimulating investments. These investments are expected to speed up the development of high quality bio-based alternatives for fossil fuels based products. A second mechanism is that the increase in demand will help to scale up, which makes it possible to gain economies of scale, and to have for example more efficient cascading in which many different components of biomass are used where it has the highest value added. Also a bigger market makes producers less dependent on a few suppliers or customers.

There are numerous ways by which the Dutch government could increase demand for bio-based products, for example through standards, public procurement, certification and public awareness campaigns (OECD, 2018[59]).

Regulatory standards can help to increase demand. The transition to a bio-based chemical and plastics industry can be achieved through quotas for renewable plastics and standards for life-cycle assessments (LCA) of products. An example where standards helped was when in China single-use plastics had to become biodegradable, which was a huge push for industry to invest more in higher quality biodegradable plastics (Swift, 2019[83]). Similar standards could be set at the Dutch or European level. Standards can sometimes relate to the composition of materials for products, for example that a certain share of a fuels are required to be bio-based. The same can be done for bio-based plastics that are not biodegradable as they can be recycled together with fossil-based plastics, but this is harder in the case of biodegradable plastics as these cannot be recycled together with non-biodegradable plastics. If the government wants to push for biodegradable products, then it could set a standard that some products, e.g. single-use plastics, have to be biodegradable.

In addition, public procurement could help to have enough demand for industry to scale up to a more efficient level of production. The public and semi-public sectors are large in the Netherlands, meaning that public procurement could make a big difference for the demand of bio-based products, such as bio-based food packaging in canteens, office equipment, furniture, construction, etc (InnProBio, 2017[84]). The public sector could also commit for multiple years of procurement, reducing uncertainty and stimulating investments in cheaper products to increase profits of the bioindustry. The Netherlands could learn from the BioPreferred Program of the United States Department of Agriculture (United States Department of Agriculture, 2021[85]).

Also certification, as is done for fair trade or FSC wood, could also help to increase demand for bio-based products. Without certification it is almost impossible to get a market for bio-based products as differentiation is needed to distinguish from their often cheaper fossil fuel based counterparts. In addition, public awareness campaigns can help customers to buy more bio-based products. For public awareness campaigns, however, it may be desirable for the government to also control or monitor certification to ensure that these campaigns contribute to the climate goals.

8.6. Dutch innovation in emerging technologies: insights from patent data

In order to provide empirical insights into the Dutch industry's innovation efforts on emerging technologies for the low-carbon transition, a patent data analysis was conducted based on the OECD's STI MicroData Lab infrastructure. The use of patent data as a measure of innovative activity is widespread, particularly in the field of climate change mitigation technologies for which the European Patent Office has developed a dedicated classification scheme (referred to as the Y02/Y04S tagging scheme) to identify relevant inventions in global patent databases such as PATSTAT.

Although patents do not provide a measure of all innovation, they provide a wealth of information on both the nature of the invention and the applicant – including the location of innovation activity, allowing for interesting cross-country comparisons. More importantly, patent data can be disaggregated into highly specific technological areas. Finally, patent data provide information about not only the countries where new technologies are developed but also where they are used.

Before describing the indicators used in this section, we briefly review how the patent system works. When a firm or an inventor from a particular country discovers a new technology, they must decide where to market this invention and how to protect the associated intellectual property. A patent in a given country grants the applicant the exclusive right to commercially exploit the invention in that country. Accordingly, firms patent their inventions in a country if they plan to market the invention in that particular country. Patenting is costly, in terms of both the costs of preparing the application and the administrative costs and fees associated with the approval procedure. Thus, inventors are unlikely to be willing to incur the cost of patent protection in a country unless they expect there to be a market for the technology concerned. The set of patents protecting the same invention across several countries is called a patent family.

The data used for this section comes from the PATSTAT database, maintained by the European Patent Office. PATSTAT is unique in that it covers more than eighty patent offices worldwide and contains over a hundred million patent documents. It is updated biannually. Patent documents are categorised using both the international patent classification (IPC) and the Co-operative Patent Classification (CPC).

Patent applications related to the five emerging low-carbon technologies discussed in this section were identified using IPC and CPC codes. PATSTAT includes the country of residence of the inventors of those technologies for which patent protection is sought (independent of the country in which the applications are actually filed). This information is used to measure a country's innovation performance.

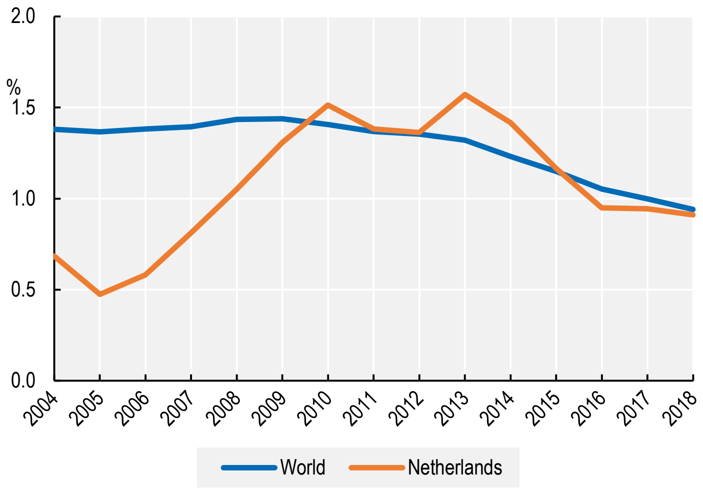
A well-known limitation of patent data is that the value of individual patents is heterogeneous, making cross-country comparisons of innovative activity based on simple patent counts problematic. In this analysis, international patent filings through the Patent Co-operation Treaty (PCT) are used as the main measure of innovation. It has been shown that only patents of a certain value are transferred internationally. Thus, PCT patents provide a quality threshold that make cross-country comparisons more robust. In addition, PCT patents are available with a shorter lag than other measures of patent quality, such as patent citations. With this, we are able to observe patent activity until 2018. To observe trends in patent filings over time, we focus on the last 15 years of available data, covering the period 2004-18.

Over the period 2004-18, 33 648 PCT patents were filed globally in the five low-carbon technologies combined: bio-based materials, CCUS, electrification of industrial heating processes, hydrogen and recycling of plastics and metals. This represents 1.2% of all PCT patent filings in all technologies. However, this share has decreased over time, from 1.4% in 2004 to less than 1% in 2018.

Of these 33,648 low-carbon patents, 555 were filed by inventors located in the Netherlands. Therefore, Dutch inventors are responsible for 1.65% of global patent filings in the five low-carbon technologies under consideration. This is slightly less than the proportion of Dutch patents across all technology fields, which stands at 1.87%. On average, therefore, Dutch inventors do not appear specialised in these emerging low-carbon technologies, as their performance simply reflects the Netherlands' general contribution to global innovation efforts in all technologies.

Figure 8.10 shows the trends in low-carbon patenting activity, for the five selected technologies combined, by Dutch inventors and inventors worldwide. There has been a considerable increase in innovation efforts directed at the five low-carbon technologies in the Netherlands between 2004 and 2010: the proportion of patents covering these five technologies in total patenting activity of the Netherlands tripled, 0.5-1.5%. Interestingly, this period corresponded to a significant increase in public support for RD&D in low-carbon technologies, in particular toward CCUS and hydrogen.[7] Since then, Dutch efforts have been closely following the global average, decreasing regularly until 2018. In 2018, it represented around 1% of total Dutch patenting activity, exactly on par with the global average, suggesting that Dutch inventors are not particularly specialised in low-carbon innovation. The slowdown in low-carbon innovation activity has been observed more generally (including in other areas such as renewable energy) and has been partly attributed to the decrease in global oil prices, which makes low-carbon and energy-saving innovation less profitable.

Figure 8.10. Patents for the five low-carbon technologies as a share of total patents in all technologies

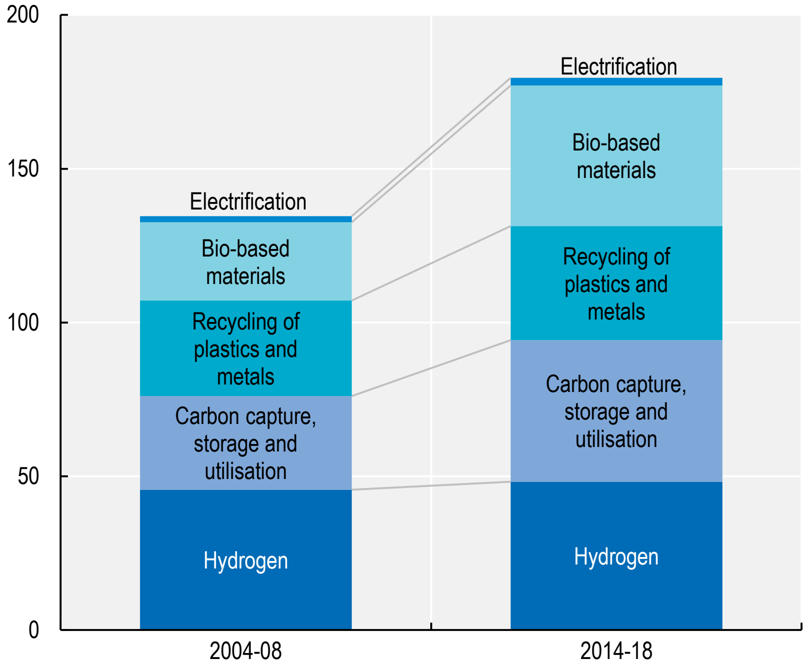


Note: Data refers to patents invented in the five selected low-carbon technologies. Statistics are based on two years moving average.
Source: OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, January 2021.

Looking at individual categories, most of Dutch low-carbon innovation efforts are directed at hydrogen technologies (48 PCT patents in the 2014-18 period), closely followed by CCUS (46 patents) and bio-based materials (also 46). Recycling of plastics and metals is slightly below (37 patents over that period) while patents related to electrification of production processes appears extremely marginal (2 patents). The relatively low number of patents related to electrification is also observed for the rest of the world, albeit to a lesser extent than in the Netherlands. A plausible reason for this relatively low number of patents for electrification is that this technology is more mature and that therefore less frontier innovation is taking place. Figure 8.11 shows the evolution of Dutch inventors' patent filings between the periods 2004-08 and 2014-18. The largest increases can be found in the CCUS and bio-based materials categories. In comparison, hydrogen and recycling have remained fairly constant. Technologies related to electrification of production processes have remained marginal throughout the period.

The finding of a sharp increase in the number of patents for bio-based materials is in line with the increased technological readiness and policy focus on bioplastics and other bio-based materials, as described in Section 8.5. The increase in patents for CCUS technologies can plausibly be explained by an increased likelihood that these technologies will be needed in the fight against climate change. Section 8.1 describes an increasing policy focus on CCS in the rest of the world, most prominently in the United States and the United Kingdom. Another plausible explanation may be related to the first carbon storage operation that was installed in the Netherlands in 2004, which may have triggered more research into this technology.

Figure 8.11. Patents filed by Dutch inventors, by technology



Note: Data refers to patents invented in the Netherlands for selected low-carbon technologies. Patent counts are based on the filing date.
Source: Source: OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, January 2021.

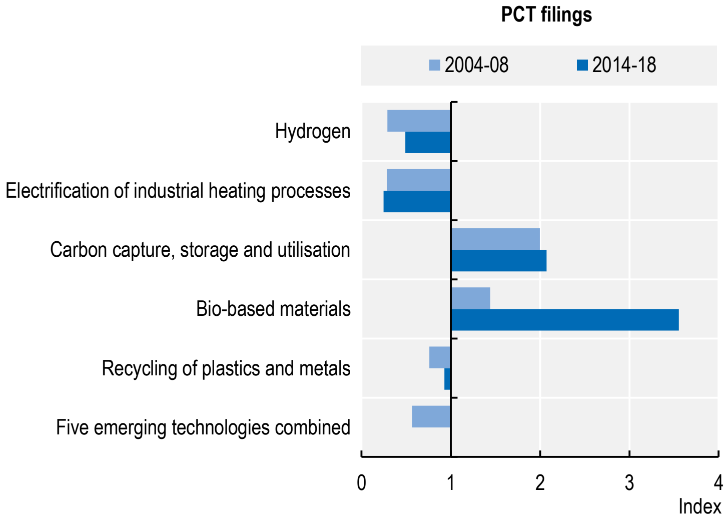
Figure 8.12 shows the Relative Technological Advantage (RTA) of Dutch inventors for the five emerging low-carbon technologies in the two periods (2004-08 and 2014-18), based on PCT patents (the last line corresponds to the five technologies combined). The RTA is defined as the share of global patents in each technology filed *by Dutch inventors* divided by the share of patents in the same technology filed by inventors *from all countries*. Therefore, an RTA of one corresponds to a situation where the performance of Dutch inventors is exactly equal to the world's average effort toward this technology (this is actually the case for low-carbon technologies in the 2014-18 period, where the bar lies exactly on the vertical line). An RTA above one indicates relative specialisation in the technology (i.e. the Dutch output is higher than the world's average output); an RTA below one indicates under-specialisation in the area.

As shown in Figure 8.12, the CCUS and bio-based materials categories, which have seen the largest increases over the recent period, also correspond to the areas where Dutch inventors appear most specialised. In bio-based materials in particular, the share of Dutch innovation efforts going into this field is more than three times that of the world average in the most recent period (2014-18). In CCUS, Dutch inventors are twice as specialised as the average world's inventor. Specialisation in bio-based materials has markedly increased over the last fifteen years, while specialisation in CCUS was already similar fifteen years ago. This is in line with the TRL levels and policy attention to these technologies described in Section 8.5 for bio-based, and to a somewhat lower extent also in Section 8.1 on CCUS. In the other three technological fields – namely hydrogen, electrification of industrial heating processes and recycling of plastics and metals – Dutch inventors appear under-specialised. The increase in the combined RTA for the five technologies (last line) is entirely driven by recent efforts toward bio-based materials.

These results confirm findings in Sections 8.2, 8.3 and 8.4; that more policy efforts are needed to achieve the climate goals for the Dutch industry. In addition to higher R&D subsidies, a business case must be made for electrification of heat, hydrogen and recycling. This can be done, for example, by changing the (future) relative prices of electricity, hydrogen and recycling relative to their fossil fuel counterparts.

For a small country like the Netherlands, and given that research into emerging technologies like hydrogen typically entails large fixed costs, specialising in all of these emerging low-carbon technologies with a view to promote national champions in all these new technological areas is less obvious. A sensible strategy therefore seems to be to focus on areas where Dutch inventors possess some comparative advantage, which include CCUS and bio-based materials. Other technologies could be “imported” from abroad, but adoption requires absorptive capacities, which also necessitates R&D activity – although not targeted at frontier research.

Figure 8.12. Relative Technological Advantage (RTA) of Dutch inventors by technology

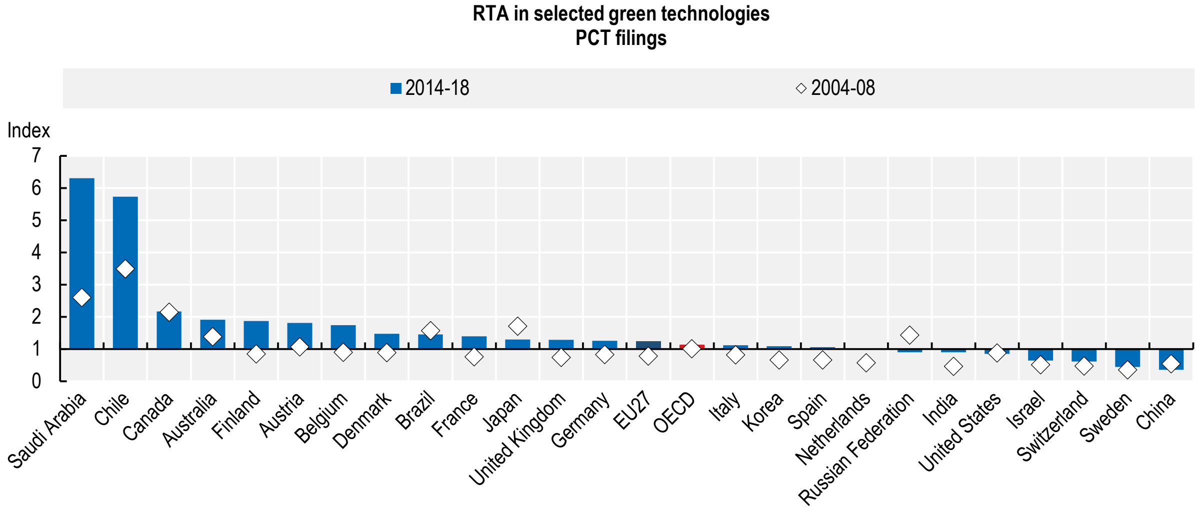


Note: Data refers to patent invented in the Netherlands for selected low-carbon technologies. Patent counts are based on the filing date under the Patent Co-operation Treaty (PCT).
Source: OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, January 2021.

The average absence of specialisation of the Netherlands in the five technologies of interest can be compared to the RTA of other countries. This is done in Figure 8.13. Many countries appear more specialised than Dutch inventors in these emerging low-carbon technologies, and many have also become more specialised over the last 15 years. It is important to keep in mind that RTA only reflects *relative* performance, not absolute number of patents. Yet, it is interesting to observe that some countries such as Saudi Arabia, Chile or Australia have disproportionately high numbers of patents in these areas compared to their overall innovation performance. In short, the data suggests that Dutch inventors have not taken a head start in the global innovation race in emerging low-carbon technologies.

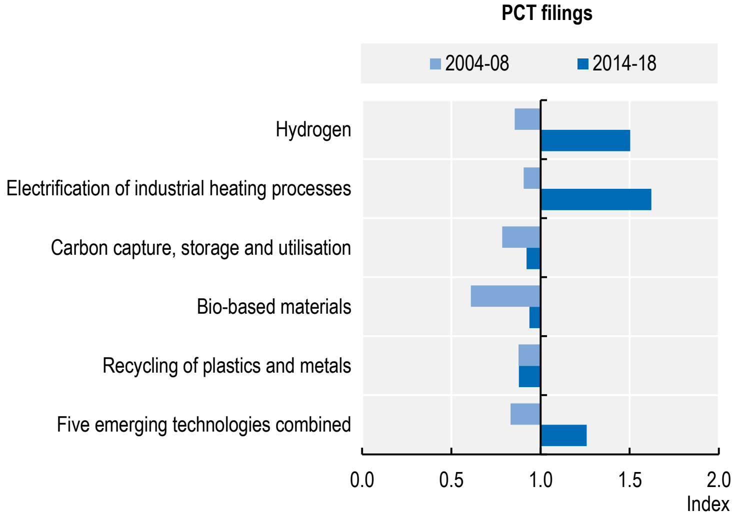
Figure 8.14 reproduces Figure 8.12 for Germany and shows the Relative Technological Advantage (RTA) of German inventors for the five emerging low-carbon technologies in the two periods (2004-08 and 2014-18). On average across the five technologies, inventors operating in Germany appear slightly more specialised in low-carbon innovation than the Netherlands, but the difference is not large. What is striking from Figure 8.14 is the strong specialisation of German inventors in both hydrogen and electrification of heating processes – two technologies where inventors based in the Netherlands relatively under-perform. Moreover, this specialisation is recent and was not the case fifteen years ago.

Figure 8.13. Relative Technological Advantage (RTA) of the Netherlands compared to other countries for the five selected low-carbon technologies



Note: Data refers to patent applications filed under the Patent Co-operation Treaty (PCT) in selected low-carbon technologies. Patent counts are based on the filing date and the inventor's country, using fractional counts. Only countries featuring more than 50 low-carbon technology patents over the period 2014-18 are included.
Source: OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, January 2021.

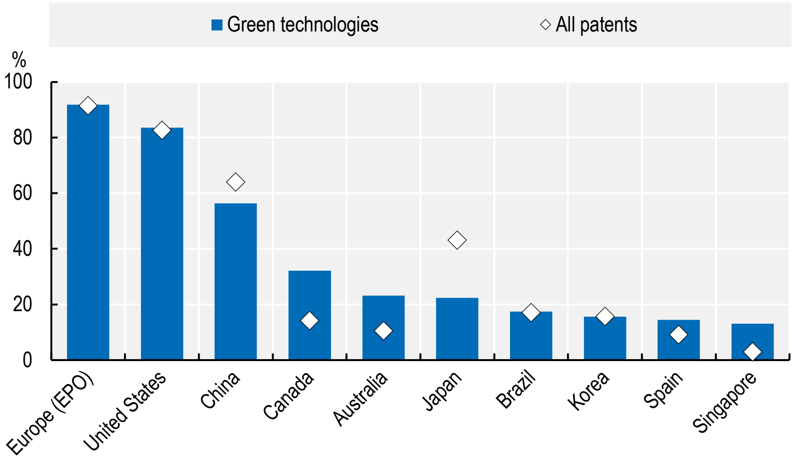
Figure 8.14. Relative Technological Advantage (RTA) of German inventors by technology



Note: Data refers to patent invented in Germany for selected low-carbon technologies. Patent counts are based on the filing date under the Patent Co-operation Treaty (PCT).
Source: OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, January 2021.

As mentioned above, patents include information not only on the country in which the invention was developed (the indicator that was at the centre of the analysis until now) but also on countries or regions (for multinational patent offices) where intellectual property protection is sought. Figure 8.15 presents the main foreign patent offices in which inventions developed in the Netherlands seek patent protection. These correspond to the expected markets for Dutch inventions. In the figure, the bars refer to low-carbon technologies, while the diamonds refer to all technologies.

Figure 8.15. Top 10 foreign markets for inventions made in the Netherlands, 2010-18



Note: Data refers to IP5 patent families invented in the Netherlands, by IP offices in which family members were filed.
Source: OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, January 2021.

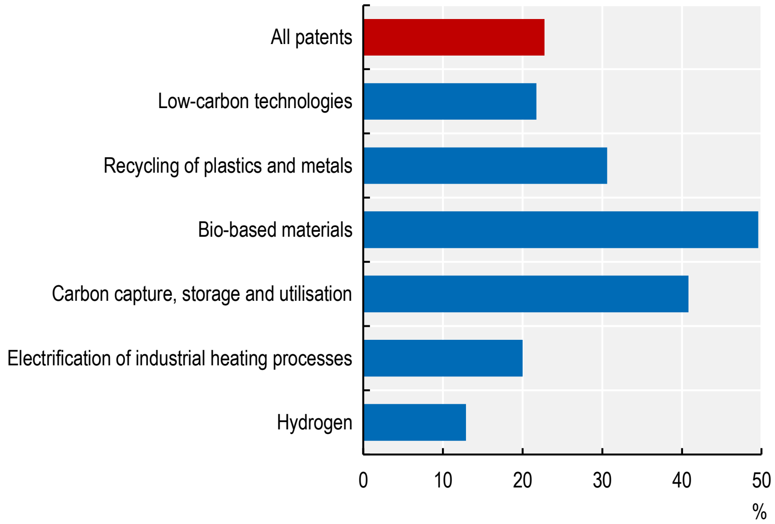
The main destination patent offices for Dutch inventors are the European Patent Office (EPO) and the United States patent office, with respectively 90% and 80% of low-carbon inventions being applied for in these offices. These rates exactly correspond to the rate observed for all technologies. In contrast, China and Japan do not appear as attractive markets for low-carbon technologies relative to others, while Canada and Australia see a much higher rate of "technology export" in low-carbon technologies than in other innovations developed by Dutch inventors. A plausible explanation for this is that Canada and Australia appear to specialise themselves in low-carbon technologies, as shown in Figure 8.13.

Conversely, is the Netherlands an attractive market for foreign inventors in emerging low-carbon technologies? Figure 8.16 addresses this question by showing the share of patents granted by the EPO that are then transferred to the Netherlands (and hence, protected in the country). The EPO is the main entry point of foreign technologies in most European countries (contrary to the Dutch patent office, which mostly targets domestic applicants interested only in the local market).

Figure 8.16 shows that around 23% of all patents granted by the EPO are ultimately transferred and protected in the Netherlands. The share is very similar at 22% for emerging low-carbon technologies, implying that the Netherlands was not – in the recent period until 2018 – seen as a particularly attractive market by inventors for these technologies. There are, however, marked differences across technologies. Fifty percent of bio-based materials patents filed at the EPO and 40% of CCUS patents are validated in the Netherlands, and 30% of recycling patents, against only 20% of patents related to electrification of heat processes and, perhaps most surprisingly, 13% of patents in hydrogen-related technologies. Combined with the absence of specialisation of Dutch inventors in hydrogen patents, this signals that the country was not seen – at least until recently – as an attractive market for hydrogen technology. The knowledge and technology base in the country, therefore, is currently poor, and the number of available technologies ready to be deployed might similarly be low. Given the critical importance of hydrogen for the decarbonisation of the Dutch industry, and the recent political focus on this technology, this observation has important policy implications: both domestic innovation and international transfer of foreign technologies are currently weak and could be in need of policy support.

Figure 8.16. Share of European Patent Office patents validated in the Netherlands

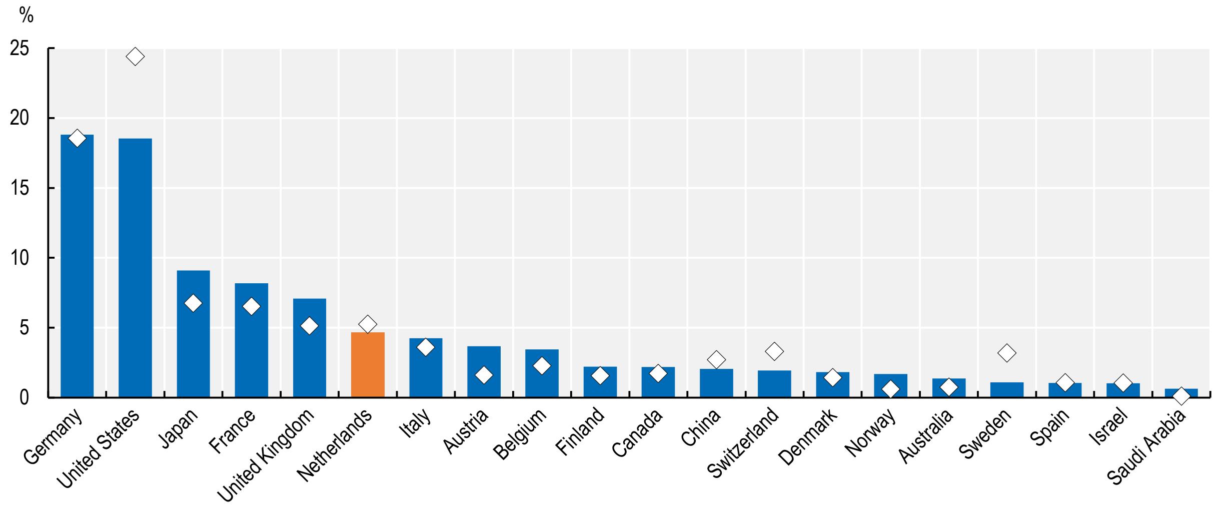
As a share of patents granted at the European Patent Office



Note: Data refers to EPO patent grants protecting selected green technologies, and validated in the Netherlands, by date of grant.
Source: OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, January 2021.

Figure 8.17. European Patent Office patents in low-carbon technologies validated in the Netherlands, 2014-18

Top 20 inventor countries



Note: The blue bars refer to EPO patent grants protecting emerging low-carbon technologies, and validated in the Netherlands, by date of grant and inventors' country, using fractional counts. The diamonds represent the rate for all patents.
Source: OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, January 2021.

Where are low-carbon technologies protected in the Netherlands currently coming from? Figure 8.17 shows the proportion of EPO patents validated in the Netherlands by inventor country. The main supplier of foreign low-carbon technologies in the Netherlands is Germany, followed by the United States, Japan, France and the United Kingdom. This is a reflection of the general innovative capacity of these countries, but there are some differences with the rate observed for all patents (represented by a diamond). For example, low-carbon patents from the United States are less likely to be validated in the Netherlands than the average US invention filed at the EPO. The opposite is true for inventions coming from Japan, France and the United Kingdom.

There are also some specificities in particular technologies. For example, Norway is an important importer of CCUS inventions into the Netherlands, as are Austria and Belgium for recycling technologies.

8.7. Cross-technology policy lessons

Considering the cross-technology perspective, we can conclude that the carbon levy and the SDE++ subsidies are crucial policy instruments for the development and deployment of the key emerging technologies for Dutch industry's decarbonisation. In particular they support the business case for CCUS/CCS, electrification of heating and hydrogen. While the carbon levy and SDE++ are expected to make up for the cost disadvantage arising through operational expenses for most technologies related to CCUS/CCS and the electrification of low-temperature heating. However, if the Netherlands wants to realise its green hydrogen ambitions with these two instruments only, it will be challenging since these operational costs of hydrogen are not covered. Given that the development and deployment of the main emerging technologies are so dependent on the carbon levy and on SDE++, it is important to further strengthen these two core instruments. For SDE++, a policy consideration would be to reserve part of the SDE++ budget for green hydrogen to push for the necessary investments to make green hydrogen more cost-effective in the future. For the carbon levy to remain a credible instrument, it is important that the carbon levy takes effect in the future and that uncertainty about possible abolition is reduced. While the carbon levy can also help to accelerate the transition to a circular economy, for the recycling of plastics and metals and for the bioeconomy, additional policies are necessary to increase the demand for recycled products and biobased materials. Standards for minimum recycled content and public procurement can boost the demand for recycled materials and bio-based products.

One risk of a very different nature, from the policy side, is that insufficient account is taken of the importance of the industrial clusters and the differences between them. As pointed out earlier in the report, much of high-emitting industry is organised in clusters connected through advanced pipeline infrastructure. It is important to recognise that tailor-made policy from government is needed to help the clusters make the transformative changes required (Climate Friendly Materials Platform, 2021[86]). The role for the cluster level is the co-ordination of local companies and utilities and to facilitate the transition with the implementation of supporting policies. This is important for the development and adoption of key emerging technologies, for example because of important economies of scale for infrastructure related to CCS, green hydrogen, chemical recycling and biofoundries.

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Notes

[1] Porthos stands for Port of Rotterdam CO_2 Transport Hub and Offshore Storage.

[2] In this project, the CO2 is separated from the production stream prior to gas transport to shore. The CO2 is then injected into the same reservoir from which its gas originated.

[3] Institut du Développement Durable et des Relations Internationales.

[4] Also, electricity tax applies to electricity supplied via a connection to the energy grid only, leaving electricity production for own use ("auto-generation") untaxed. Electricity auto-generation from renewable energy sources is also exempt from taxation.

[5] Often this involves steam methane reforming of natural gas. Asia still produces a large proportion of hydrogen from coal (e.g. ammonia and methanol producers).

[6] Power-to-X technologies are energy conversion technologies that can be used to store power surpluses from renewable energy sources.

[7] Average annual public RD&D support to CCUS and hydrogen was respectively EUR 15.5 million and EUR 4 million over 2004-10, against EUR 1.8 million and EUR 1.9 million over 2011-18. There was no public funding for either technology before 2004 (IEA, 2021[87]).

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