CHEMISTRY for CLIMATE

Acting on the need for speed

Roadmap for the Dutch Chemical Industry towards 2050

Chemistry for Climate: Acting on the need for speed

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A cooperation of:

This roadmap has been made by a team of Ecofys, a Navigant company, and Berenschot consultants in close cooperation with VNCI.

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Voorwoord

Samenvattende conclusies van de chemische industrie

Een ploegenachtervolging bij het langebaanschaatsen, zo zou je de transitie naar een duurzame samenleving kunnen zien. Hoe kan de Nederlandse schaatsploeg, waar de chemische industrie deel van uitmaakt, het meest succesvol zijn in een wereld vol concurrenten? Om die vraag te beantwoorden, heeft de Vereniging van de Nederlandse Chemische Industrie (VNCI) een analyse gemaakt van mogelijke routes en de bijbehorende voorwaarden.

De finish ligt in 2050 en bestaat uit een vitale Nederlandse economie waarin de uitstoot van broeikasgassen met 80-95 procent is teruggebracht, in lijn met de afspraken van het Parijse Klimaatakkoord. Een enorme uitdaging. De resultaten van dit onderzoek laten zien dat er technologieën zijn waarmee de Nederlandse chemische industrie deze ambitie kan verwezenlijken. Samenwerking met de overheid is cruciaal voor de doorontwikkeling en implementatie hiervan in een internationaal competitief speelveld.

Chemiebedrijven, goed voor 43.000 banen en een omzet van 45 miljard euro,[1] maken producten mogelijk die onmisbaar zijn voor ons welzijn, onze welvaart en een duurzame samenleving. Door zich naast het energiegebruik (de 'schoorsteenemissies') ook te richten op verduurzaming van de grondstoffen, kan de chemiesector deze producten blijven maken. Hiermee versterkt de chemie haar bijdrage aan de mondiale emissiereductie.

Samenwerking

Samenwerking met en steun van de overheid en synergie met andere sectoren zijn onontbeerlijk.

De eindstreep kan alleen gehaald worden als de sector gedurende de hele transitie vitaal blijft en haar concurrentiekracht op de wereldmarkt weet te behouden. Een zo spoedig mogelijke introductie van een wereldwijde CO_2-prijs is een voorwaarde om straks investeringen te kunnen doen in nieuwe processen die momenteel nog niet rendabel zijn.

De opgave is gigantisch. Dit onderzoek laat zien dat de vereiste versnelling alleen mogelijk is bij een drastische transformatie van de industrie en door middel van interactie met andere maatschappelijke spelers. De teamspirit tussen alle relevante partijen in de ploeg, inclusief de overheid, zal bepalend zijn voor de mate waarin de chemische industrie in 2030 en uiteindelijk in 2050 de gemeenschappelijke ambities weet te realiseren.

Investeringen

Om rendabele mogelijkheden voor CO_2-emissiereductie nu te kunnen implementeren, zijn meerjarige investeringsagenda's voor alle chemieclusters vereist op basis waarvan de industrie kan investeren passend in een langere termijnvisie. Hierbij is nauwe samenwerking nodig met andere sectoren, vooral de energiesector. En met de overheid. Daarvan verwachten we het realiseren van de (regionale) infrastructuur voor warmte en CO_2 en toegang tot voldoende hernieuwbare energie.

Technologieën die een hoge CO_2-emissiereductie mogelijk maken en nu nog niet rendabel en betrouwbaar zijn, vragen om doorontwikkeling, zodat ze op weg naar 2050 zo snel mogelijk commercieel exploitabel kunnen worden ingezet en zo kunnen bijdragen aan de noodzakelijke CO_2-reductie. De Nederlandse chemie bedrijft topsport, en topsport kan niet zonder investeringen. In de veelal lange ontwikkelingsfase, wanneer technologie nog niet rendabel is, kan (tijdelijke) overheidssteun de ontwikkelingssnelheid aanzienlijk verhogen en risico's en resulterende kosten verminderen. Een belangrijke rol van de overheid is het faciliteren van cross-sectorale programma's op cruciale thema's zoals waterstof, elektrificatie, CCS, recycling en bioraffinage, inclusief opschaling in demonstratiefabrieken. Op termijn en bij de juiste marktcondities kunnen deze technologieën een forse bijdrage aan emissiereductie leveren.

Daarnaast zullen individuele chemiebedrijven hun productportfolio blijven vernieuwen. Zo dragen ze blijvend bij aan de circulaire economie en aan de verduurzaming van andere sectoren (denk aan isolatie van huizen en lichtere auto's). Deze innovaties zullen de totale maatschappelijke kosten voor CO_2-emissiereductie verminderen. Zonder chemie geen energietransitie.

Snelheid

Snelheid is vereist.

Om in 2050 succesvol de finish te halen, als sector én als Nederland, zijn investeringen nu nodig. We kunnen ons daarbij niet alleen richten op de investeringen die op korte termijn resultaat opleveren, maar moeten ook nu al volop inzetten op de doorontwikkeling van de technologieën die nodig zijn voor 2050 maar nu nog niet rendabel zijn. Gebeurt dit niet, dan is het een verloren race.

Wat ons betreft staat Nederland straks niet alleen bekend als het land dat goed is in water en agro, maar ook in duurzame chemie. Met alle maatschappelijke voordelen van welvaart en werkgelegenheid van dien. Wij rekenen op een gelijkwaardige inzet van onze medespelers, zodat we deze internationale klimaatuitdaging slim en concurrerend kunnen aangaan.

De tijd dringt. In termen van investeringen is 2050 heel dichtbij. Vandaar dit rapport, op dit moment.

Mark Williams

Chairman of the Association of the Dutch Chemical Industry (VNCI)

1) Bron: CBS

Management samenvatting

Doel: 80-95 procent broeigasgasreductie
Het klimaatakkoord van Parijs, gesloten in december 2015, roept op tot acties om de broeikasgasemissies de komende tientallen jaren drastisch terug te dringen.

Acties die door de chemische industrie, samen met de partners in de waardeketen, genomen worden zullen bijdragen aan een reductie van de emissies in de chemische industrie en in andere sectoren van de economie.

De Nederlandse chemische industrie heeft Ecofys / Berenschot gevraagd om potentiële paden naar een reductie van de broeikasgasemissies met 80-95% in 2050 te analyseren.

Reductie is technisch haalbaar
Deze studie concludeert dat het, met innovatie, technisch mogelijk is voor de chemische industrie om de nodige emissiereducties te bereiken, bij een voortgaande groei van haar toegevoegde waarde met 1 procent per jaar. De studie is gebaseerd op een uitgebreide analyse van opties, inclusief alternatieve voedingen (zoals biomassa), elektrificatie met hernieuwbare elektriciteit en het sluiten van de koolstof-kringloop (bijvoorbeeld het recyclen van plastics en het afvangen en hergebruiken van CO_2 [CCU]) en het afvangen en opslaan van CO_2 [CCS]).

Significante investeringen zijn nodig
Deze studie identificeert een pad dat een totale emissiereductie van ongeveer 90% oplevert in 2050. Het pad neemt beperkingen in energie- en voedingsbronnen in aanmerking en probeert deze op hun maximale waarde in te zetten.

Terwijl het Nederlandse overheidsbeleid focust op proces- en energie-emissies, gebruikt dit pad een meer holistische aanpak, inclusief eind-van-de-levensduur-emissies van koolstof die in de producten zit, waarvoor een versnelde reductie ook nodig is:

- De investeringen die voor dit pad nodig zijn liggen rond de 63 miljard euro, waarvan 26 miljard euro voor investeringen in de chemische industrie en ongeveer 37 miljard euro in het energiesysteem.
- Daar bovenop zouden de jaarlijkse brandstof- en voedingkosten met ongeveer 3 miljard euro toenemen (ongeveer 50%), bij de huidige prijzen.
- De totale (wereldwijde) emissiereductie bedraagt ongeveer 55 Mton CO_2eq (sinds 1990).
- De gemiddelde kosten om in dit pad de emissies te verminderen bedragen ongeveer 140 €/tCO_2eq (exclusief het energiesysteem). Terwijl de kosten van verscheidene reductiemaatregelen significant lager zijn dan in veel andere Nederlandse sectoren, zijn veel van deze maatregelen op bedrijfsniveau nog niet winstgevend.

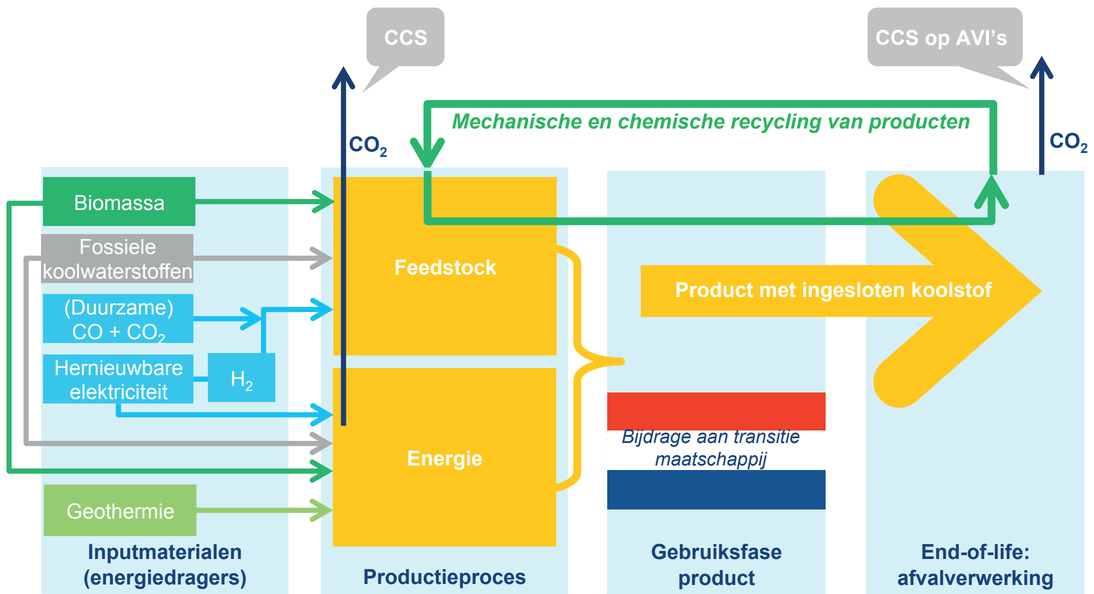

Figure 1 De chemische industrie heeft veel verschillende opties om de emissies van broeikasgassen te verminderen.

Een actieve rol van de overheid is nodig om reductiemaatregelen die nu nog niet economisch haalbaar zijn te stimuleren.
De Nederlandse chemische industrie opereert in een wereldwijd concurrerende omgeving. Wereldwijde CO_2-prijzen maken nog niet de volledige transitie mogelijk.

Sommige reductie-opties zijn nu al winstgevend; deze kunnen worden versneld door regionale ontwikkelings- en investeringsprogramma's. Veel van de reductiemaatregelen in de chemische industrie zijn echter onder de huidige omstandigheden onrendabel, met de stijging in de brandstof- en voedingkosten in dezelfde orde van grootte als de huidige winst van de industrie. Een actieve rol van de Nederlandse overheid is daarom essentieel voor de implementatie:

- Om toe te werken naar een Europees en wereldwijd gelijk speelveld dat de transitie op de lange termijn mogelijk maakt, en
- Zolang dat er niet is, om de nodige financiële ondersteuning te bieden voor de Nederlandse chemische industrie en zodat zij kan investeren in het versnellen van de ontwikkeling van nu nog onrendabele (innovatieve) maatregelen.

De energietransitie en de industrietransitie gaan hand in hand – verbonden door infrastructuur
Grootschalige toegang tot betaalbare en betrouwbare hernieuwbare energiedragers zal cruciaal zijn voor een blijvende concurrentiepositie. In het gepresenteerde pad heeft de chemische industrie 280 PJ duurzame biomassa nodig en 170 PJ hernieuwbare elektriciteit (ter vergelijking: de huidige opwekking van hernieuwbare elektriciteit in Nederland bedraagt 54 PJ), wat 11.4 GW wind-op-zee-capaciteit vraagt in 2050. Aangezien koolwaterstoffen de voornaamste bouwstenen voor veel chemische producten zullen blijven, moeten koolstofkringen gesloten worden (onder andere CCU), en worden hernieuwbare vormen van koolstof geïntroduceerd. CCS wordt toegepast voor fossiele koolstofstromen.

Infrastructuur zal een belangrijke factor zijn, inclusief een elektriciteitsnet voor het transport van grote hoeveelheden hernieuwbare energie, evenals leidingen voor waterstof, CO_2 en warmte, plus adequate afvalverwerkings- en recycling-infrastructuur. Dit laat zien dat de transitie van de chemische industrie hand in hand gaat met de energietransitie; het benutten van de synergieën vraagt om nauwe samenwerking met de energiesector.

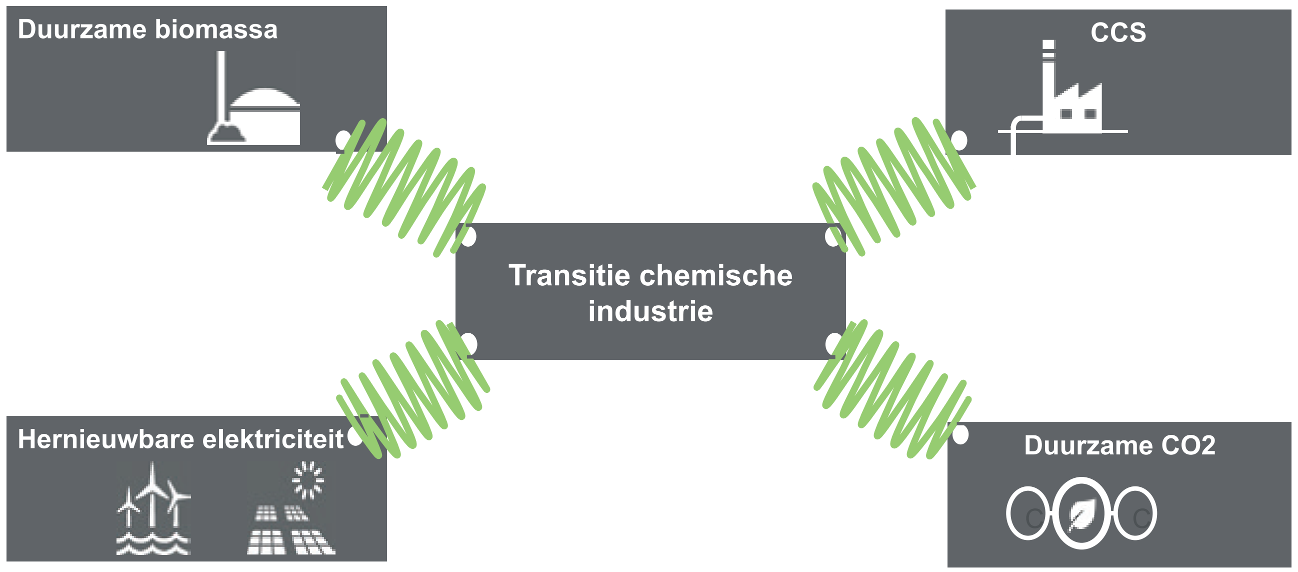

Figure 2 De transitie van de chemische industrie vraagt een zorgvuldig evenwicht in het gebruik van de verschillende mogelijkheden voor emissiereductie.

De overheid is een essentiële partner voor een succesvolle transitie
Anticiperend op gunstigere marktomstandigheden voor duurzame processen, raadt Ecofys / Berenschot aan om een gezamenlijke taskforce (overheid – industrie – energiesector) op te richten om deze ontwikkelingen snel te initiëren. Deze lange-termijnsamenwerking zal werken aan innovatie, regionale investeringsplannen en de noodzakelijke nationale infrastructuur met:

- Een gezamenlijk vergaand industrie/overheid-innovatieprogramma dat zich richt op het verder ontwikkelen van de noodzakelijke technologieën, tot het punt dat ze betrouwbaar grootschalig kunnen worden ingezet. Zo'n programma zou de noodzakelijke investeringen en de kosten van brandstof en voedingen verminderen, en de Nederlandse chemische industrie dus in staat stellen om implementatie te versnellen zodra de marktomstandigheden gunstiger worden.
- Een overheid die ervoor zorgt dat het energiesysteem en de daarmee samenhangende infrastructuur op tijd klaar zijn, in lijn met de industrietransitie.

Het is nu tijd voor actie
De transitie vraagt een fundamentele herziening van de productieprocessen van de industrie. Vanwege het kapitaalintensieve karakter zal er maar één kans zijn om dit goed te doen in de 32 jaar die resteren tot 2050. Vanaf nu moeten alle investeringen in productie en innovatie rekening houden met het klimaatdoel van 2050.

Executive summary

Objective: 80-95 percent greenhouse gas reduction
The Paris Agreement, concluded in December 2015, calls for actions to drastically reduce greenhouse gas emissions over the next few decades.

Actions taken by the Dutch chemical industry, together with its value chain partners, will contribute to emission reductions in the chemical industry as well as all other sectors of the economy.

The Dutch chemical industry has asked Ecofys / Berenschot to analyse potential pathways towards 80-95 percent reduction of greenhouse gas emissions by 2050.

Reduction is technically feasible
This study concludes that, with innovation, it is technically possible for the Dutch chemical industry to achieve the necessary emission reductions, while continuing to grow its added value by 1 percent per year. The study is based on an extensive analysis of options, including alternative feedstocks (e.g. biomass), electrification using renewable power, and closing the carbon cycle (e.g. recycling of plastics and Carbon Capture & Utilization (CCU)), and Carbon Capture & Storage (CCS).

Significant investments are needed
This study identifies a pathway that yields an overall emission reduction of approximately 90% by 2050. The pathway takes constraints in energy and feedstock resources into account and aims to use them at maximum value.

While the Dutch policies focus on process- and energy-emissions, this pathway takes a more holistic approach including end-of-life emissions from carbon embedded in products, for which an accelerated reduction is also needed:

- The investment required for this pathway is expected to be around EUR 63 billion, which is comprised of around EUR 26 billion to be invested in the chemical industry, and around EUR 37 billion in the energy system.
- In addition, annual fuel and feedstock cost for the industry would increase by approximately EUR 3 billion (around 50%), at present prices.
- Overall (global) emission reductions amount to around 55 Mtonne CO_2eq (since 1990).
- Average abatement costs for this pathway are approximately 140 €/tCO_2eq (excluding the energy system). While the abatement costs of several measures are significantly lower than many in other Dutch sectors, many of the associated abatement measures are not profitable at a company level.

An active role of the government is needed to stimulate abatement options that are not yet economically feasible.
The Dutch chemical industry operates in a global competitive environment. Carbon dioxide prices around the world do not enable the entire transition yet.
Some of the abatement options are currently profitable; these can be accelerated through regional development and investment plans. Many of the abatement options in the chemical industry are however under current

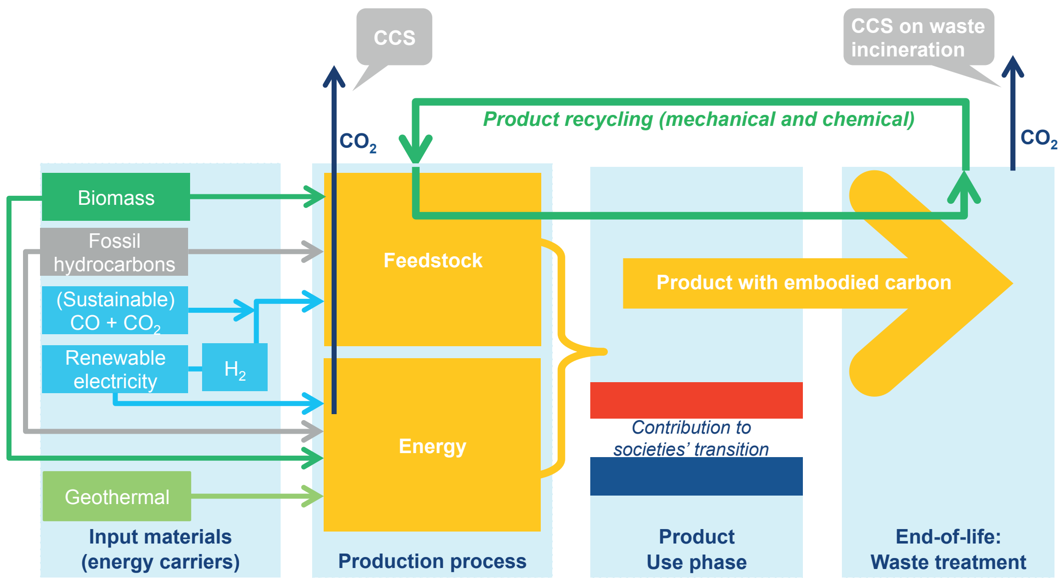

Figure 3 The chemical industry has many different abatement options for greenhouse gas emission reduction.

circumstances uneconomic, with the increase in fuel and feedstock cost being of the same order of magnitude as the industry's overall current profit. An active role of the Dutch government is therefore essential for the uptake of these:

- To work towards an EU and a global level playing field which enables the transition on the long term, and
- In its absence, to provide the necessary financial support for the Dutch chemical industry to enable it to invest in speeding up development of yet unprofitable (innovative) measures.

Energy transition and industry transition go hand in hand – connected by infrastructure

Large-scale access to affordable and reliable renewable energy carriers will be key for a lasting competitive position. In the pathway presented, the chemical industry will need 280 PJ of sustainable biomass and 170 PJ of renewable electricity (for comparison: current generation of renewable electricity in the Netherlands: 54 PJ), requiring 11.4 GW of off-shore wind capacity, by 2050. As hydrocarbons will remain the main building block for many chemical products, carbon loops need to be closed (amongst others CCU), and renewable sources of carbon will be introduced. CCS would be applied for fossil carbon streams.

Infrastructure will be a key factor, including an electricity grid for transportation of large amounts of renewable energy, as well as pipelines for hydrogen, CO_2 and heat, plus adequate waste handling and recycling infrastructure. This illustrates that the chemical industry transition will go hand in hand with the energy transition; leveraging the synergies requires close co-operation with the energy sector.

Government is an essential partner for a successful transition

Anticipating more favourable market conditions for sustainable processes, Ecofys / Berenschot recommends establishing a joint task force (government – industry – energy sector) to kickstart these developments. This long-term co-operation will work on innovation, regional investment plans, and the required national infrastructure with:

- A joint industry/government far-reaching innovation program aiming to develop the necessary technologies to the point that they can be deployed reliably at full scale. Such a program would reduce the required investments as well as the cost of fuel and feedstock, thus enabling the Dutch chemical industry to accelerate implementation once the more favourable market conditions materialize.
- Government ensuring that the energy system and the associated infrastructure are developed timely alongside the industry transition.

The time to act is now

The transition will require a fundamental overhaul in the industry's production processes. Its capital-intensive nature means that there will be only one chance to get this right in the 32 years remaining until 2050. From now on, all major investments in production and innovation will need to consider the 2050 climate target.

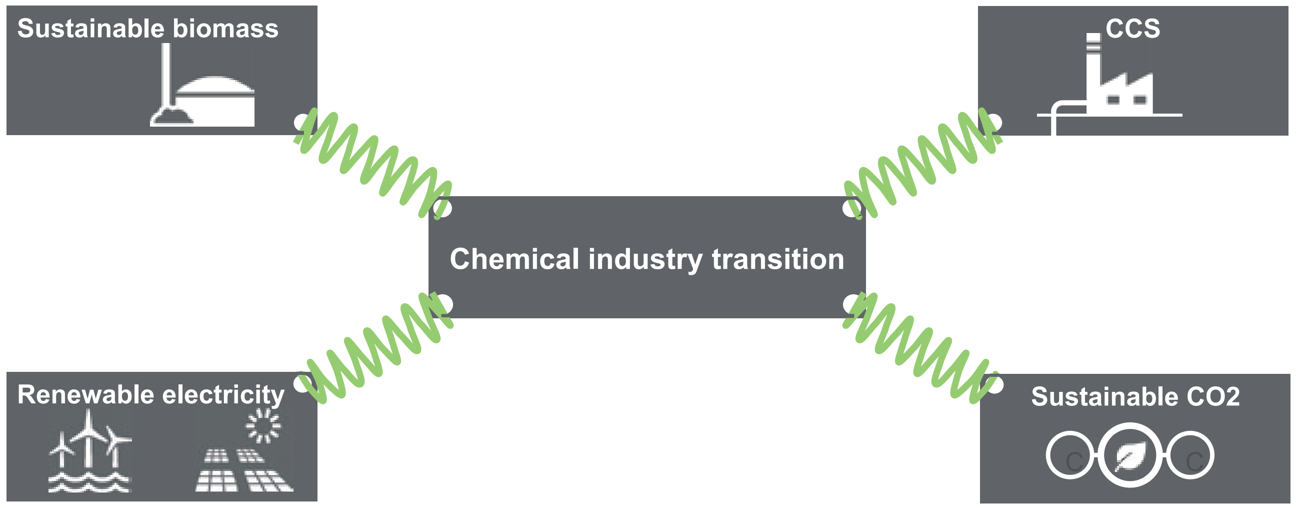

Figure 4 The chemical industry's transition requires a careful balancing of use of different constrained abatement options.

List of abbreviations

Abbreviation	Description
ARRRA	Antwerp-Rotterdam-Rhine-Ruhr Area industrial cluster
ATR	Autothermal Reforming
BTX	Butene, Toluene, Xylene
C2/C3	Hydrocarbons with either 2 or 2 carbon atoms, like ethylene and propylene
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilization
CEFIC	European Chemical Industry Council
ESCO	Energy Service Company
GHG	Greenhouse gases
MVR	Mechanical Vapour Recompression
SMR	Steam Methane Reforming
TRL	Technology Readiness Level
VNCI	Association of the Dutch Chemical Industry (VNCI)
WACC	Weighted Average Cost of Capital

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1 The Dutch chemical industry: taking a leading role in combating climate change

The Paris Agreement, concluded in December 2015, calls for action to drastically reduce greenhouse gas emissions over the next few decades. This Roadmap for the Dutch chemical industry analyses several pathways that can lead to an 80-95% reduction of greenhouse gases (GHG) emissions from energy use and processes, as well as emissions that can occur at the end-of-life of chemical products, by 2050 vs 1990. This requires a significant transition, not just in the way the chemical industry operates, but also in the way it interacts with other stakeholders in society.

1.1 Time for action – the chemical industry taking up the challenge

In 2012, VNCI developed the 'Roadmap 2030' in close cooperation with her members, describing ways to realise the ambition of 40% reduction of greenhouse gas emissions in 2030, as compared to 2005. Now, five years later, climate change and the energy transition are even more prominent on the agendas of policy makers and companies. The Paris Agreement of 2015, in which the world agreed to limit the average temperature rise to well below 2°C, accelerated the climate change debate to a large extent. To reach this temperature target, global emissions of GHGs should decrease as rapid as possible, such that a "net zero" emission situation is reached in the second half of the century. The goal of the European Union is an 80% to 95% reduction by 2050, as compared to 1990 [1].

In the Energy Agenda of 2016, the Dutch government sets out the necessary steps for the transition towards a reliable, affordable and secure energy supply with low CO_2 emissions up to 2050 [2]. More recently, the newly formed Dutch government formulated its ambition, in the Government Statement 2017 – 2021, to reduce direct greenhouse gas emissions by 49% in 2030 compared to 1990 [3].[2)] At the same time, (the perception of) technological solutions has evolved, for instance with regards to the sustainability and availability of biomass, price developments of renewable energy production, the recovery and utilisation of CO_2, circularity, and the exchange of material and energy flows with other sectors. The directions for solutions, as stipulated in the Roadmap 2030, are all still relevant, but there are shifts in the expectations of the potentials of these solutions and the required investments.

The Dutch chemical industry already plays an active role in accelerating the reduction of GHG emissions. The sector intends to further strengthen this role, together with governments, the energy sector, societal parties and other industries. The sector is well-positioned, with strong

2) This ambition applies to direct GHG emissions from combustion of fossil fuels and direct GHG emissions from other activities in the Netherlands. It does not apply to the emissions that arise at the end-of-life of products due to the embedded.

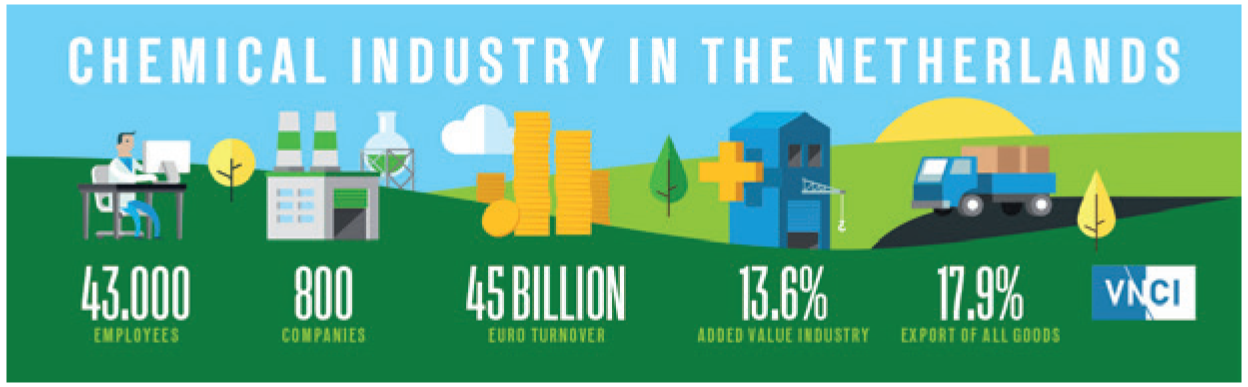

Figure 1-1 Key facts about the Dutch chemical industry

economic links, promising prospects and a positive trade balance. Its products are used in many sectors and contribute to the value creation in each of these sectors. Moreover, the chemical industry can provide solutions for other sectors to reduce CO_2 emissions and sees many opportunities to do so in the future. The position of the chemical industry in the climate debate differs from most other industrial sectors in that it uses fossil fuels not only as an energy carrier, but it also uses carbon as a building block for its products. Since this carbon can lead to CO_2 emissions when products reach their end-of-life, the industry realises that end-of-life emissions should be considered as coherent to the Paris Agreement. Solutions lie partly within the chemical industry and partly with downstream parties in the value chain.

The chemical industry is closely linked to the energy sector with respect to energy and feedstock use. It needs a holistic strategy to drastically reduce GHG emissions in both energy and material flows. Developments regarding the energy transition and sustainable industrial transitions, such as the use of bio-based materials, product innovations and circular economy are considered equally relevant. Since these developments are important for the sector to achieve its ambition, close cooperation with other sectors and governments is essential.

This Roadmap for the Dutch chemical industry aims to:

- investigate pros and cons of possible pathways for the Dutch chemical industry to reduce the emissions of GHGs from both energy and material flows by 80-95% in 2050 compared to 1990;
- identify the opportunities that such transitions create for both the Dutch economy and the industry itself;
- explore the conditions required to successfully implement the transition; and
- recommend actions for the chemical industry and other stakeholders to accelerate this transition.

1.2 The Dutch chemical industry is well-positioned

The Dutch chemical industry is one of the strongest chemical sectors in the world. With only 0.2% of the world population, the Netherlands produces 2% of the world sales of chemical products [4]. The Dutch chemical industry operates at the heart of society, providing products and services to virtually all other economic sectors. The industry comprises 800 companies with a combined turnover of EUR 45 billion [5], employing some 43,000 people in the Netherlands alone. The sector makes a significant contribution to the Dutch economy, with a share of 1.6% of GDP [6], an export value of EUR 78 billion and an average result before taxes of EUR 3.7 billion per year (between 2011-2015). 80% of the chemicals produced in the Netherlands are exported, of which again 80% are exported to European countries [5].

The location of the Netherlands, with strong access maritime export links and continental Europe, has aided the development of a highly integrated and clustered chemical industry. 20 of the largest 50 multinational chemical companies have operations in the Netherlands. The Dutch have a strong knowledge position in the chemical arena due to their chemical industry, and the presence of world-leading technical universities and technology institutes.

Compared to other regions in the world, the Dutch chemical industry is highly clustered and integrated. This applies at domestic level, and also to the international connections to Belgium and Germany. This results in competitive benefits, most notably the cost-efficient exchange of material and energy, for the Antwerp-Rotterdam-Rhine-Ruhr Area (ARRRA) cluster. In September 2017, VNCI launched the joined trilateral strategy for the chemical industry of the Netherlands together with Flanders and the North Rhine-Westphalia region, which aims to further strengthen the ARRRA cluster.

The Dutch chemical industry is very diverse, with over 800 companies, producing a wide range of products. Two main routes dominate the emissions of greenhouse gases. The intermediates produced in these two routes can be converted to a large variety of other chemicals. This roadmap therefore focuses on these routes; however, in many cases alternative, product-specific, direct alternative routes to this variety of other chemicals will exist.

The Dutch chemical sector has a relatively large share in petrochemicals. Six Dutch naphtha crackers produce most of the petrochemical building blocks (ethylene, propylene and BTX) for many products, ranging from construction materials to paints, and from car parts to mobile phone components. The relative weight of naphtha-based routes is an asset to the sector in case a share of feedstock is replaced by bio-based materials because of the relative flexibility of crackers. An alternative route is based on methanol (methanol-to-olefins). Chemical recycling of polymers is another alternative to produce petrochemicals.

The second route considered here is the production of fertilizers. To produce ammonia, the basis for most fertilizers, nitrogen in air is bound to hydrogen via a series of reactions, which involves the steam reforming of natural gas and the Haber-Bosch ammonia synthesis. Ammonia is used to produce urea, nitric acid and melamine. An alternative to this route is to make hydrogen via an electrolysis process and combine this with nitrogen from air. Other sources for CO_2 are needed to make urea, since this can no longer be obtained from the conventional ammonia process.

A third category of feedstock is salt (NaCl), which is converted via electrolysis process to chlorine, hydrogen and caustic soda. Chlorine is the basis for vinyl chloride, which is in turn the raw material for PVC. Chlorine is also a raw material for a range of other chemical products, like phosgene and synthetic fibres. The energy consumption of chlorine production is close to the theoretical minimum [7], but the energy use over the full PVC production chain is > 20 times higher than the theoretical minimum energy [8]. The energy consumption of chlorine production could be decreased significantly with the relatively new Oxygen-depolarised cathodes (ODC) technology; although the actual saving is reduced, as ODC requires oxygen, and no longer produces by-product hydrogen [7]. Furthermore, as chlorine production uses electricity as energy source, using renewable electricity eliminates the CO_2 emissions associated with chlorine production. The production of chlorine is therefore not modelled for this roadmap.

- Rotterdam-Rijnmond, the largest chemical cluster in the Netherlands. 45 chemical companies and 5 oil refineries are operating in the areas of Pernis, Botlek, Europoort, the Maasvlakte, Moerdijk and Dordrecht. The excellent infrastructure with Rotterdam Harbour, a rail connection to Germany, pipelines and roads facilitate transport of raw materials, energy and products. The focus is traditionally on petrochemical production, but some companies have increasingly been using biobased processes.
- Chemelot, in the South of Limburg, houses some multinational companies like SABIC and OCI Nitrogen, but also many innovative start-ups and R&D facilities. The site is characterised by a strong integration, e.g. of utilities and services. Chemelot is also building expertise about scaling up processes from demonstration to commercial. The focus is on polymers, (bio) organic synthesis and chemical engineering.
- Zeeland, with the mainport Terneuzen, houses chemical companies like Dow, Yara, Sabic and Arkema. Zeeland Refinery is also based here. The strengths of the area are the good shipping facilities (connected to deep water), industrial symbiosis, and good transport connections.
- Delfzijl, with the availability of salt and natural gas, is focused on basic chemicals such as chlorine and methanol, and their downstream products. A sea harbour, railway and several ovide excellent logistics. Delfzijl Eemsdelta is already actively making the area more sustainable by using biomass and renewable electricity and has the ambition to accelerate these activities in the future.
- Emmen is the smallest chemical cluster, with a strong aim to become frontrunner of bio-polymers and bio-composites.
- Amsterdam, an upcoming industrial area, with a strong focus on sustainability. The cluster has close connections to two universities and the Science Park, and a well-developed infrastructure.

Six clusters of chemical industries can be observed in the Netherlands, as shown in Figure 1-2.

Figure 1-2 Clusters of chemical industries in the Netherlands [4]

The chemical industry in the Netherlands is a strong economic sector. It requires significant amounts of energy to drive its processes and it uses a large share of its fossil fuel input as raw material for its products. The key strengths can be summarized as follows:

- A large trade surplus and large hinterland
- Well connected through seaports and pipelines; the ARRRA cluster
- A skilled workforce & strong universities
- Well-maintained assets
- Large number of leading chemical companies present
- Strong clusters, with high degree of integration and innovative power

1.3 Success factors

The transition towards a low GHG emitting chemical industry comes with both opportunities and substantial challenges. Three key success factors have been identified for a successful transition.

The need for speed
This roadmap examines diverse transition pathways for the chemical industry to bring down its GHG emissions by 80-95% in 2050 as compared to 1990. The year 2050 seems far away. Looking at the technological developments and their impact on society of the past decades, one can imagine that the world will look quite different in the 32 years to come. However, for the chemical industry, 2050 is as close by as one investment cycle. Most assets in the chemical industry have long lifetimes, ranging up to 30-50 years. To have low emission processes in place by 2050, the chemical industry cannot afford to wait to act.

Leadership
During the Roadmap process, the importance of leadership as one the most important success factors for a transition to a low GHG emission society was emphasized by several stakeholders from the chemical sector. While, with a good policy framework, all stakeholders felt willing and capable to lead the transition within their companies, they argued that not all conditions for a quick and smooth transition have yet been met. Leadership from top management is especially important, as the transition is currently at a point where the business cases for many (future) low-emission technologies are not yet sufficiently profitable to meet current investment thresholds (in some cases business cases are improving rapidly, such as for off-shore wind). At this point in time, leadership and vision are required to navigate well between the current and future business environment, and proactively accelerate the transition. This, however, comes with significant barriers:

- For most companies, decisions are taken outside the Netherlands and are driven by global economics;
- The business cases of several key technologies need improvements, upscaling and de-risking;
- Making sufficient staff available with the right skill-sets without short-term benefits requires long-term vision;
- Uncertainties about the impact of climate change policies, e.g. about level playing field and if and how carbon pricing will be implemented.

This Roadmap emphasizes the importance of leadership as a success factor for the transition to a low greenhouse gas emission chemical industry, while at the same time addressing the related barriers. Specific recommendations on this matter are described in Chapter 6.

Collaboration
Although the chemical industry is committed to take up the challenge to drastically reduce GHG emissions, such a transition can only be successful if external conditions are right. There are two main success factors that relate to the energy transition and to the transition towards a sustainable chemical industry, which are mutually reinforcing:

1. **A successful accelerated *energy transition* to realise carbon free production of heat and electricity by 2050.** A successful implementation of the Energy Agenda [2] and follow-up actions is essential. Continuous effort of all stakeholders involved is required, as is a critical and periodic reflection on the results and adaptation of the plans if the speed turns out to be too low. Societal acceptance will also have to increase for certain solutions, such as large-scale wind parks and underground carbon storage. The chemical industry can play a strong role in the energy transition, for instance, as a large user of emission-free energy, it can act as a balancing hub when large volumes of renewable electricity are fed into the grid, or as a provider of solutions for sustainable energy technologies.

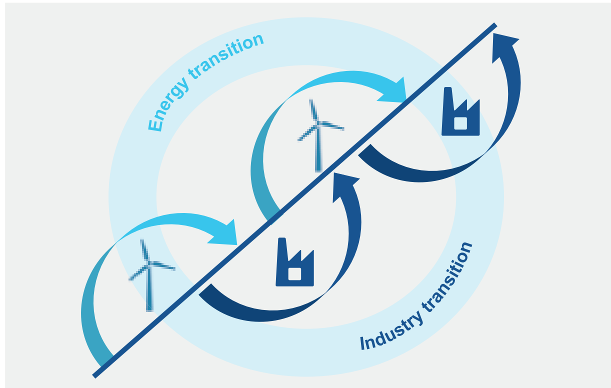

Figure 1 3 Energy transition and sustainable industry transition are mutually reinforcing

2. **A successful *sustainable industry transition* by creating an encouraging and competitive environment for innovation and technological progress.** Examples include closing material loops and industrial symbioses, and alignment of the use of biobased materials. Both produce products that have similar chemical structures and, and have new functionalities and effective programmes to support product and process innovations and demonstration. The chemical industry can also play a key role in the sustainable transition of other industries. The sustainable industry transition is reinforced by the energy transition and vice versa. On the one hand, the energy transition enables the industry to develop and implement sustainable solutions. On the other hand, solutions developed by the industry can help accelerate the energy transition.

Since the opportunities for the chemical industry are closely linked to the developments in the energy transition and the industry transition, this roadmap takes both developments into consideration. Moreover, it examines how low-emission opportunities in the chemical industry affect the energy transition and how these opportunities support other industries to become more sustainable. In chapter 6, the importance of cooperation with government(s) is elaborated specifically.

1.4 About this Roadmap

This Roadmap thoroughly analyses the potential transition pathways towards a low-emission Dutch chemical industry:

- To do so, chapter 2 defines the challenges the industry is faced with in order to reduce its emissions. Current emissions, both in energetic and other GHG emissions and end-of-life emissions are presented, as well as the scope of these emissions.
- Chapter 3 identifies potential opportunities to reduce the chemical industry's emissions through six solution themes. In this chapter, the roadmap transition pathways are introduced.
- Chapter 4 presents the outcomes of the model results from these transition pathways, as well as related investments for the chemical industry and energy sector.
- Chapter 5 presents the chemical industry as a solution provider for emission reductions in other sectors. This is based on the premise that products that ensure lower emissions in several sectors are often enabled by the chemical industry.
- In chapter 6, the analyses from previous sections is translated into roadmap actions. This chapter outlines the enabling factors with which the implementation of necessary actions can be supported. Factors from both inside and outside the chemical are regarded and proposed.
- To conclude, chapter 7 presents the key findings and recommendations from this roadmap towards 2050 for the Dutch chemical industry and its stakeholders.

Detailed explanations and background information regarding the roadmap process and modelling can be found in the Annexes.

2 Defining the challenge to lower greenhouse gas emissions

The chemical industry targets to reduce its own emissions and the emissions released at the end-of-life of chemical products, while maintaining economic growth. The aims are a 49% reduction of energetic and process emissions in 2030 (in line with the Dutch governmental agreement of 2017) and an 80-95% reduction of both energetic and process and end-of-life emissions in 2050, both targets compared to 1990. The 1990 emissions are estimated to be 15% lower than 2005 emissions, mainly due to lower feedstock use in 1990. Despite 35% production growth in of over this period, energy and process emissions remain almost equal, indicating an improvement in energy efficiency.

2.1 GHG emissions of the Dutch chemical industry

An inventory of GHG emissions from the chemical industry from 2005 was constructed for the previous roadmap of VNCI [9], which used a 40% reduction target in 2030 versus 2005. Table 2-1 shows that in 2005, 61% of the primary energy input to the sector was used for non-energetic purposes: as raw material to build chemical products. The table also indicates that the sector emitted 6.7 Mtonne of other GHGs, mainly N_2O from the nitric acid production. Since 2005, the chemical industry has implemented several measures to reduce its emissions. Most notably is the reduction of N_2O emissions from nitric acid production by over 80%, leaving 1.1 Mtonne CO_2 eq.

Table 2-1 Overview of 2005 GHG emissions of the chemical industry

Emission source	PJ	Mtonne CO_2e
Fossil fuel – energetic use	294	16.7
Electricity – energetic use	37.1	6.4
Biomass – energetic use	2	0
Total Energetic use	333.1	23.1
Fossil fuel – non-energetic use	550[2)]	38.5
Electricity – non-energetic use	0	0
Biomass – non-energetic use	27.5	0
Total non-energetic use	577.5	38.4
Total primary energy use	910.6	61.5
Other GHG emissions – non-CO_2	-	6.7
Total emissions		68.3

Setting a 1990 baseline

This Roadmap's ambitions are aligned with the EU and Dutch targets, which are compared with 1990 emissions. Therefore, a new baseline for emissions in 1990 was constructed, based on CBS-data [10] and the 2005 inventory by ECN [9] (see Annex 3 for details). Figure 21 shows that total emissions in 1990 are estimated at 58 Mtonne, about 15% less than in 2005. The other GHG emissions, mainly N_2O, remain almost at the same level during this period. Since the productivity of the sector has grown by 35% from 1990 – 2005, it can be seen that the energy and other GHG emission intensity has decreased over this period. This is due to efficiency improvements and CHP. The emissions that can be related to non-energetic use of energy show the largest increase, from 28 Mtonne to 38 Mtonne, mainly caused by higher productivity due to the debottlenecking of naphtha crackers. In section 2.2 we explain that we refer to this type of emissions as "end-of-life emissions".

Projected sector baseline growth to 2050

The Roadmap investigates the opportunities for the chemical industry to drastically reduce emissions while maintaining economic growth. The premise of this

3) Note: Non-energetic use is related to the use of energy carriers in the Netherlands and does not include end-of-life emissions related to the import of chemical semi products, like ethylene and methanol.

work is a constant growth of 1% per year of value added for the chemical industry up to 2050. However, the emissions will not grow linearly with economic growth. A decoupling of emissions from economic growth can be expected, mainly due to a shift to less energy-intensive, higher value-added activities in the sector. The factor of decoupling is assessed based on projections of shifts between product groups in CEFIC's EU Chemical Industry Roadmap [7]. Although there are differences between the structure of the chemical industry in The Netherlands and the EU, the EU projections can serve as a valid proxy for The Netherlands. The result is a year-on-year growth rate of 0.43%/y up to 2050 for energetic emissions.

Emissions due to non-energetic use of fossil fuels are not included in the CEFIC study. Given the projected decline in the EU petrochemical sector in the selected CEFIC scenario, it is not to be expected that much new cracking capacity will be installed in Europe. Combined with other competitive and market considerations, we therefore assume that no new cracker capacity will be installed. Hence, feedstock-related emissions due to the use of petrochemicals produced in the Netherlands are projected to remain constant at 2015 levels in the baseline development.

With the 1990 GHG emissions inventory constructed as described above and the projected growth of emissions up to 2050, implication of the target of 80-95% emission reduction compared to 1990 can now be established. Figure 21 shows that this target translates to 60-70 Mtonne CO_2e reduction in absolute terms in 2050. The figure also shows that the 49% target for reduction of energy and other GHG emissions in 2030 compared to 1990 would lead to an absolute 15 Mtonne emissions reduction in 2030. The remaining 56 Mtonne is built up of end-of-life emissions (38 Mtonne) and remaining energetic and non-GHG emissions (18 Mtonne), the energetic emissions are assumed to grow by 0.43% per year.

Other impacts, such as process safety, and environmental / sustainability impacts (other than GHG) are not addressed in this roadmap.

2.2 Emissions across the value chain: what is included?

The chemical industry releases emissions that are generated at production sites due to the use of energy or as process emissions. According to GHG Protocol Corporate Accounting and Reporting Standard [11] [12], these types of emissions are referred to as direct emissions. Next to these direct emissions, the Protocol distinguishes indirect emissions caused by upstream and downstream activities. Scope 2 emissions are related to purchased electricity and heat, whereas scope 3 emissions are generated at a broad scope of other up and downstream activities, as illustrated in Figure 2-2.

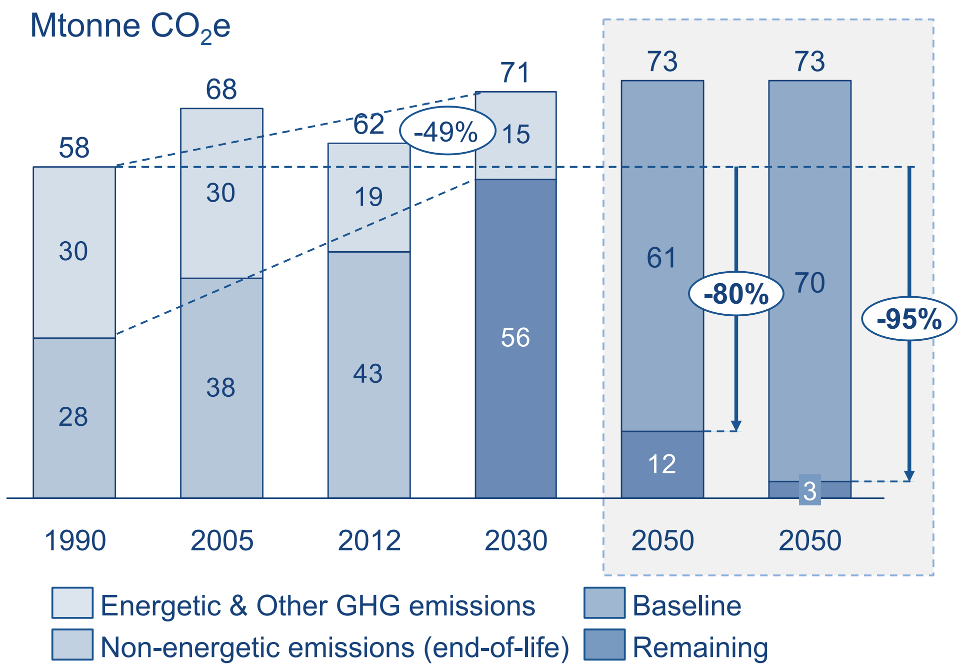

Figure 2-1 Projected development of emissions compared to 1990 and 2005. Non-energetic emissions are due to the non-energetic use of energy carriers. In section 2.2 we explain that we will refer to this type of emissions as "end-of-life emissions". Note that the target of 49% reduction in 2030 vs 1990 only relates to energetic and other GHG emissions, whereas the 2050 targets vs 1990 relate to both energetic, other GHG and non-energetic emissions.

Not shown in this figure are the so-called avoided emissions. Avoided emissions are emission reductions that occur outside of a product's life cycle or value chain, because of the use of that product. Examples of chemical products that avoid emissions include lubricants for wind turbines, advanced fertilizers that enhance crop yields, fuel-saving tires, light-weight materials for the automotive industry, and isolation materials. Chapter 5 presents more examples of how the chemical industry can provide solutions to other sectors to avoid GHG emissions. These contributions are not quantified in the same level of detail as the scope 1, 2 and feedstock related scope 3 emissions and are not included in overall emission reduction schemes for the chemical industry.

In addition, we quantify part of the scope 3 emissions, namely the "end-of-life treatment of sold products", by quantifying the use of fossil energy of non-energetic purposes (natural gas, oil products) that is used by the Dutch chemical industry. The carbon in this feedstock is, for a large part, embodied in the products that are sold by the Dutch chemical industry and the end-of-life emissions can, as a proxy, be calculated multiplying the energy content of this feedstock with the relevant emission factors. By choosing these boundaries, this roadmap focuses on the emissions that can be regarded as being under direct control by the Dutch chemical industry or directly related to the operations of the Dutch chemical industry as well as on emissions that occur at the end-of-life of products made from materials produced by the Dutch chemical industry.

Emissions that occur upstream, e.g. due to production, transport, distribution and storage of energy and materials are not taken into account. These emissions are typically a few percent of the scope 1 and scope 2 emissions for the production of a chemical product, see for instance [13].

The focus of this roadmap is to provide possible pathways for GHG emission reductions for the Dutch chemical industry. In the quantification, we will focus on the scope 1 and 2 emissions of the Dutch chemical industry and part of the scope 3 emissions, namely end-of-life treatment of sold products. This scope is identical to the scope used in the previous roadmap. For a more accurate estimate of end-of-life emissions of products sold by the chemical industry, a full material balance for the chemical industry would be needed. This is because part of the products in the Netherlands are produced from imported base chemicals and thus not captured by feedstock use in the Netherlands. Such a balance is not available for the Netherlands and would be required to get a full overview of the end of life emissions, as well as the upstream emissions of the imported base chemicals. Also, the accounting of other scope 3 categories for a sector is not straightforward, and many of the other scope 3 categories are relatively small (such as employee commuting etc.).

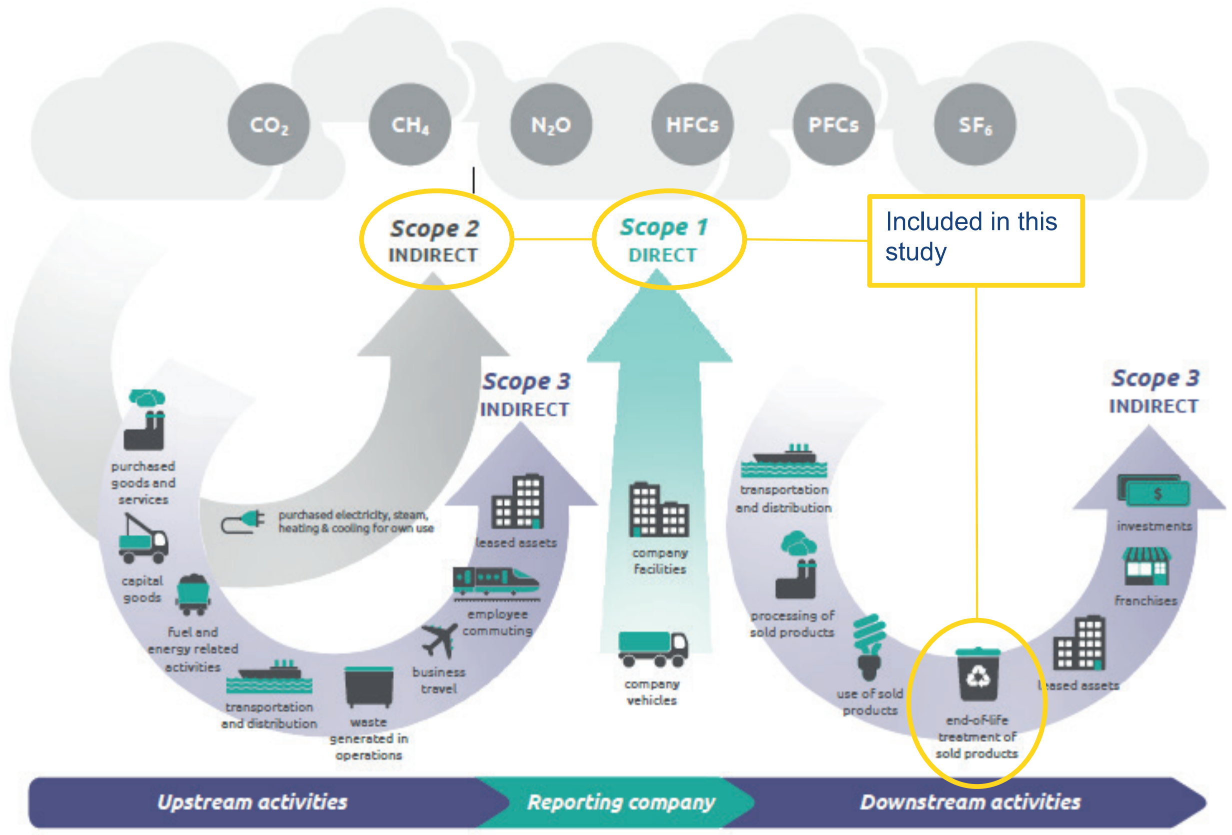

Figure 2-2 Overview of the GHG Protocol scopes and emissions across the value chain (3). In this study, scope 1 and scope 2 emissions are included as well as part of the scope 3 emissions, namely the "end-of-life emissions of sold products".

3 Identifying the opportunities

The opportunities to reduce GHG emissions are grouped into six solution themes: closure of the materials chain, alternative feedstock, energy efficiency, renewable energy, CCS, and sustainable products.

For each of the solutions themes, a maximum technical potential in terms of carbon reduction has been calculated for 2050 (and indicated for 2030), together with the corresponding energetic and non-energetic consequences. To explore the diverse range of GHG reduction opportunities for the chemical industry, this Roadmap initially defined three diverse thematic pathways. These pathways focus on circular & bio-based economy, electrification of production processes and using fossil fuels with carbon capture solutions. Each of the pathways explores the boundaries and challenges when implementing different solutions to the extreme. Based on the findings of these pathways, two plausible combination pathways are presented.

3.1 Introduction to approach

The reduction of GHG emissions in the chemical industry is possible through a diverse range of options. Some options focus on the reduction of energetic or other GHG emissions, while other options explore the abatement of end-of-life emissions. In the process of developing this Roadmap, three possible transition pathways for the chemical industry have been defined to explore the diversity of possible abatement measures. These transition pathways – Circular & Biobased, Electrification and Carbon Capture and Storage (CCS) – are based on a different deployment of measures and form a wide range of 'extreme' possibilities, as demonstrated in Sections 3.3 and 4.1 and in Annex 3. Consequently, the three thematic pathways do not provide a representative or preferred development agenda for the chemical industry, but have primarily been used to shape the boundaries of what is technically feasible for different solutions. Based on the insights from this exploration and subsequent input from the Steering Group, two additional integrated combined and plausible pathways have been composed. The outcome and implications of these two pathways are presented in detail in chapter 4.

The implication of each pathway has been defined for both technical and economic parameters. The technological potential of different options was assessed through six solution themes derived from the Roadmap 2030, as set out in chapter 3.3. For the economic parameters, this roadmap distinguishes between investment costs that have to be realised in the chemical sector and required investments in the energy system.

Investment costs for the abatement measures
Per abatement measure, investment costs have been estimated based on literature and expert input. All investment costs are amortized with a simple payback time of 8 years (for utilities 5 years) which, using a WACC of 17%, corresponds to a technical lifetime of 25 years (for utilities 8.7 years). This payback period is too high for many incremental investments in energy efficiency, but can be considered representative for strategic investments (for example new production routes).

Energy system investments
The economic implications of the different pathways are not limited to the chemical sector. As such, the transition towards alternative energy sources requires several system investments. The use of renewable electricity, for instance, requires investments in offshore wind or equivalent, which are costs borne by the energy sector. Although these costs are not accounted for by the chemical sector, it is important to show the financial implications for the energy system as a whole. Therefore, an estimation of energy system investments is carried out for each of the transition pathways in 2050. For this the Energy Transition Model is used, see Annex 2 for details. To these investment costs, we add the investments for CCS on waste incinerators and bio-refineries, where applicable.

Costs for energy and energy used as feedstock
Since future fuel costs come with high uncertainties and depend on system developments, it was decided, in consultation with the steering group, to use 2017 energy prices (see Annex 2). Using these prices, the energy and feedstock costs in 2015 are estimated at around EUR 6 billion. Due to changes in the energy and feedstock mix, these costs will differ per pathway. Any other annual operation and maintenance costs are not taken into account.

3.2 Thematic pathways

This Roadmap explored thematic transition pathways based on three diverse narratives:

- The pathway Circular & Biobased strongly aims at closing the materials chain through recycling (both

	Narrative	Main focus
Circular & biobased	• New business models occur, where products are (designed to be) used longer, perhaps in altered forms • The use of feedstock changes; besides bio-based materials, products come back to the sector as feedstock	• Biobased feedstock • Mechanical recycling • Chemical recycling
Electrification	• The Dutch chemical sector cooperates with energy sector to generate abundant supply of renewable electricity • Where feasible, the sector turns to electricity and/or hydrogen for both energy and feedstock	• Hydrogen from electrolysis • Combined with CCU for feedstock • High energy efficiency
Clean fossil	• A large integrated CO2 grid develops, connecting all chemical clusters and sites to underground offshore storage. • On end-of-life part, CCS exists on waste incineration plants;	• Carbon capture (pre-combustion, post-combustion, or oxyfuel) • Offshore (North Sea) storage

Figure 3-1 Narrative and focus of the three thematic pathways; all thematic pathways include significant mechanical recycling, and energy efficiency improvements.

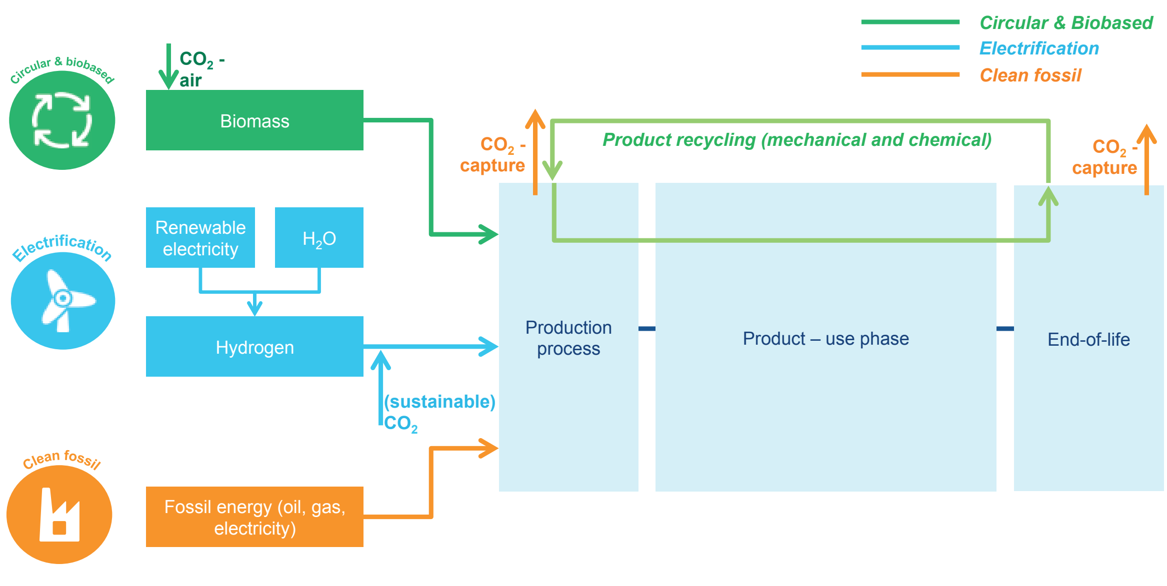

Figure 3-2 Carbon cycles in the three thematic pathways

mechanical and chemical) and the use of biobased feedstock. In this pathway, the use of biobased materials as raw materials is central, and products come back to the sector via a strong focus on closure of the materials chain. New business models occur, with a focus on high value production creation and circularity.

- In the Electrification pathway, the Dutch chemical industry stimulates an enormous renewable generation capacity, requiring an abundant supply of climate neutral electricity. Where feasible, the sector turns to electricity for both energetic and non-energetic purposes. This pathway includes a focus on energy efficiency and intensification and has a strong emphasis on the use of hydrogen in a wide variety of applications. It will create the biggest opportunities / requirement for demand side management.

- The CCS pathway has a strong focus on the application of CCS in the chemical sector and at the end-of-pipe at waste incineration plants. In this pathway, a large integrated CO_2 grid development is assumed, connecting all chemical clusters and sites to underground offshore storage.

The thematic pathways reduce emissions in different ways and in different parts of the value chain. The focus areas of the transition pathways lead to different carbon (reduction) cycles, concerning energetic and other GHG emissions as well as end-of-life emissions. These cycles are schematically shown in Figure 3-2.

Hybrid versions of the above cycles are conceivable and might lead to interesting new concepts. For example, hydrogen produced from electrification could be used to treat pyrolysis oil to allow it to be fed into existing naphtha crackers, creating a drop-in route that retains large parts of current invested capital in chemical industry.

The shaping of each of the transition pathways has been done in a rather extreme way, to give insight into the opportunities and challenges that arise when implementing each of these pathways to its full potential. In doing so, the technical, economic and sustainable boundaries of the solution themes and pathways have been elaborated. Each of the pathways is based on a on a different mix of the potentials of each of the solution themes.

3.3 Plausible combination pathways

The insights derived from the three thematic transition pathways have been used to create two plausible combination pathways that combine some of the most attractive parts of each of the thematic pathways, and avoid the least attractive parts. These pathways are not meant to represent a full optimization of all possibilities, but are based on an exemplary mix of different potentials that arise from the three thematic pathways. By doing so, we bundle some of the best parts and avoid the extremes, e.g. with regards to investments costs and demands on resources and infrastructure, while still leaving room for a rather wide range of optional outcomes. Both pathways have been constructed so that in 2030 at least a 49% reduction of energy and other GHG emissions is obtained and in 2050 at least an 80% reduction of all emissions: energy, other GHG emissions and end-of-life.

- In plausible combination pathway 1 (“2030 compliance at least costs”) we build the potential based on the most cost-effective measures, given energy prices in 2017.

- In plausible combination pathway 2 (“direct action and high-value applications”) we optimized the system to the highest value by using energy and feedstock resources, whilst considering external constraints.

The calculation of each of the combination pathways has been performed in a logical manner, considering the consequences for the most important chemical compounds with consistent volumes in their streams through the industry towards the end-products, in a fully functional chemical production chain. As an outcome, the two combination pathways show examples of how the transition of the chemical industry could be realized. They furthermore identify the technologies and routes that we see as vital to further develop in the upcoming years.

3.4 Solution themes

To structure the diverse range of possibilities for the chemical industry, all pathways have been shaped through six solution themes, which are consistent with the Roadmap 2030. These solution themes are widely explored, using a content-based approach combined with a stakeholder process, and quantified for their maximum technological potential in the Dutch chemical industry. For each solution theme, a maximum technical potential in terms of carbon reduction has been calculated for 2050 (and indication for 2030) as well as corresponding energetic and non-energetic consequences. The themes are presented in Figure 33 and elaborated on in detail in the following paragraphs, with the exception of sustainable products (because the effects of this theme, such as bringing new chemical products to the value chain partners, are visible outside the sector and are presented in Chapter 5).

3.4.1 Closure of the materials chain

Given the legislative developments in the European circular economy, closure of the materials chain is expected to play an important role in the years to come. In general, reuse, mechanical recycling, and chemical recycling of products are three available methods to close the materials chain.

Reuse

The “smallest loop” is achieved when products are reused. Through reuse, the lifetime of products is extended, eventually leading to a reduced amount of waste streams. Reuse models are proven for many products, including PET, electronic components and white goods. To increase the potential for reuse, a stronger focus on design and high-value products is necessary, as well as a focus on infrastructure for reverse logistics [14]. This requires strong cooperation within the value chain, and offers the potential of higher margins; business models could completely change, for instance chemical industry owning the materials produced – and the end-consumer just paying for the use of the functionality. While this loop is not modelled as a separate abatement measure, the chemical industry can contribute to accelerate the re-use of products built from chemical materials.

Mechanical recycling

Mechanical recycling brings chemicals, both organic and inorganic, back to the value chain, thus reducing the demand for virgin materials. Accenture estimates that 18% of the total European chemicals output to customers could be circulated through mechanical recycling [14]. This figure includes both the recycling of polymers, rubbers and other organics, as the recycling of inorganic material, such as fertilizers through ground water filtration. Mechanical recycling of organic chemicals predominantly concerns the recycling of polymers. Today, around 30% of plastic waste is mechanically recycled in the European Union [15]. In the Netherlands, these figures are higher. For instance, the recycling rate of *plastic packaging* is already above 50% in the Netherlands [16], whereas this figure for the EU is 39.5% [15]. In 2015, the European Commission adopted the Circular Economy Package presenting ambitious targets for recycling throughout the European Union, including a share of plastic packaging waste prepared for reuse and recycling of 55% in 2025 (similar to the already maintained Dutch level). [17] These developments imply that recycling will play an increasingly important role in our future value chain.

Combining available knowledge, we estimate that around 40-50% of plastics can be mechanically recycled, considering a yearly amount of plastic waste in the European Union of 25 Mt [15]. This figure is in line with the target set by Holland Chemistry for 2030 [18].

Mechanical recycling of plastics is a mature technology. Yet, realising the full potential of the technology requires a strong emphasis on the optimisation of waste streams and infrastructure needs for sorting, cleaning and processing of end-of-life materials. Although these requirements are challenging, the Netherlands has the right partnerships and infrastructure in place to continue the ongoing development.

Chemical recycling
Chemical recycling refers to technologies that break down plastics into their chemical precursors, which can be reused in chemical production. For chemical recycling several technologies are foreseen, each operating at different temperature levels and producing different end products. Broadly, these technologies can be categorized in four groups [19]:

- Through *solvolysis*, a plastic waste stream is degraded using a solvent, where a combination of solvent and temperature level leads to separation of different types of plastics (PE, PP, PS). This method is used to separate pure compounds from a plastic waste mix.
- *Pyrolysis* refers to technologies where plastic waste is heated in the absence of oxygen. In this process, the temperature level remains below 700ºC. Pyrolysis possibly leads to a diverse range of products (functional molecules, olefins, oils), where conditions of the process (including the use of catalysts) determine the end product. Pyrolysis oil can be used as cracker feed (for amongst others the production of ethylene and propylene).

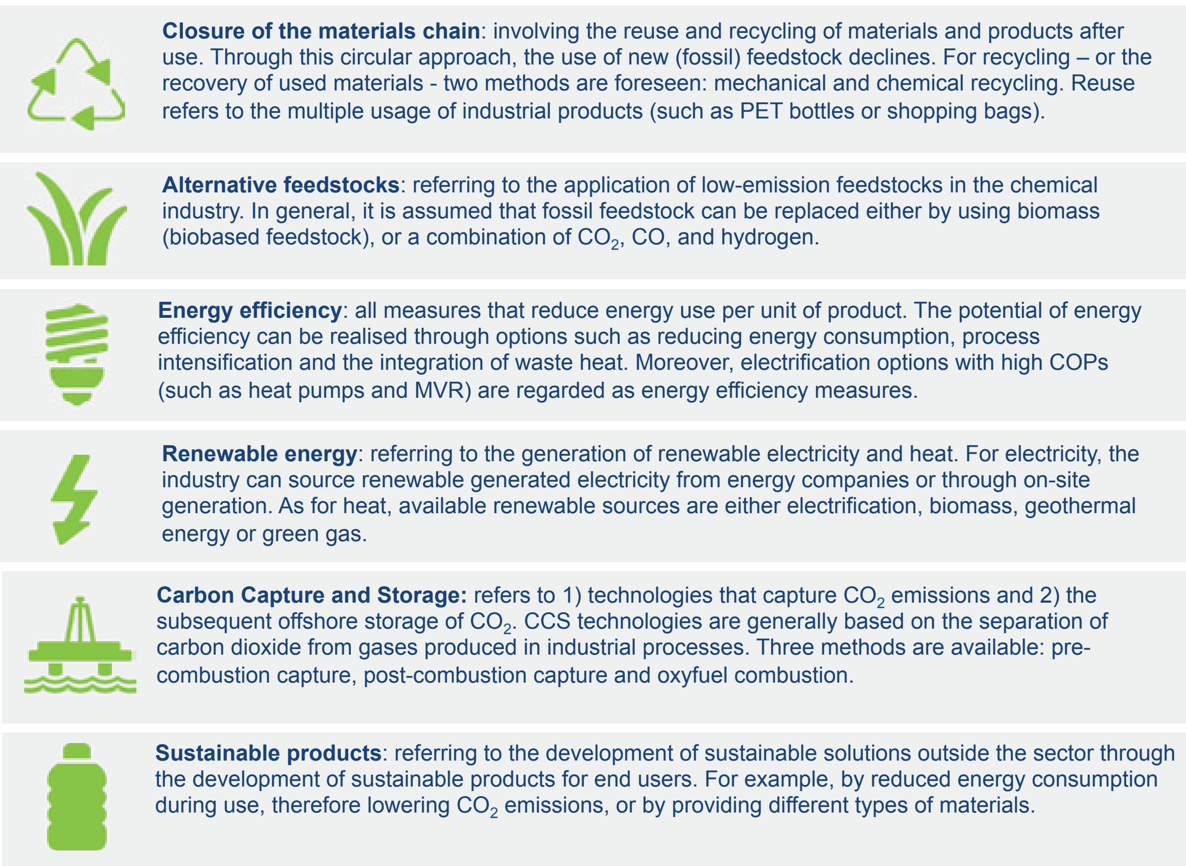

Figure 3-3 The six solution themes for reducing greenhouse gases

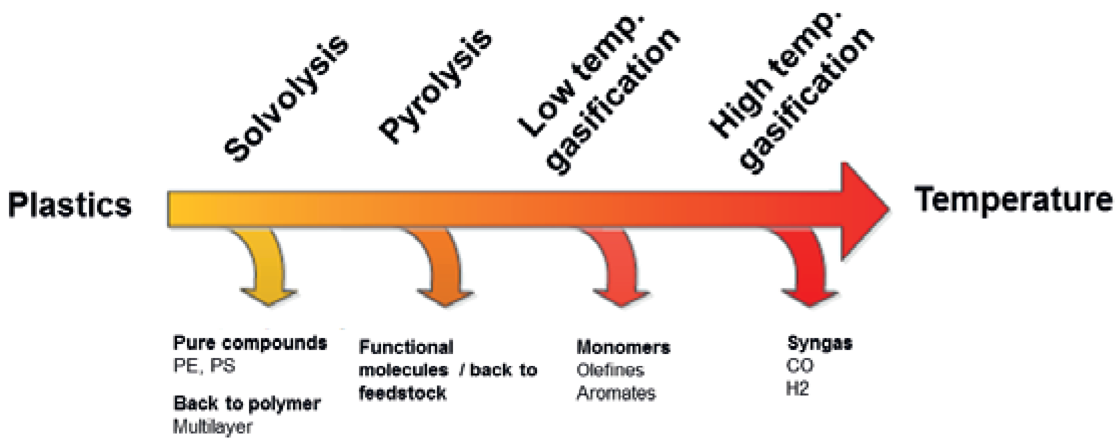

Figure 3-4 Different chemical recycling routes. Based on ECN (2015) [19]

- Through *low temperature gasification*, plastic waste is heated with a limited amount of oxygen at temperature levels between 700 and 900 ºC. Temperature levels in this process are kept relatively low to produce a gas in which valuable components are maintained, such as benzene and ethylene.
- The process of *high temperature gasification* is executed with pure oxygen at temperature levels above 1200 ºC. This leads to a syngas (CO and H2) for application in synthetic routes.

In general, chemical recycling can be used to process plastic waste streams that cannot be (efficiently) recycled mechanically, although the (continuous) quality of the waste streams is a challenge. Accenture estimates that in the long run, 8% of European chemical output to customers can be circulated through chemical recycling [14]. This translates to around 30% of yearly plastic waste volumes, considering the yearly amount of plastic waste in the European Union of 25 Mt [15]. Chemical recycling is not yet applied at significant scale, but with a strong emphasis on innovation, we estimate that chemical recycling would have the potential to become a key asset for the chemical industry after 2030.

3.4.2 Alternative feedstocks

Generally, two main alternatives to fossil feedstocks are taken into account in this study: the use of bio-based feedstock and the use of hydrogen as feedstock in combination with CO_2.

Bio-based feedstock
Bio-based chemicals can be produced from many types of bio-based feedstock, e.g. starch, sugars, vegetable oils, animal fats or lignocellulosic material from for example wood. Biomass feedstock can, according to its molecular structure, be converted using a wide spectrum of technologies, such as:

- *Fermentation* to convert sugars into multiple products following metabolic routes;
- *Transesterification* to convert fat (triglycerides) into biodiesel;
- *Gasification* of (ligno-)cellulose (e.g. wood) to produce a synthesis gas, which in turn can be used as feedstock to produce ammonia, methanol and other chemicals.

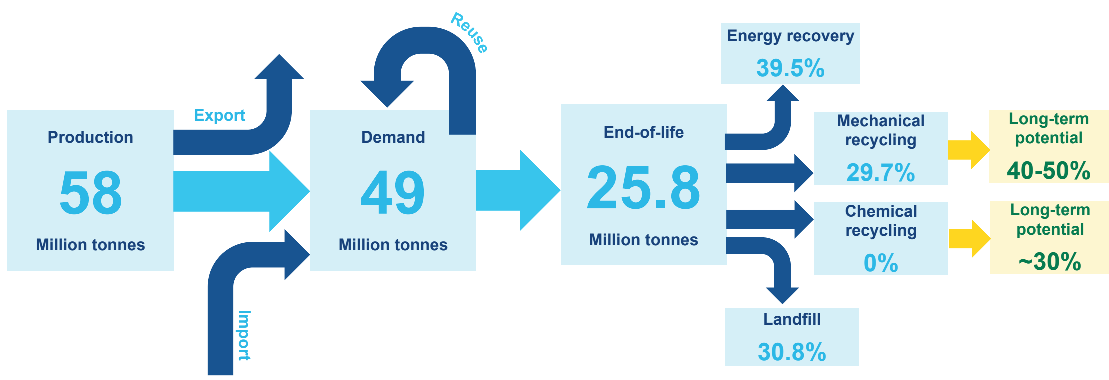

Figure 3-5 European plastics production, demand and waste treatment in 2015, including long-term potential. Team analysis based on Plastics Europe [15], Accenture [14].

- *Pyrolysis* is the thermal decomposition of biomass at modest temperatures in the absence of oxygen to produce a pyrolysis oil, also referred to as bio-naphtha. Some grades of pyrolysis oil can, after hydrotreating to remove oxygen-atoms, be fed into a naphtha cracker to produce various high and low value products.

Biobased materials can be distinguished into novel materials, offering a new functionality such as PLA and PHA's, and drop-in biobased materials, chemically identical to traditional materials, only differing in the source of the raw materials. Examples are bio-PE, bio-PET and biobased nylons. In this Roadmap, we mainly focus on drop-in bio-based materials, as these routes offer the largest potential for emission reduction, whilst also including some potential for the bio-based materials to offer new functionality. If the development and uptake of these functionality driven bio-based materials is faster than projected, this could lead to more efficient bio-based decarbonisation potential. This is because the molecular structure of these materials is often closer to that of the biomass than the molecule structure of the drop-ins. Dutch industry is already very active in developing bio-based production routes. A recent overview identified 30 different projects, varying from idea to commercial products, applying six different production routes [20]. Most projects focus on bio-based materials offering new functionalities, see the highlight box below for some examples. Globally, the production capacity for bioplastics was 4.16 million tonnes 2016 [21].

Since bio-based material already contain many high-energetic bonds between carbon and oxygen, many developments focus on producing oxygen-containing chemicals, like bio-ethanol, glycols and PLA. In the assessment of the potential for bio-based materials, we focus on the bio-naphtha (which can be made on the basis of HVO-bio-diesel or on the basis of pyrolysis oil) route for C2/C3 chemicals and on conversion of crude glycerin / vegetable oils / used cooking oil towards BTX.

The latter route still requires R&D to develop the pyrolysis process and to improve economic attractiveness [7].

Compared to the conventional route to make ethylene, the energy demand of this route is the same, as bio-naphtha can replace fossil-based naphtha. The energy consumption is considerably higher in the case where ethylene is produced on the basis of syngas from wood (for which significant investment is required), and somewhat lower in the case ethylene is produced on the basis of (imported) bio-ethanol.

With regards to bio-based materials two remarks must be made:

- The first remark relates to the debate on availability and best use of biomass. Although biobased material shows a growing potential in terms of technology, the availability of sufficient sustainable biomass may well be the limiting factor in the future. Different projections for the availability of biomass circulate, depending on the assumptions. According to McKinsey, the fair share of the global biomass production that the Netherlands can use is between 200 and 600 PJ [22]. PBL mentions a nationally available maximum of 200 PJ, and an import potential for the Netherlands between 100 and 760 PJ (based on number of inhabitants), considering different development scenarios. Yet, it is important to note that if biobased production grows to substantial amounts, the chemical industry will need to compete for available sustainable biomass with other sectors, such as energy, transport and food/feed (probably driving up the prices). The Corbey commission estimates the availability of biomass for the Dutch chemical industry at 140 PJ in 2030 [23], which we used in the "High Value Constrained World" plausible pathway for 2030.[4] For 2050, we have doubled that amount, based on the assumption that the Dutch chemical industry will contribute to the wider availability of sustainable biomass globally.

Promising Dutch bio-based developments [20]

- From low value organic waste to chemical products
  - ChainCraft (fermentation of vegetable waste to fatty acids)
  - AkzoNobel/Enerkem (Waste2Chemicals, conversion of plastic waste to syngas and methanol)
- From sugars to furans
  - Avantium, Synvina and Corbion (furan di-carbonic acid, a building block for the bio-based form of PET)
- From local and imported woody biomass to bio-refineries
  - Bioforever (wood waste to ethanol and butanol)
  - Avantium, Zambezi (wood to glucosel)
  - Redefinery (wood pellets to sugars and lignin)
  - Bio-BTX (wood (or glycerin) to BTX
  - Empyro (wood and other feeds to pyrolysis oil)

- The second remark relates to the sustainability and emission factor of biomass: Production of biobased materials requires natural resources, such as fertile land, fresh water and phosphate fertilizers. Production of biobased materials in many cases leads to upstream emissions from the use of fossil energy or due to land cultivation. Furthermore, biomass production for materials can compete for land with other applications, notably food production. For this reason, it is argued by several parties that the development of a set of sustainability criteria for the use of biomass, for instance relating to a minimum CO_2e reduction, a ban on direct land use change or mandatory rules for sustainable agricultural practices is needed [24]. Such upstream emissions from the use of biomass are not taken into account in our modelling (they are very much dependent on the crop and the location), and as such the modelling of the effect of the use of biomass, while methodically in line with the described approach, could give an excessively positive impression of its effect.

4) Note that no distinction has been made between the different forms of biomass (for example bio-diesel vs wood), although producing 1 PJ of bio-diesel requires more than 1 PJ of raw biomass.

Hydrogen

Hydrogen can act as a carbon-free feedstock for some chemical routes. Ammonia for instance is directly synthesized with the use of hydrogen and nitrogen. Other drop-in chemicals, such as methanol, ethylene, propylene and BTX, have the potential to use hydrogen as feedstock, in combination with a carbon source (for instance CO_2).

For the production of hydrogen, electrolysis based on renewable electricity or steam methane reforming in combination with CCS are routes to reduce carbon emissions. Electrolysis in combination with large offshore wind parks, potentially clustered at distant offshore banks, offers an opportunity to guarantee large volumes of hydrogen for baseload use in the chemical industry. Electrolysis is based on the splitting of water into hydrogen and oxygen using an electric current. For electrolysis, several technologies are (currently) in development [25]:

- *Alkaline electrolysis*: with a Technology Readiness Level of 7-9, alkaline electrolysis is the state-of-the-art industrial process for electric based hydrogen production. The process is characterized by having two electrodes operating in a liquid alkaline electrolyte solution of potassium hydroxide (KOH). Investment costs of alkaline electrolysis are currently high at 1000 – 1200 €/kW, but expected to decrease with a strong development focus to around 600 to 800 €/kW beyond 2030.

- *PEM electrolysis***:** PEM (Proton-Exchange-Membrane) electrolysis is a more recent technology (TRL 7-8) that does not use a KOH or equivalent solution for the production of hydrogen. PEM electrolysis splits deionized water into hydrogen and oxygen on either side of a solid polymer electrolyte membrane. The system costs of PEM electrolysers are currently about twice that of alkaline systems, but are expected to decrease significantly while the technology develops, to around 500 €/kW beyond 2030.

Alternative for CO_2 + Renewable H_2: CO + Renewable H_2

Steel plants produce large quantities of CO, which are in general used in power plants to produce power or as fuel in the steel plant. Rather than combusting the gas, it can be used to replace CO_2 to produce for example C2/C3. The advantage is that less hydrogen is required than when CO_2 is used. The net balance is positive, reducing electricity use and investment costs. In the Dutch steel plant, a considerable amount of CO is available, and likewise just over the border in Belgium.

- *High-temperature solid-oxide electrolysis (SOE)*. When operated at temperatures of 700-1000ºC, the process of electrolysis is expected to require lower amounts of electricity per unit of hydrogen as part of the energy input comes from waste heat. This technology is still at an early stage of development (TRL 6-7), and is expected to become commercial around 2030. Investment costs can potentially drop to 300 €/kW, with the right development focus.

Considering the use of hydrogen as feedstock for ammonia, methanol, BTX and C2/C3, we estimate a reduced fossil demand of around 530 PJ and an increased electricity use of around 890 PJ, based on the electrolysis route (including the effects of energy efficiency improvements; based on the thematic pathway Electrification). Yet, it should be noted that these routes will only have a positive impact on CO_2 emissions if the electricity used is based on (almost completely) renewable sources. The generation of sufficient amounts of renewable electricity is a significant challenge; see also chapter 4.3.

The investment costs for hydrogen electrolysers are rapidly dropping. In this roadmap, we have assumed that the investment costs for hydrogen electrolysis is currently 525 €/kW (with 4500 full-load hours – based on the assumption that wind energy is used to generate the required electricity).

Many products can be made with renewable hydrogen and CO_2, including products containing oxygen. This offers opportunities for formic acid and acetic acid (both are currently not produced in the Netherlands); these routes are expected be deployed before large scale synthesis of C2/C3, as much research effort goes into the development of such routes [expert opinion], and their deployment is also "composition-wise" more logical.[5]

5) For these products, CCU + renewable hydrogen demands less energy (as not all oxygen in the CO_2 needs to be captured by the hydrogen).

Availability of CO_2

Currently, there is plenty of CO_2 emitted to provide the required CO_2 feed to produce methanol, C2/C3 and BTX. In the modelling, it is assumed that this CO_2 would be emitted if not used as feed. However, by recycling the CO_2 into a new product, the emission of CO_2 at the initial source is avoided. At the end-of-life of the new product, the CO_2 is released again. The benefit lies in the fact that one cycle of CO_2 emissions is avoided. In this analysis, it is assumed that the CO_2 is sourced from outside the chemical industry; it is assumed that the investment costs to capture this CO_2 are in the scope of the chemical industry; to prevent adding the energy use of other sectors to the chemical industry's energy use, the energy costs are borne by the emitter.

In a low carbon 2050, this would change and it can no longer be assumed that "other CO_2 emissions are unavoidable" and other CO_2 sources are needed. Approaching 2050, the amount of available „sustainable" CO_2 would increasingly become scarce; it could for example be harvested from bio-boilers equipped with carbon capture, and would compete with alternative uses of "sustainable CO_2" – to generate negative emissions. Direct air capture of CO_2 could provide a solution, but at increased energy consumption, and with a requirement for further development.

Functionality driven CCU provides many opportunities in niche markets, like polyols, the formation of polyethylene / poly propylene carbonates and the production of ethanol and cyclic carbonates.

3.4.3 Energy efficiency

Improving the energy efficiency, or combating the waste of energy in industrial processes, has long been the key abatement measure when it comes to carbon reduction. Since energy is an important cost factor for energy-intensive processes, improving energy efficiency is a normal business routine. Investments in energy efficiency are evaluated on the basis of their ROI and have to compete with other investments. Although a considerable improvement has already been achieved in the past decades, there is still more potential for the chemical industry towards 2050. The potential of energy efficiency can be realized through several factors:

- **Process intensification and efficiency:** Process intensification is split into process intensifying methods and process intensifying equipment [7] . Although the potential for process intensification is significant, implementation in a brownfield situation will only be considered as part of a broader investment with larger benefits than energy efficiency thus justifying the typically longer pay-back times. Most signification improvements are expected for technical efficiencies (such as advanced heat exchangers, mixers, spinning disk reactors, HiGee separation technologies, or combinations like reactive distillations, heat exchange reactors) for specialty chemicals and consumer chemicals.
- **Electrification with high COP technologies:** techniques with high Coefficient of Performances, such as Mechanical Vapour Recompression **(MVR)** and (high temperature) heat pumps, are regarded as energy efficient measures rather than electrification measures. Showing COPs of nearly 10 and 3-4 respectively [26], these technologies have the potential to save large amounts of fossil energy. According to McKinsey, heat pumps for low temperature heat and **MVR** for medium temperature heat have potential in the short to medium term. In the longer term, more efficiency can be gained through the adoption of heat pumps for high temperature heat. [22]

Combined, we assume a lower bound for energy efficiency measures of 0.5% per year, and a higher bound of 1.0% per year, both for technologies with a typical payback time of 5 years and less.

The chemical industry can both optimize the use of residual heat flows in industrial processes and deliver residual heat to other sectors. This can contribute to up to 1,5 Mton/year reduction outside the sector, mainly for buildings.[6)]

3.4.4 Renewable energy

To ensure a carbon emission reduction of 80-95% by 2050, the use of renewable energy is essential. In the chemical industry, it is assumed that all used electricity will come from carbon neutral sources by 2050. In addition, the sector is able to contribute to renewable energy sources directly, through on-site production. In general, opportunities for renewable energy are rather different for renewable electricity versus renewable heat.

Renewable electricity

Apart from sourcing renewable electricity from energy companies, the potential for on-site generation purposes is limited as a result of space and safety (wind) or efficiency (solar). However, the chemical industry is able to accelerate the energy transition by initiating innovative contracts with energy companies. In October 2016 for instance, AkzoNobel, DSM, Google and Philips announced an exclusive 'Power Purchase Agreement' for the establishment of offshore wind park Krammer by Zeeuwind and Deltawind. Such agreements show significant potential to facilitate the growing demand for renewable electricity in the chemical industry towards 2050.

6) This has not been taken into account in the calculation of the emission reduction from energy efficiency, as emissions are reduced outside the sector.

SOURCING OF HYDROGEN FOR FEEDSTOCK APPLICATIONS

Deep reduction of the feedstock related emissions can be achieved by using hydrogen from decarbonized sources. In this report, it is assumed that this will be produced from renewable electricity, by electrolysis.

Off-shore wind would be the primary source for this. Other domestic renewable power sources will not be available as these will already be fully used to decarbonize the existing energy demand. There are also limitations to the availability of imported biomass, which should be prioritized for direct feedstock use instead of burning it for renewable electricity. Therefore, only off-shore wind can provide for the large volumes of hydrogen needed by use as a carbon-free feedstock.

This would require a large additional capacity of wind, not well suited for transportation by the regular high-voltage Alternating Current (AC) power grid. Such large amounts of offshore wind need to be electrolysed into hydrogen directly, either offshore, or - after transportation by dedicated Direct Current (DC) lines - at coastal locations. Either way, this would be a largely separate infrastructure. This has been considered in our analysis.

It should be mentioned that there are two alternatives for our base assumption of hydrogen sourcing:

- In the short term, carbon-free hydrogen can be produced readily from natural gas with pre-combustion CCS. According to a recent report by Berenschot and TNO [86], this would be available much sooner (today) and at much lower cost, compared with hydrogen from offshore wind at present. Although not considered for the longer term, this option does provide carbon-free hydrogen at lower market price, thus being a suitable alternative to kick-start developments.
- In the long-term, hydrogen could become available on a global scale from solar farms around the equator and/or wind farms in extremely windy regions, both combined with electrolysis. This possibility is speculative at the moment. If this materializes, it could enter the market at prices below the costs of our base assumption, thus boosting the possibilities in the long term.

Finally, a sound infrastructure for hydrogen transportation and storage is necessary. This is especially the case in our base assumption for hydrogen production from off-shore wind, as this is a very intermittent weather-dependent source, while the hydrogen will be used in fully continuous feedstock processes. As studied in the report by Berenschot and TNO, such an infrastructure could become available by refurbishing the current Dutch gas infrastructure at relatively low cost, and probably be shared with other hydrogen applications for regular energy production (this may happen anyway, independent of any feedstock application). The required investments are likely to be provided by the energy sector; this is yet another example of the strong intertwinement between the transition of chemical industry and energy sector.

Renewable heat

As for heat demand, available methods are electrification (Power to Heat) biomass and geothermal energy. Looking at electrification opportunities, electric and hybrid boilers show large potential to replace gas boilers, delivering steam and hot water up to 350ºC[7)] [26]. Based on this temperature, for electric boilers, operating at a 95% efficiency rate, an estimated potential of around 65 PJ electricity is feasible in the chemical industry. Techniques with high Coefficient of Performances, such as Mechanical Vapour Recompression and heat pumps are considered as energy efficiency measures rather than electrification measures.

The use of biomass is suitable for on-site production of heat through high quality pellets or shreds. Modern biomass boilers have an efficiency rate of around 90% and are easily applicable in existing processes. Moreover, biomass installations operate at different temperature levels, delivering heat both at low-medium and high temperature levels [27]. This is a benefit for the chemical industry, since a significant amount of heat demand is associated with high temperature levels. As with the use of biobased feedstocks, the use of biomass for heat production will depend on future availability of biomass.

Looking at geothermal energy, there is still a lot of uncertainty about the potential contribution to industrial heat demand because of a lack of (applied) research.[8)] Yet, this technology is expected to be able to provide around one third of the heat demand below 200ºC. It should be noted that a substantial part of this low temperature heat is available to the chemical industry as cascaded waste heat available from high temperature processes,

7) Power to Products

8) If technology

Electric furnaces

Due to the high temperature requirements, and the process set-up, the application of the heat generation technologies described here (electric boilers, geothermal heat, bio boilers) is very limited, or very difficult at best in current naphtha crackers. However, in the future, electric furnaces may well offer further decarbonized routes towards production of chemicals, when renewable electricity is used. Furnaces are in the chemical industry mainly used in ethylene plants, to crack the naphtha. Replacing these furnaces by electric furnaces has the potential to significantly reduce the energy consumption of the process, while eliminating its energy related emissions. In combination with the use of bio-naphtha, the non-energetic emissions would also be reduced. This still requires further innovation.

thereby limiting the application of geothermal heat [7]. Altogether, we estimate a potential for geothermal heat of up to around 30 PJ in the chemical industry, based on temperature levels below 200 °C [28]. Yet, since geothermal projects are cost-intensive and risky and, social acceptance has still to be build up; it is not likely that such projects are initiated on individual company level. Cooperation within and outside the chemical industry (for example at cluster level) is necessary.

3.4.5 Carbon Capture and Storage

Industrial CCS technologies are generally based on the separation of carbon dioxide from gases produced in industrial processes. Three methods are available: pre-combustion capture, post-combustion capture and oxyfuel combustion.

- With **post-combustion capture**, CO_2 is captured after combustion of fuels. This process is focused on the separation of CO_2 from other substances (such as H_2O and N_2) from exhaust gases.
- **Pre-combustion capture** refers to removing CO_2 from fossil fuels before combustion is completed. In this process, a syngas is produced made from carbon monoxide and hydrogen. The former is reacted with water to produce CO_2, which is captured, and hydrogen. Syngas is produced in steam reforming and autothermal reforming processes (see text box).
- With **oxy-fuel combustion**, the fossil fuel is burned in an atmosphere of pure oxygen, to prevent N_2. In this environment, the CO_2 needs to be separated from water vapour. The latter can be condensed out, while the former can be piped or transported directly to a storage facility.

With moderate technological developments, long-term opportunities also exist in other chemical sectors (capturing the CO_2 emissions associated with the use of fuel). Altogether we estimate a maximum capture potential for the chemical industry of 14 Mton per year. It is assumed that from all energetic emissions, a capture rate of maximum 85% is technically feasible, while CCS would be worthwhile applying to 80% of the energy related emissions. For process emissions this is 100%.

On top of this potential, the emissions associated with the incineration of plastics could be recovered. In the annex, it is calculated that 9 Mton (at most) of CO_2 can be captured from waste incineration of plastics (polymers) made in the Netherlands, assuming a capture efficiency of 85% and assuming that all plastics (polymers) made in the Netherlands are incinerated in waste incinerators equipped with CCS in and outside the Netherlands.

These numbers (for the chemical industry as well as for the waste incinerators) are based on high-level estimates in literature; in the practical reality, the exact cost depend strongly on the exact layout of a site (most importantly: the number of emission points per site, and to which extent a CO_2 pipeline to connect with is available close by); therefore, before depending on roll out of CCS as major abatement route, these costs should be determined in detail, taking the practicalities into account.

PBL states that in the short term, the roll out of CCS accounts for a delaying factor, as the application of the technology requires many infrastructural developments [29]. Moreover, public acceptance and cost effectiveness remain barriers towards the large-scale implementation of CCS [7]. For storage of CO_2, the use of empty oil and gas fields and aquifers are most probable. According to the Dutch Noordzeeloket, offshore CO_2 storage capacity in former gas fields adds up to 1200 Mt [30]. This would ensure some 85 years of storage for chemical industry emissions, excluding potential usage of aquifers or onshore gas fields.[9]

3.4.6 Cost effectiveness

To get insights into the economic aspects of different CO_2 abatement measures, all solution themes have been quantified based on their marginal abatement costs. These figures, as displayed in Figure 36, show the cost-effectiveness of different CO_2 abatement measures for the chemical industries, including both capital and 2017 energy and feedstock costs. Other costs (such as labour costs, the costs for the collection of waste, maintenance, the costs to purchase of raw materials such as absorbents required for post combustion CCS) are not taken into account. Investment costs are annualized as ≈ 1/8 of the total investment costs (a higher share for utilities); see Annex 1 for details.

9) Assuming the chemical industry would be the only sector using CCS (also excluding waste incinerators).

Steam Methane Reforming (SMR) and Autothermal Reforming (ATR) present other routes to supply hydrogen using pre-combustion CCS. This principle is based on the production of hydrogen from a fossil source (natural gas), resulting in H_2 and CO_2 (also using the water-gas shift reaction). These are well-known processes with TRL of 8-9, utilized throughout the world for many decades for the production of hydrogen albeit without CO_2 capture so far.

- With SMR, around 2/3 of CO_2 is released as process emissions in concentrated form, which is relatively cheap to capture. Yet, the remaining 1/3 of CO_2 is emitted with the combustion gases from an external heating process, and is more difficult to capture and requires a separate installation.
- With ATR, both the chemical and the heating processes take place in the same reactor, releasing 100% of CO_2 in concentrated form, enabling a cheaper capture of CO_2 in a single process. Yet, ATR uses pure oxygen as input, requiring a separate oxygen plant with additional investments and energy usage.

At this point in time, the SMR and ATR routes are the most cost-efficient methods by far, compared with the electrolysis-based methods. It is expected that the latter will decrease in cost over time, as already explained. Another important difference is that the H_2 from electrolysis is "green" hydrogen from a renewable energy source, whereas the H_2 from the SMR and ATR reforming plants represents a decarbonized "CCS" route (sometimes called "blue" hydrogen). So although both are carbon-free, these are part of different transition pathways.

Figure 3-6 come at different costs. These are typical numbers and costs depend in many cases heavily on the exact process and to what extent existing installations can be re-used. This is clearest indicated for the cost-effectiveness for bio-based and CCU-based platform chemicals, where the figure indicates a range to show the variety for the modelled processes. Also, for chemical recycling, an alternative process (converting non-recyclable mixed waste, including plastics, into syngas and then into clean methanol) would come at abatement costs < 100 €/tonne CO_2, depending on the value of methanol [AkzoNobel]., depending on the value of methanol [AkzoNobel].

The figure illustrates that, in general, reducing the end-of-life emissions comes at higher abatement costs than reducing the energy related emissions, pointing at a strong need for innovation to bring these costs down. Moreover, although these costs are often not profitable at company level, they seem to be significantly lower than for many solutions in other Dutch sectors, such as households and transportation [29] [31].

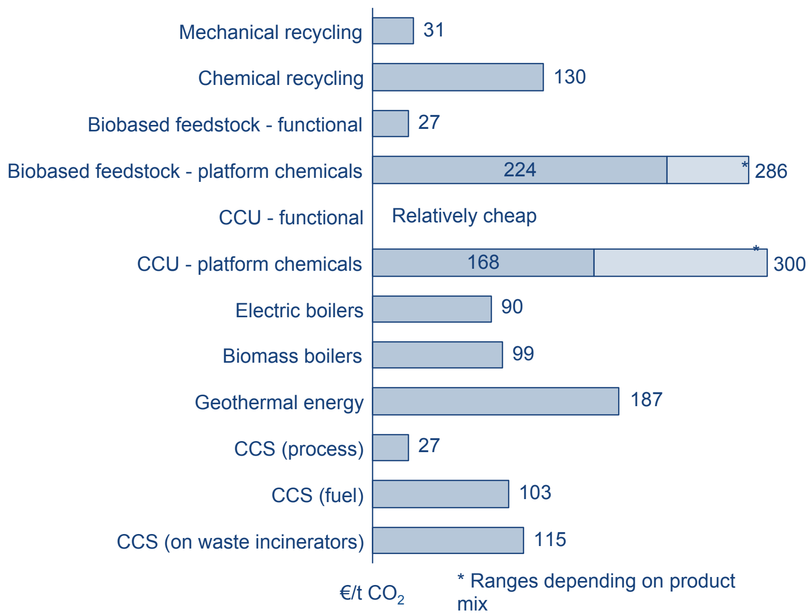

Figure 3-6 Cost-effectiveness of the abatement measures (Note: only includes investments cost and energy and feedstock OPEX based on current prices).

4 Implications for the chemical industry: quantifying the opportunities

The six solution themes altogether show a broad range of opportunities for the chemical industry to significantly lower emissions towards 2050. Three thematic pathways explored different routes to achieving deep reduction of both energetic and other GHG emissions and end-of-life GHG emissions in 2050. The pathways differ not only in the focus on solution theme but also in the level of target achievement. However, the extremity of the pathways poses cross-boundary challenges, both inside and outside the chemical industry, for instance the availability of sufficient volumes of sustainable biomass. Therefore, two plausible combinations of these pathways are presented as possibilities to reduce energetic and other GHG emissions by 49% in 1990 and all GHG emissions by 80-95% in 2050. The first plausible pathway aims to achieve the 2030 target at lowest cost for the chemical industry, aiming mostly at reducing other GHG and energy related emissions up to 2030. The second plausible pathway follows a more balanced approach in this regard that is also aims to make a start with reducing end-of-life emissions up to 2030, whilst using the energy and feedstock resources at their highest value. This pathway is built on the knowledge that the challenges of climate change need direct action to ensure that technologies are developed and implemented and that the costs come down on the longer term.

4.1 Viewing the transition in extremity: insights into the thematic pathways

Considering the technological potential of the six solution themes as presented in Section 3.3, each of the three thematic pathways demonstrates a different route to achieving 80-95% reduction of both other GHG and energy related emissions and end-of-life emissions in 2050. Yet, although these routes can lead to the required emission reductions for the chemical industry, the extremity of the pathways poses cross-boundary challenges, both in and outside the chemical industry. A resume of the most important findings per thematic pathway is given below. More detailed outcomes are presented in Annex 2.

Circularity & Biobased
In the Circular & Biobased pathway, the largest share of emissions is abated by the change from fossil feedstock towards biobased streams and a strong focus on circularity of feedstocks through recycling. The largest abatement potential for this transition pathway concerns the use of biobased as alternative feedstock, requiring a 100% switch from naphtha to bio-feed for the production of ethylene and propylene, a 100% syngas based shift for ammonia and methanol, as well as a 100% biobased BTX route ('bio-btx').

Although the pathway Circular & Biobased shows many opportunities for the creation of new business models for the chemical industry, an extreme deployment comes with strong cross-boundary limitations. This pathway requires around 700 PJ of sustainable biomass in 2050, which seriously puts pressure on available (sustainable) sources and affects the competition with other sectors. Moreover, moving towards a circular economy requires a complete value chain turnaround, including more intensive clustering, increased flexibility of plants and processes to deal with 'waste' and bio-materials and significant logistical developments. When looking at costs, the Circular & biobased pathway would require up to 24,5 billion euros in investments towards 2050, mainly for the use of alternative feedstocks. For the energy sector, investments of 10,1 billion euros are expected towards 2050 in this pathway, mainly as a result of biorefining.

Electrification

In the electrification pathway, the largest share of emissions is abated by using hydrogen from electrolysis in combination with CCU as alternative feedstock. The Electrification pathway shows large potential for the chemical industry in terms of carbon neutral production processes, leading to strong CO_2 emission reductions towards 2050. The Dutch chemical industry is uniquely positioned being clustered, geography close to the sea-shore, and it benefits by origin from its close ties with the energy sector. These conditions provide the right basis to successfully deploy electrification opportunities. Yet, the demand for large volumes of hydrogen (from electrolysis) and energetic electrification requires around 980 PJ of electricity, equalling around 62 GW of offshore wind development[10)]. This requirement brings about significant costs, both in the chemical sector and in the energy sector. Furthermore, due to the conversion efficiencies from electricity to hydrogen to chemical building blocks, the total energy demand for this pathway is about 30% higher than in the other two thematic pathways. The emissions, however, will still go down by about 95% in 2050, since the electricity is carbon free.

Costs in the electrification pathway are significantly higher than the other pathways, with required investments of 91,3 billion euros towards 2050 (mainly for electrolysis). The energy sector would be faced with even higher investments of 152,4 billion euros as a result of required offshore wind capacity and related infrastructure costs.

CCS

The CCS pathway emphasizes the reduction of emissions through Carbon Capture and Storage possibilities. This pathway involves the least modifications in business models and production processes. This pathway emphasizes the possibility of business as usual, where CO_2 is efficiently captured and stored. This line of thinking does however require a strong infrastructure grid for CO_2 for transport and storage. Moreover, public acceptance remains a barrier towards the large-scale implementation of CCS.

In the CCS pathway, the largest share of emissions from energy & processes is abated by CCS, adding up to around 12 Mton per year.[11)] The direct influence of the chemical industry in the CCS pathway remains limited to the abatement of CO_2 from energetic and other GHG emissions, since the reduction of emissions on the end-of –life part requires CCS on waste incinerators in and outside the Netherlands. Generally, investments in the CCS pathway are lowest compared to the Circular & Biobased and Electrification pathways, with 12,4 billion euros until 2050 for the chemical industry. Yet, these investments only include abatements for energetic and other GHG emissions. Outside the sector, investments of 15,9 billion euros would be required, of which the largest part for CCS on waste incinerators. Overall, this pathway does not deliver the emission reduction aimed for in 2050.

Note that emission reductions due to application of CCS on waste incinerations could partly be implemented abroad, but are included in the numbers above.

4.2 Presenting plausible combination pathways

Two plausible combination pathways have been explored. The first plausible pathway ("2030 compliance at least costs") aims at achieving the governmental goal of reducing the process and energy related GHG emissions by 49% in 2030 and implements the measures in the order of their cost effectiveness in terms of costs per tonne of avoided emissions, using a significant amount of biomass for energy generation.

The second plausible pathway ("direct action and high-value applications") aims at reducing both other GHG / energy and end-of-life related GHG emissions directly from the start, gearing up technology development and implementation. This pathway takes external constraints into account, like using all energy and feedstock for the applications with the highest value for the society, considering a fair share of biomass, the required capacity for off-shore wind, and the capacity for storage of CO_2 in empty gas fields. This pathway is built on the knowledge that the challenges of climate change need direct action to ensure that technologies are developed and implemented and that costs can come down in the longer term. Just focusing on reducing emissions in the short term brings the risk of being too late with new technologies or a lock-in with old technologies, impeding the implementation of new technologies. Since 2050 is just one investment cycle away for many chemical processes, such a lock-in situation is a serious risk.

4.2.1 Plausible combination pathway 1: 2030 compliance at least costs

In plausible pathway 1 the aim is to achieve the 2030 governmental goal of reducing the other GHG and energy related GHG emissions by 49% in 2030 based on the measures that are most cost effective against energy prices of 2017, using a significant amount of biomass for heating purposes. This pathway also aims to reduce all GHG emissions (other GHG, energy and end-of-life) by 80-95% by 2050. This pathway implicitly assumes that the development of technologies to abate end-of-life emissions is done outside the Netherlands up to 2030 and the implementation of these technologies will be done between 2030 and 2050, which means the Netherlands would miss the opportunity to lead in technology development and implementation.

Figure 4-1 shows the results of the analysis. In 2030 the other GHG and energy related emissions will be reduced by 49% compared to 1990. As can be seen from the figure, a large part is achieved by reducing the N_2O emissions from nitric acid production. As these emissions are currently already reduced by more than 90%, this will require no further effort up to 2030. One of the main options to reduce the emissions is to produce heat in bio-based boilers. This will require 70 PJ of biomass in 2030. Further emission reduction up to 2030 is obtained from improving the energy efficiency and mechanical recycling. The figure also show that end-of-life emissions will hardly decrease in this pathway up to 2030. This means that to achieve the 80-95% target for 2050, considerable efforts are needed after 2030. This will be achieved by closing the

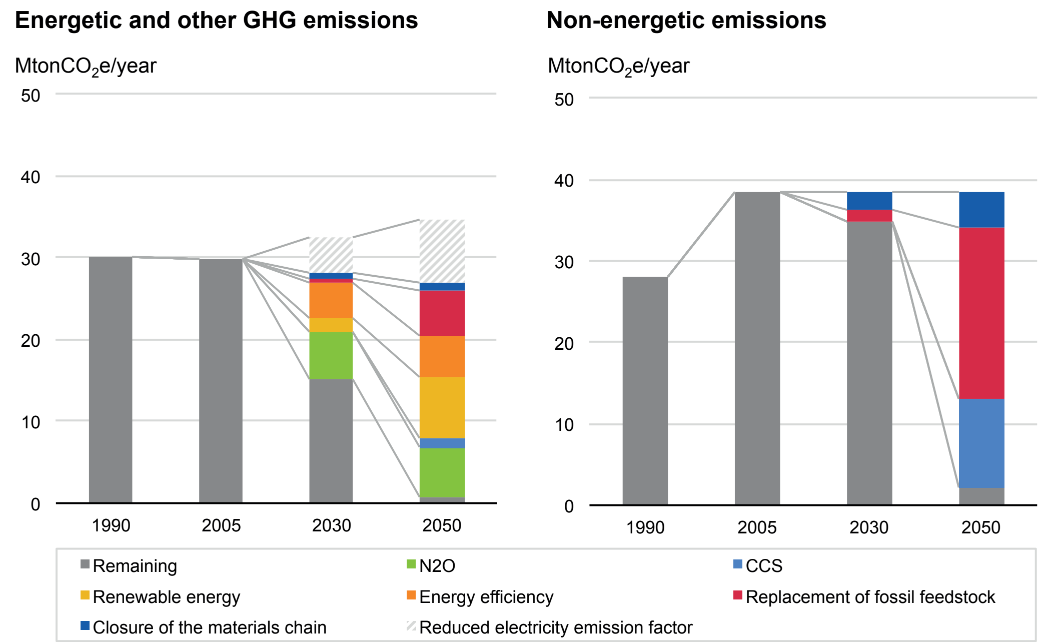

Figure 4-1 Potential for emission reduction by 2030 and 2050 in combination pathway aimed at compliance with the 2030 governmental aim to reduce process and energy emissions by 49% in 2030.

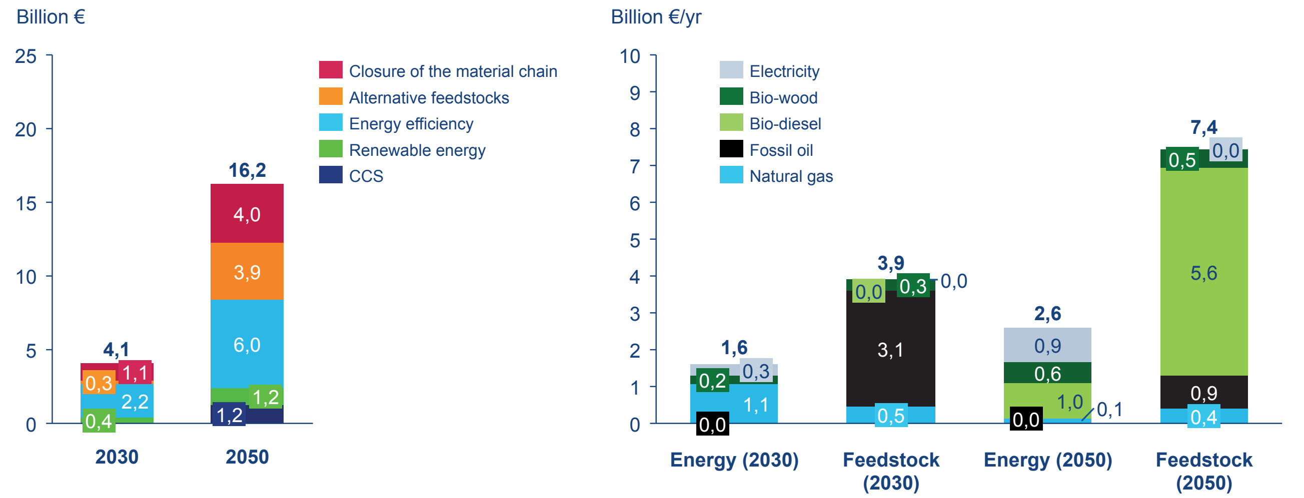

Figure 4-2 Projected investment costs (left, in billion Euro) and energy and feedstock costs (right, in billion Euro/year) in the chemical sector up to 2030 and 2050 for the combination pathway to illustrate optimized costs. Energy and feedstock costs are calculated with 2017 prices. All costs are relative to the current situation.

10) Solely considering offshore wind, with 4500 full load hours for hydrogen / electrolysis windfarms and 3500 full load hours for remaining wind farms (see Annex 3 for more details).

11) In this pathway, 14 Mton of CO_2 is actually captured and stored. The lower abatement figure includes emissions from the capturing process.

material loop with both mechanical and chemical recycling. Functional biobased materials will be implemented to the full potential in this pathway. Further reduction of feedstock related emissions will be achieved by making bio-diesel and producing plastics. It is assumed that these plastics will be recycled multiple times and ultimately incinerated in a waste incinerator with CCS. CCU for chemicals where the functionality can be delivered with a molecule structure resembling CO_2 is included, whilst for platform chemicals it is not, because of the high costs for hydrogen electrolysis. Heat will be produced in bio-boilers. CCS will be put on process emissions, energy related emissions and on waste incinerators. It should be noted that CCS on bio-fired boilers is not included, since this would only make sense at the larger installations. This could lead to a deeper reduction.

More details for the implementation of the various abatement measures in this pathway are given in chapter 4.3; we summarize the financial implications of this pathway below.

Figure 4-2 shows that the investments costs in the chemical industry are projected to be EUR 16.2 billion in 2050[12] (of which about EUR 1.1 billion is assumed to have already been invested in energy efficiency up to now). Total energy and feedstock costs of about EUR 10 billion per year are about 65% higher than the current costs (based on 2017 energy prices). In these projections, it needs to be taken into account that although feedstock costs are generally higher, the related measures also result in higher CO_2 emission reductions.

Figure 4-3 shows that the total investments needed outside the chemical industry of EUR 24,9 billion are dominated by the costs for putting CCS on waste incinerators, followed by offshore wind and bio-refining.

4.2.2 Plausible combination pathway 2: Direct action and high-value applications

In plausible combination pathway 2, the system was optimized to the highest value of using energy and feedstock resources, taking into account external constraints with regard to biomass use and availability, waste management policies, and storage capacity of CCS. The maximum amount of biomass is assumed to be limited to 140 PJ in 2030 and 280 PJ in 2050 [23][13]. In this pathway, biomass is first used for the highest value applications. Functional biobased materials will be implemented to the full potential is this pathway. The remainder of the biomass will be used for the production of BTX and bioplastics. Circularity is applied to its full potential, reflecting the full roll-out of the guidelines of the EU Waste Management Directive through all of the EU. CCU for chemicals where the functionality can be delivered with a molecule structure resembling CO_2 will be implemented to its full potential. Methanol, and part of C2/C3, are produced on the basis of hydrogen (in combination with CCU); the total electricity use in this pathway in 2050 is 170 PJ (corresponding to 11,4 GW off shore wind[14]). The rate of energy-efficiency improvement is set at 1% a year. Heat will be provided by geothermal sources as far as possible, with the remainder of the heat demand provided by electrical boilers. There will be no bio-based boilers in this pathway. CCS will be applied to the remainder of the energy use and to the waste incineration plants.

Figure 4-5 shows that the investments costs in this pathway are projected to be EUR 5 billion in 2030 and EUR 27.4 billion in 2050 (of which about EUR 1.3 billion is assumed to have already been invested in energy efficiency up to now). Total energy and feedstock costs are about EUR 9 billion per year, 10% lower than the first combination scenario. In the projections shown in Figure

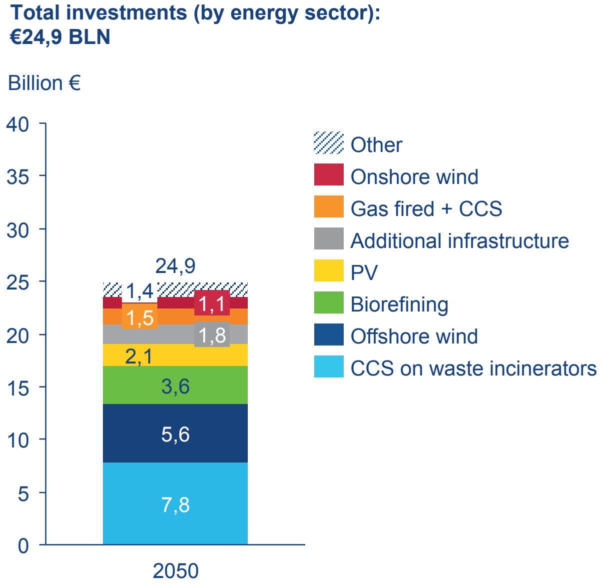

Figure 4-3 Investments costs for the energy system and CCS on waste incinerators

12) Note that all investment costs to be made in the chemical industry in this report are investment costs when the investment would be done now; innovation has the potential to reduce these costs.

13) To place this 280 PJ in perspective: If this 280 PJ would be bio-naphtha, and if this would all be used to make C2/C3 (ignoring the product slate and thus the production of other chemicals such as BTX, other side products and return streams), and including the fuel related energy, 280 PJ would be sufficient to produce 4½ Mtonne of C2/C3.

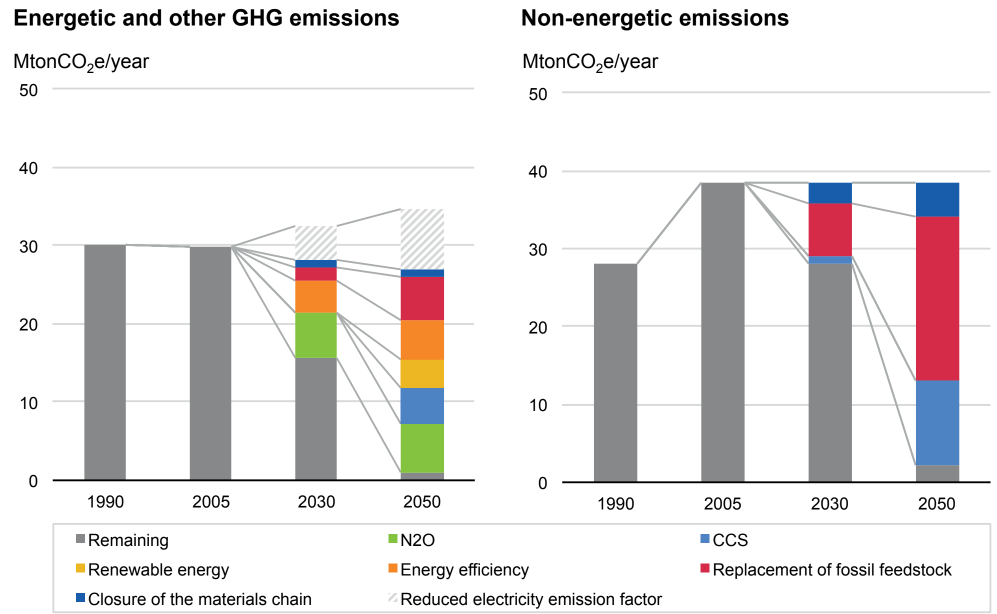

Figure 4-4 Potential for emission reduction by 2030 and 2050 in combination pathway to illustrate a high-value approach in a constrained world.

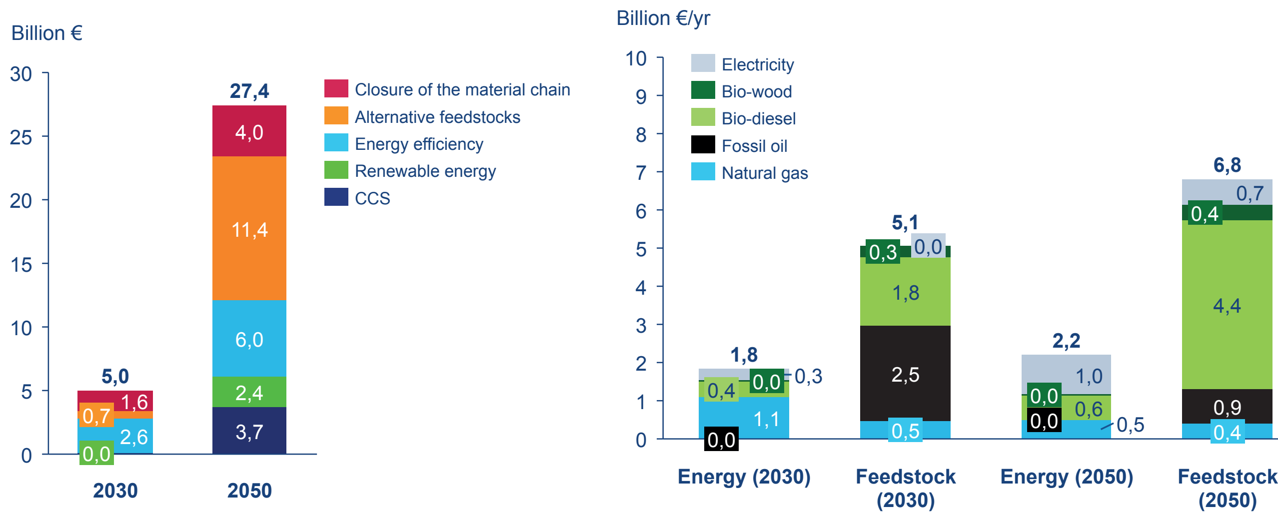

Figure 4-5 Projected investment costs (left, in billion Euro) and energy and feedstock costs (right, in billion Euro/year) in the chemical sector up to 2030 and 2050 for the combination pathway taking into account external constraints. Energy and feedstock costs are calculated with 2017 prices. All costs are relative to the current situation.

14) Assuming 4500 full load hours for hydrogen / electrolysis windfarms and 3500 full load hours for remaining wind farms (see Annex 3 for more details)

4-5, it needs to be taken into account that although feedstock costs are generally higher, the related measures also result in higher CO_2 emission reductions.

More details for the implementation of the various abatement measures in this pathway are given in chapter 4.3; below, we summarize the financial implications of this pathway.

From Figure 4-6 it can be seen that the system costs for this pathway are significantly higher than for the first combination pathway, mainly because of the higher costs for off-shore wind.

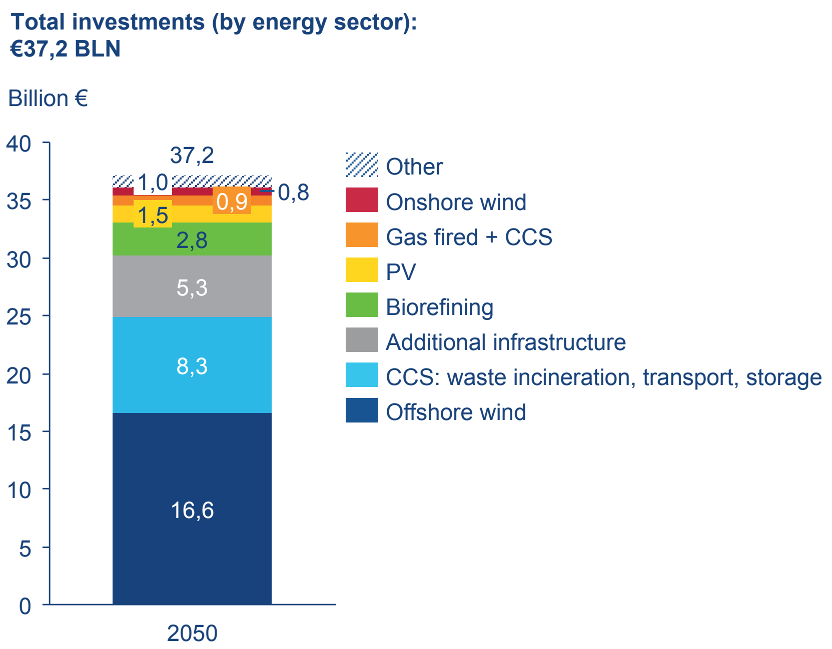

Figure 4-6 Total system costs for combination scenario 2 ("direct action high-value applications").

4.3 Discussion on the two plausible pathways

The two plausible pathways are compared in the figure below.

Table 41 gives an overview of the target achievement in both plausible pathways. In both pathways the 49% reduction of other GHG and energy related emissions can be achieved by 2030. However, whereas the end-of-life related emissions will increase by 25% in the "2030 compliance at least costs" pathway, these emissions will remain almost equal in the "direct action and high-value applications" pathway, implying a significant decrease of these since 2005. The overall emissions reduction in pathway 2 is 25%, more than 10% higher than in the "2030 compliance at least costs" pathway 1, due to the actions that are already taken to reduce the end-of-life emissions.

The table also illustrates that both pathways show ways forward to reduce the overall emissions by 95% in 2050. However, as is shown in Table 42, the investment costs in the chemical industry of EUR 27 billion[15)] up to 2050 are considerably higher in the "direct action and high-value applications" pathway than in the "2030 compliance at least costs" pathway. If the investments to be made outside the chemical industry are also considered – in the energy system and for CCS on waste incinerators – this difference increases further. The main reason for this difference is the higher demand for electricity for electrolysis to produce hydrogen.

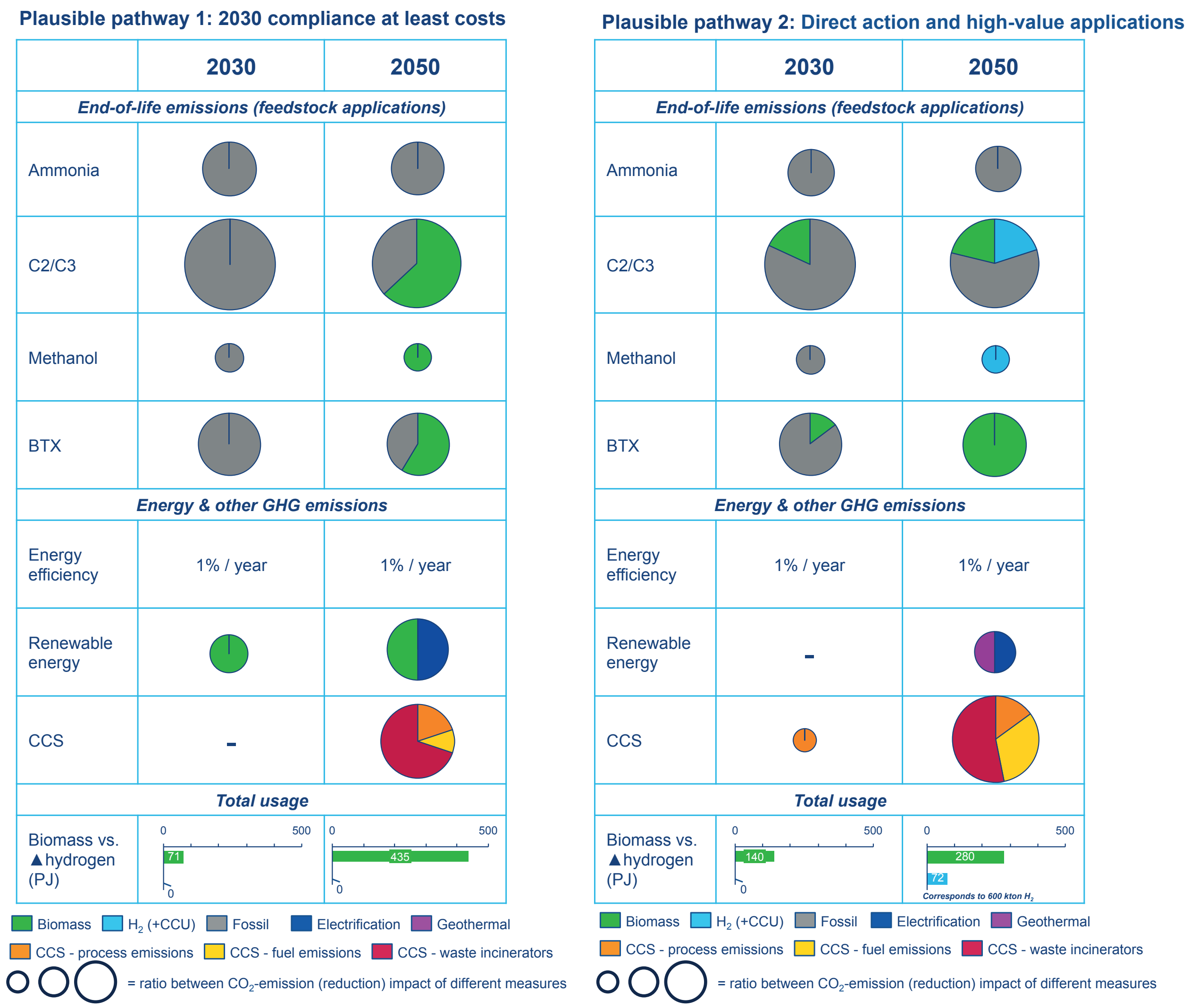

Figure 4-7 Comparison between the two plausible pathways

15) Minus EUR 1.3 billion as these investments in energy efficiency are assumed to have already been made.

Table 4-1 Summary of target achievement per pathway compared to the 1990 emissions.

	Energy and other GHG emissions		End-of-life emissions		All emissions	
	2030	2050	2030	2050	2030	2050
Plausible pathway #1 "2030 compliance at least costs"	-49%	-97%	+25%	-93%	-14%	-95%
Plausible pathway #2 "direct action and high-value applications"	-49 %	-97%	+1%	-93%	-25%	-95%

Table 4-2 Investment costs[16] up to 2050 per pathway

	Investment cost up to 2050 (billion EUR)	
	In the chemical industry	Outside chemical industry
Plausible pathway #1 "2030 compliance at least costs"	16	25
Plausible pathway #2 "direct action and high-value applications"	27	37

Table 4-3 shows that the energy and feedstock costs are in pathway 2 slightly lower than in pathway 1, but still 50% higher than the current costs.

Table 4-3 Annual fuel and feedstock costs (at 2017 prices)

	Energy and feedstock costs (2050)
Plausible pathway #1 "2030 compliance at least costs"	10
Plausible pathway #2 "direct action and high-value applications"	9

Note that emission reductions due to application of CCS on waste incinerations could partly be implemented abroad, but are included in the numbers above.

16) Note that all investment costs to be made in the chemical industry in this report are investment costs when the investment would be done now; innovation has the potential to reduce these costs.

Comparing the two plausible pathways, the "high value direct action pathway" requires earlier and higher investments (in the chemical industry and in the energy sector) with lower energy and feedstock costs than the "2030 compliance at least costs pathway". While in 2030 costs for the "2030 compliance at least costs pathway" are lower, in 2050 the average abatement costs per tonne of CO_2 avoided are in the same order of magnitude (130-140 EURO/tonne CO_2). As illustrated above, the differences between the two pathways in 2050 are relatively limited. Nevertheless, there are several reasons why the seemingly more expensive "high value direct action pathway" is preferable:

- The "high value direct action pathway" takes (limits to) the global development of **availability** of sustainable biomass and renewable electricity as well as the position of the chemical industry in broader society into account. For instance:
  - It assumes availability of a more feasible amount of sustainable biomass than the "2030 compliance at least costs pathway" and better positions the chemical industry in the event that other sectors would demand more biomass (leading to shortages and driving up price);
  - It develops bio-based routes as well as hydrogen-based routes and thus opens up a broader basis for future feedstock availability;
- The "high value direct action pathway" puts more emphasis on the feedstock transition towards 2030, tackling the most difficult transition **in an earlier stage**. This increases the likeliness of in-time delivery in 2050, strengthens the Dutch innovation position, and supports best routes to be established earlier:
  - This potentially avoids stranded assets such as energy efficiency investments in plant that is replaced by these new routes;
  - As production is often established at the location where innovation takes place, it strengthens the attractiveness of the Netherlands as production location for a sustainable chemical industry [32].
  - The earlier focus on innovation leads to accelerated cost reductions (refer to Figure 61), and thus has a bigger potential to drive down the costs projected in this roadmap;
  - This increases the likeliness to deliver on the targets in 2050;
  - This enables export of the developed technologies;
- The "high value direct action pathway" more explicitly **follows the developments in the energy transition**; focusing on the increased usage of hydrogen. As more offshore wind is expected, the chemical industry could benefit from these investments (lower "fuel" costs expected) while playing a role in balancing supply / demand. At the same time, this pathway contributes to risk reductions in terms of competitiveness, as the industry is less dependent on global commodity markets (for biomass) and hydrogen is a more resilient carrier (i.e. it can be produced in different ways - following either electricity or gas markets).

The "2030 compliance at least costs pathway" illustrates that there is a **benefit in maximizing the availability of sustainable biomass**. The Dutch chemical industry has a distinct interest in actively contributing, globally, to increasing the availability of sustainable biomass. It could further reduce overall (system) costs. While this increase is already required for the "high value direct action pathway", any further increase would be beneficial.

The analyses in this chapter is based on technical and economic assessments of opportunities. The transformation required will not be easy and requires, amongst others, the concerted actions of many stakeholders, a global level playing field, focussed innovation, significant investments in infrastructure and leadership by politicians and business leaders. Chapter 6 describes first steps that can be taken to initiate the transformation. Yet, before going into detail on the necessary steps to facilitate the transition in the chemical industry, it is worthwhile to consider how the chemical industry can be a transition facilitator itself, for other sectors. Therefore, chapter 5 describes how the chemical industry enables low emission solutions, shaping a broad overview of the role of the chemical industry in society.

5 The chemical industry as solution provider

Apart from the transition opportunities in its own sector as defined in previous chapters, the chemical industry has the opportunity to contribute to emission reductions in other sectors. After all, chemical products are used in a large diversity of applications that enable value chain partners to generate added value. Moreover, chemical products provide solutions to help value chain partners to lower their GHG-emissions. An economy that focusses on low GHG emissions will introduce new ways to operate processes and will require new products and new business models. The chemical industry can provide these solutions, by using its innovative power and collaborating even more with value chain partners. The impact of these solutions to avoid emissions can already be found in many end-use applications. In this way, the chemical industry contributes to a stronger economy and reduced emissions, both in and outside the chemical sector.

5.1 Introduction

The products of the chemical industry are used by many other economic sectors, both producing intermediate products and end-use applications. Thus, apart from realizing emission reductions in its own sector (as the previous chapters present), chemical products help reduce emissions and contribute to a higher level of sustainability in other parts of the economy. Furthermore, these sectors can create added value, amongst others, by using chemical products. For instance, the agricultural sector has a higher productivity because of the use of fertilizers and pesticides. Another example can be found in the automotive industry, which uses plastics to produce a whole range of different components.

This chapter introduces the chemical industry as solution provider for other sectors in our economy. In doing so, a qualitative exploration of the solutions chemical products can offer will be given. We follow a categorisation of end-use applications as detailed in the Energieagenda [2] to structure transition pathways towards a low-carbon energy supply system in the Netherlands by 2030 and 2050. The approach taken is based on the development of these transition pathways for four functionalities (power and lighting, transport and mobility, high-temperature heat and low-temperature heat). Additional to these

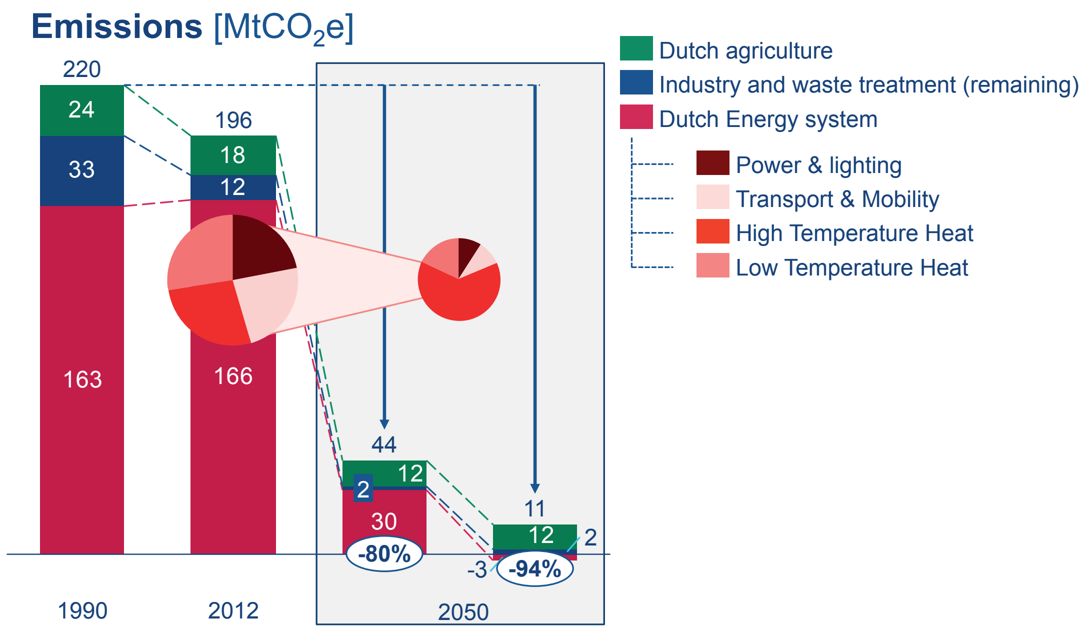

Figure 5-1 Projected development of greenhouse gas emissions in the Netherlands [2] [33] [34]

four functionalities, the agrifood sector is considered as it is an important economic sector in the Netherlands, closely linked to the chemical sector and the products are distributed all over society. This sector is also relevant due to the considerable contribution to non-CO_2 greenhouse gas emissions, notably methane. Finally, the chemical industry can contribute to lower non-CO_2 greenhouse gas emissions in other sectors, e.g. CFCs as cooling agents.Figure 5-2 shows what the emission reduction challenge looks like for the four functionalities. It also shows the challenge for the agricultural sector and the remaining industry and waste sector, based on supporting analyses from RLI [33] and Quintel [34]. By taking these six sectors into account we are also aligned with the EU Low Carbon Roadmap [35], which sets out how these sectors could contribute to an 80% emission reduction by 2050, as illustrated in Figure 5-3. The functionalities can be directly linked to the end-use sectors distinguished by the EU:

- Agrifood – Non-CO_2
- Transport and mobility – Transport sector
- Power and lighting – Power sector
- High-temperature heat - Industry
- Low-temperature heat – Residential and tertiary sector
- Other sectors – Non-CO_2

Following the same categorisation, we will identify key decarbonisation levers and highlight the roles the chemical industry can assume to enable these levers.

5.2 Identifying avoided emissions throughout the value chain

The added value per unit of GHG emissions in sectors downstream of the value chains is typically significantly higher than in the chemical sector. In other words, other sectors benefit from the material production, and hence emission generation, by the chemical industry. There is high value creation downstream whereas the highest emissions occur upstream.

Emissions that occur upstream or downstream in the value chain of chemical products are out of scope in this roadmap, except for the emissions that occur at the end-of-life phase. However, since products of the chemical industry are used in many other sectors, they can contribute to the transition towards a society with low GHG emissions.

Since avoided emissions can be achieved throughout the whole value chain, all life cycle stages should be addressed, including extraction, production, use and disposal. Unfortunately, this can substantially increase the complexity of calculating the avoided emissions. The calculation can be simplified by comparing the solution to a reference case and omitting all life cycle stages that are equal. Still, quantifying avoided emissions remains difficult. The following issues should be well considered:

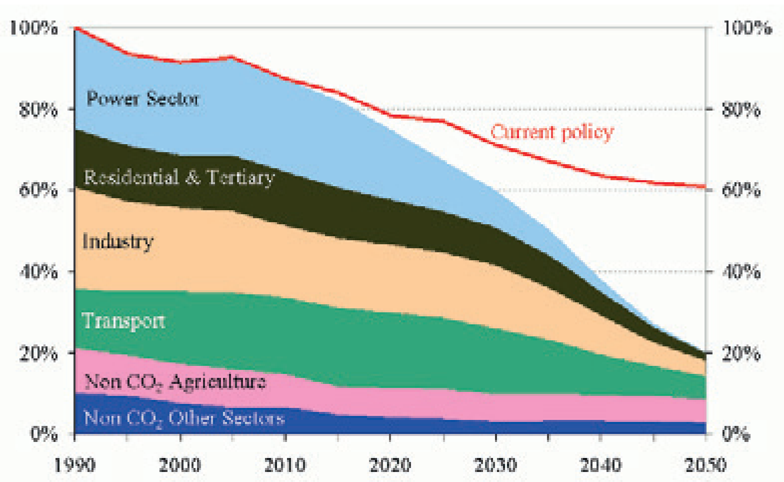

Figure 5-2 EU GHG emissions towards an 80% domestic reduction (100% =1990) [35]

- The avoided emissions of a solution with chemical products are compared with a baseline. Usually, this is either a specific alternative or the market average of technologies. Defining a baseline in the absence of the use of the chemical product is not always straightforward.
- Avoided emissions can be calculated for a certain year or for the lifetime of the end-use application. For applications with longer life spans, calculating the future avoided emissions comes with additional complications, since the baseline can change over time. For instance, the emission factor of space heating or electricity production can change.
- Finally, it is important to note that the avoided emissions occur throughout the whole value chain and cannot be attributed to a single actor in that value chain. Avoided emissions are often achieved by the joint action of various actors across the value chain. There is no consensus yet on how to allocate these savings between the various actors.

Since 2009, the International Council of Chemical Associations (ICCA) has published several studies that aim to quantify the impact of emission reduction enabled by the chemical industry in a fact-based and transparent way. The most recent study, published in 2017, analyses the emission reduction of six representative solutions: wind and solar power, efficient building envelopes, efficient lighting, electric cars, fuel efficient tyres and lightweight materials [36]. These solutions improve energy efficiency or contribute to an increase of renewable energy supply. The solutions represent an important share of the emission reductions enabled by contributions from the chemical industry, but there are more solutions in other sectors as well. While the chemical industry contributes extensively to these solutions, their contribution occurs alongside those from other enabling parties in the value chain.

The study found that the selected solutions can achieve a reduction of 2.5 $GtCO_2e$ globally in 2030, in a 2°C mitigation scenario compared to a reference scenario. According to this study, the largest contribution comes from wind and solar power, as is shown in Figure 5.2. The chemical industry contributes to the deployment of renewables through the supply of key materials for wind turbines and solar PV panels, including gear oils for wind turbine gearboxes, resins for blades and coating materials for wind turbines, and silicon ingots, semiconductor gas and sealant for PV panels. The share of the Dutch chemical industry in this global market cannot easily be determined due to the large trade flows of chemical products. However, if we take the share in world sales of chemical products of 2% as a proxy [4], the potential for avoided emissions, in which the products of the Dutch chemical industry play a role, can be roughly estimated at 50 $MtCO_2$ per year in 2030.

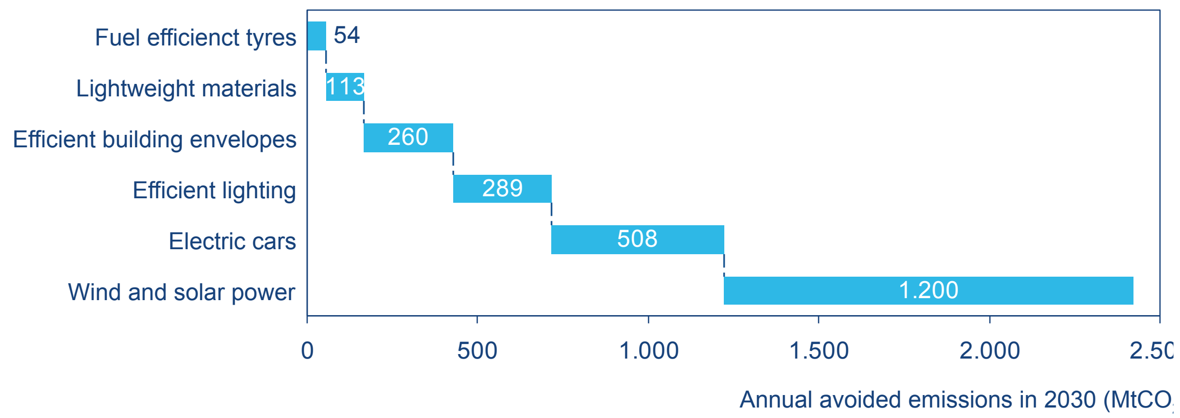

Figure 5-3 Contribution of the solutions for GHG emissions reductions in 2030 in a 2 degrees Celsius mitigation scenario, as compared to a reference scenario [36]

5.3 Decarbonisation levers and the role of the chemical industry

Based on expert consultation and literature research, the main decarbonisation levers have been identified per end-use category and the role the chemical industry can play to enable these levers. Note that this overview is merely an illustration of the solutions that the chemical industry can provide to other sectors to abate greenhouse gas emissions. Far more options can be thought off and are described in the extensive literature on this subject.

Before going into detail, it is important to note that macroeconomic and geostrategic forces will play a role in shaping the future of all functionalities. Therefore, it is helpful to understand how these so-called megatrends will change the functionalities, as this might lead us to solutions that the chemical industry can provide in the future. There are many categorisations of megatrends, all overlapping to a large extent. Table 5-1 gives an overview of the megatrends considered relevant for this Roadmap.

Table 5-1 Megatrends that will shape the future

Megatrend	What we will see
Urbanization	Increased numbers of urban dwellers, living in larger cities. Improved building efficiency, reduced personal transport needs, concentrated freight movements, urban farming.
Aging population	Healthy aging, longer and more active retirements, increased healthcare.
Increased prosperity	Increased affluence increases product demand and changes diets (proteins replace carbohydrates).
Digitization	Internet of Things, 3D printing. Data replacing materials. Efficiency, smart maintenance, autonomous vehicles, blockchain.
Collaborative innovation	Disruptions from traditionally unrelated sectors, product-as-a-service, consumer empowerment
The rise of renewables	Cheap low-carbon electricity, cheap storage, need for grid balance
New materials	Self-healing & smart materials; graphene, recyclable thermosetting polymers, etcetera

5.3.1 Agrifood sector

Agriculture and food processing are vital and important economic sectors in the Netherlands, which is second largest exporter of agricultural products in the world [37]. Furthermore, the Netherlands is listed as the number 1 country in the world for quality, affordability and supply of food in the world [38]. This category of emissions is limited to only agricultural activities: growing crops, raising livestock and cultivating land.

The main megatrends underpinning developments in the agrifood sector are shown below.

Megatrend	Implication for this sector
Urbanization	Urbanisation in combination with a renewed focus on self-sufficiency in dense urban areas (as for instance already seen in Singapore) results in increasingly advanced urban farming like hydroponics. However, rapid urbanisation is also seen to result in urban sprawl, leading to inefficient use of land and increased competition with agriculture.
Aging population	Aging population and, in general, a growing population will result in a larger resources footprint for food production; increased demand for energy, land and water. Competition with resource needs of a foreseen uptake of energy crops is something that will need careful attention
Increased prosperity	Proteins will replace carbohydrates in diets [39].

DSM – Clean Cow Project

4% of global GHG emissions are methane emitted by dairy cows. DSM developed a feed additive to supplement the cows' daily feed that aims to reduce these emissions by over 25% [85].

Table 5-2 Illustrative examples of decarbonisation levers in agriculture, and possible contributions of the chemical industry to provide solutions.

Decarbonisation levers	Contribution of chemical industry to the solution
Reducing (the impact of) meat consumption	
Changing diets is a potent decarbonization lever, yet hard to influence. Moving away from animal protein reduces GHG emissions across the value chain due to a reduction in land-use and methane emissions; e.g. red meat has a 15 times higher footprint than tofu [40]. For these and other reasons, the share of people with a vegetarian or vegan diet is on the rise in developed countries. This is however more than offset by the increased share of meat in diets across the developing world, which means technical measures to reduce impact of meat production are needed.	**Novelty feed** production can reduce manure production (less N_2O), methane emissions from ruminants, partially replace other feed (and thereby, land-use) [41]. **Advanced fertilizers** can make food production more efficient by enhancing crop yield. Synthesis of (vegetarian) **meat replacements** can reduce the demand for meat.
Reducing food waste	
One third of all produced food in the world is wasted somewhere along the value chain. Therefore, reducing food waste is a key tool to reduce emission intensity of food. From failed harvests due to disease to throwing away spoiled food by consumers, all steps along the food value chain still have promising waste reduction potential. Food waste in retail accounts for 7% of all food waste in the Netherlands [42]. The average Dutch person throws away 50 kg of perfectly good food every year.	**Smart packaging** can reduce food spoilage and therefore reduces the emission intensity of foods. Denkstatt estimates that the typical reduction of CO_2 emission of packaging is 5 times the extra CO_2 emission caused by the production of the packaging [43]. However, it also noted that not all applications are advantageous, so tailored approach needed, as well as focus on optimization.
Efficient use of fertilizer	
Targeted fertilizing may reduce the overall use of fertilizer and associated GHG emissions. Automated drip systems and even drone-based fertilizer distribution systems increase crop yield while reducing fertilizer use. Moving towards hydroponics for selected crops also results in better monitored and balanced fertilizer use, and could improve yield per square meter compared to conventional agriculture.	The chemical sector already **moves more downstream** in the value chain towards fertilizer application. This way, the sector may **aid more efficient use of fertilizer**, eliminating waste and reducing emissions of production while increasing value added per functional unit of fertilizer [44]

5.3.2 Transport and mobility

A national vision on a sustainable fuel mix for transport has been developed by over 100 organisations in 2014 [45], as a result of the Energieakkoord [46], stating that in 2030 some 25 Mton of emissions will be reduced compared to 1990 (-17%). These parties embrace the 60% emissions reductions in 2050, in line with the EU-wide ambition [2]. This will in part be realised by ensuring only 'zero-emission' personal vehicles will be sold in 2035, and in 2050 all personal vehicles on the road will need to be. This is expected to be achieved for a large part through electrification. For long-haul transport and shipping, a mix of sustainable fuels will need to be developed, including biofuels and synthetic (P2X) fuels.

The main megatrends underpinning the developments in transport and mobility are:

Megatrend	Implication for this sector
Urbanization	Urbanisation can bring substantial support to decarbonising mobility, depending what shape it takes. In dense urban areas like Singapore, reduced distances and availability of high quality infrastructure enables inhabitants to greatly reduce transport energy needs. In a great urban sprawl like Houston, TX, these benefits are harder to come by and may actually increase energy demand in mobility.
Digitization	Digitization of mobility may revolutionise personal transport. Autonomous driving and car-sharing have the potential to deliver great efficiency gains. In Heavy Road transport, these developments enable platooning to enhance aerodynamics as well as smart logistics solutions like synchromodality, enabling efficient use of different modalities in supply chains [47].

Polymer electrolyte fuel cells (PEFC)

Fuel cells will be essential for the efficient use of hydrogen in transport. PEFCs are able to operate at lower temperatures and are smaller and lighter than other fuel cells. Breakthroughs in the production process of PEFCs can make fuel cell electric vehicles cost competitive with combustion engine vehicles. This increases the introduction rate of fuel cell cars on the market [7].

Table 5-3 Illustrative examples of decarbonisation levers in transport and mobility and possible contributions of the chemical industry to provide solutions.

Decarbonisation levers	Contribution of chemical sector
Fuel efficiency	
In the short and medium term, incremental vehicle and logistics improvements are needed to further reduce emissions [48]. For road transport, this includes lower rolling resistance, weight reduction and improved aerodynamics. In the freight sector, logistic improvements and improved routing are required. In aviation, up to 2.5% annual reduction of energy use per passenger km is needed between 2015 and 2060, for shipping this is 2.8% per tkm [48]. Autonomous and connected vehicles as well as car sharing can bring further efficiency improvements.	Carbon fiber and other light-weight material solutions can help to reduce weight in vehicles, trains and aircraft and thereby increase fuel efficiency. Fuel efficient tires can lead to a reduction of GHG emissions of 2.5% (passenger cars) – 5% (trucks). Novel coatings are developed that can be applied to shipping to help reduce drag in the water. The use of lightweight materials in cars leads to an emission reduction of an additional 2% emission reduction.
Sustainable fuels	
Different modalities will see different penetrations of alternative low or zero-carbon fuels; notably biofuels, hydrogen and synthetic fuels from Power-to-X for long-haul road freight and aviation. Short distance passenger transport and urban goods distribution are likely to be dominated by electricity-power vehicles (EVs), see below.	The sector may start to produce synthetic (P2X) fuels. The transition towards a (partially) bio-based feedstock for the sector will require more bio-refining capacity, therefore co-enabling the refining of bio-based fuels as required in the transport sector.
Electrification	
Electrification of short-distance vehicles is quickly gaining momentum. This includes road (passenger) transport as well as rail transport. In the short term, (plugin) hybrid electric vehicles ((P)HEVs) support reducing emissions from transport. All electric vehicles will become mainstream.	The chemical industry is vital in producing batteries needed for electric transport as well as in the necessary battery cost reductions needed to ensure mass deployment. In a global 2030 scenario assuming 16% e-car penetration, emission savings are 10% (this number takes the production costs, and the assumed remaining emission intensity of electricity into consideration).
Modality shift	
Measures to either shift or avoid transport entirely may result in over 25% passenger activity reduction for cars by 2060 [48], especially in urban environments where alternatives emerge soonest; public, collective transportation and non-motorised transport. High speed rail may replace short-haul flights.	N/A

5.3.3 Residential and Tertiary sector - low temperature heat

Energy use for low temperature heat (space heating and tap water) takes place in the built environment, horticulture and to a limited extend in industry. It accounts for roughly 30% of the total energy use in the Netherlands. Over 90% of this demand is currently met through the use of natural gas. The Energieakkoord aims to lower heat demand through renovation and insulation of the built environment by 2030. To decarbonise the remaining energy demand, bespoke solutions will need to be developed for different environments; district heating in dense urban areas, with supply though geothermal or industrial waste heat. Green gas can help decarbonise energy use in more remote locations and electrification of heat demand through heat pumps and electric boilers connected through smart grids have a large role to play.

The megatrends underpinning the developments for the functionality low-temperature heat are:

Megatrend	Implication for this sector
Urbanization	With urbanisation, low temperature heat demand per capita will drop as more people will move from freestanding, relatively poor isolated buildings to apartments with a better energy label. With this trend to more densely populated residential areas, access to district heating as well as capital-intensive solutions such as geothermal or aquifer thermal energy storage are more likely to materialize as well.
Rise of renewables	The Rise of Renewables has the potential to unlock vast low-carbon electricity generation potential, leading to a larger uptake of electrification of low heat demand. In combination with smart grid systems this could completely transform the way we heat our homes. A too large dependence on electricity could be dangerous during cold spells where the efficiency of heat pumps drops dramatically – an effect that could be partially mitigated by deploying domestic thermochemical storage [38].

Table 5-4 Illustrative examples of decarbonisation levers in the supply of low-temperature heat and possible contributions of the chemical industry to provide solutions

Decarbonisation levers	Contribution of chemical sector
Insulation	
Reducing heat demand in the built environment is one of the largest energy saving measures in (beyond) 2-degree scenarios of IEA [48]. Insulation of buildings is an important lever to reduce both heating and cooling demand.	Provide **Insulation material** such as cavity wall, floor and roof insulation. Develop innovative insulation material based on **phase change materials**. In the Netherlands buildings are already well insulated, but further insulation would, together with efficient installations and ventilation, save yet another 13% of the emissions for the heating of buildings by 2030 globally.
Electrification	
Heat pumps to supply in heating of buildings with efficiencies up to 250-400% are seen as an option to reduce emissions, especially when the emission factor of electricity decreases. In combination with thermochemical heat storage materials, and integrated domestic heating and cooling system could be envisaged.	The chemical industry provides **working fluids** (HCFS, PFC etc), **components** as well as **thermochemical heat storage materials** (TCMs) like hydrated sulphates, zeolites or silica gels [49].
Sustainable heat supply	
Alternative sources for low temperature heat will further decarbonise demand. Green gas, geothermal heat, electricity, hydrogen as well as district heating could all play a role, depending on cost and availability.	Developing innovative working mediums to extent the temperature range of **heat pumps** and **organic rankine cycles**. Next to developing new products, chemical industries provide **excess low temperature** heat to district heating systems. Especially horticulture in the Netherlands is partly located near industry and has large demand, currently mostly met with CHP or gas boilers. Use **polymer pipes** that require less pumping energy and have better insulation properties than steel pipes.

5.3.4 Industry - high temperature heat

High temperature heat is mainly used in the industrial sector. The Netherlands has a relatively large and strong, energy efficient industrial sector, including refineries, basic metals industries, paper and board production, food and agricultural products and the chemical industry.

The chemical industry itself is a significant off-taker of high temperature heat. Pathways to lower the emissions associated with the use of heat in the chemical industry are described in Chapter 4. In this section, we highlight how the chemical industry can help to reduce the demand in other sectors as well as their own demand.

Reduction and upcycling of waste heat can be supported by further industrial clustering. For the remaining energy demand, the Energieagenda [2] highlights the importance of deep geothermal heat as well as of CCS.

mTA-salt

AkzoNobel developed an additive for salt, mesoTartaat (mTA), that prevents salt of clotting. It is claimed that producers of chlorine using membrane cells can save 5% or more on their energy use when using mTA-salt [73]

Megatrend	Implication for this sector
Collaborative innovation	Collaborative innovation may help to take away traditional industrial borders. Deep energy efficiency measures will demand high levels of industrial symbiosis and clustering to exchange material and energy flows.
Digitization	Digitization goes hand-in-hand with dematerialisation; materials replaced by bytes. This effect is and will be seen anywhere from autonomous shared electric vehicles reducing car ownership and therefore steel demand to Kodak film rolls being replaced by smartphones and Instagram. This shift will reduce bulk material demand and therefore industrial energy demand.

Table 5-5 Illustrative examples of decarbonisation levers in the supply of high-temperature heat and possible contributions of the chemical industry to provide solutions.

Decarbonisation levers	Contribution of chemical sector
Deep geothermal	
By drilling to depths of over 5 km, hot brine can be cycled and heat can be extracted for use in industrial processes.	N/A
CCS	
CCS is a critical decarbonisation levers for industry in (beyond) two-degree scenarios, both to decarbonise processes which intrinsically emit CO_2 (e.g.: producing hydrogen from natural gas) and as a low-cost decarbonisation option for other processes. Bio-energy CCS (BECCS) may result in negative emissions.	The main way the chemical industry can contribute is by cooperation with other sectors. By investing in common **infrastructure**, chemical industrial sites can co-enable low-cost CCS deployment. By using **bio-energy as feedstock** to build products that may end up in waste incinerators that have CCS technology, the industry may help enable negative emissions through BECCS. The development of **oxy-fuel** combustion by the sector is a cost-effective way to enable CCS prior to combustion.
Upcycling of waste heat	
Reducing and upcycling waste heat in industrial clusters will increase efficiency.	Developing innovative working mediums to extent the temperature range of **heat pumps** and **organic rankine cycles**. Continue material innovation for **heat exchangers** to operate at more aggressive environments (corrosive, acid and high temperatures).
Alternative fuels	
Alternative fuels (e.g.: renewable H_2 or biofuels) may help decarbonise heat demand. CCU in combination with renewable H_2 can partly replace fossil fuel demand.	The sector already shifts feedstock towards bio-based materials, which will help to supply **biofuels** to market as part of product cascading in their own crackers and through their increased bio-demand upstream of the sector. The sector can play an essential role in the application of **CCU**.

5.3.5 The electricity sector - power and lighting

Nearly all power and lighting in the Netherlands is powered by electricity. However, electrification of other functionalities will mean a rise in electricity demand by up to 7% between 2015 and 2030 according to the NEV2016. The Energieagenda focusses on decarbonization of the electricity supply by large-scale roll-out of renewable electricity technologies, notably wind and solar. The increased intermittency will require development of smart grids, energy storage solutions and demand-flexibility. CCS on power plants is also mentioned as an important decarbonization lever.

Increasing the energy efficiency of appliances is another lever to reduce greenhouse gas emissions from power generation. The EU's Ecodesign Directive is an effective tool to deliver energy savings. A correct implementation of the EU Ecodesign Directive would yield annual savings of up to 600 TWh of electricity in 2020, equivalent to 17% and. [50].

The main megatrends underpinning these developments are:

Megatrend	Implication for this sector
The rise of renewables	The Rise of Renewables carries with it intermittency and fluctuations from seasonal patterns and sunlight hours. Smart integration of renewables will require demand shifting; moving peak demand to times of renewable oversupply. Large industry can play an important role in stabilizing this renewable electricity grid.
Digitization	Digitization has created and will create a very large increase in demand of electricity. Data centers that enable internet surfing and cloud computing are tremendous energy throughs; US data centers consumed around 250 PJ in 2014, or 2% of the country's total energy demand. [10]

Anti-fouling coating for PV

DSM developed coating for PV-systems with anti-fouling and anti-reflective properties. This coating will enhance the performance of PV system in dry and desert-like climates. Already over 200 million PV modules, with a total capacity of more than 50 MW, are fitted with DSM coatings. Cumulative additional power generation is estimated at 4600 GWh. Next to this, the coatings reduce maintenance costs. [78]

Table 5-6 Illustrative examples of decarbonisation levers in the supply of power and lighting and possible contributions of the chemical industry to provide solutions.

Decarbonisation levers	Contribution of chemical sector
Energy efficiency	
Improving the energy efficiency of the end-use of electricity will reduce the demand for electricity, hence the associated emissions. This energy-efficiency improvement can be achieved in all sectors.	The chemical sector enables energy efficient technologies by co-developing and providing the **materials** to build them; LED for lighting, insulation in refrigerators, etc. LED's are now, globally, already 7 times more efficient than a traditional light bulb; with their projected efficiency improvement, this number is expected to increase to a factor 12 by 2030; for comparison, a fluorescent lamp is a factor 4 more efficient than a traditional light bulb.
Renewable Electricity	
Renewable electricity is the way to decarbonise energy demand in this category. Wind power, hydropower and Solar Photovoltaics and to a lesser extent tidal, geothermal and other technologies all will be deployed to provide renewable electricity.	The chemical sector enables and enhances some of these technologies by producing for example **novel light absorbing coatings for PV systems, coatings to reduce the frictions at wind blades or lubricants for wind turbines**. By increasing **flexibility** in chemical processes and integrating these into a smart grid, the sector can also play a role in demand shifting as required by renewables. This will reduce cost of the overall energy system.
Energy storage	
In the future, energy systems the availability of energy will not be the problem but the timing. Energy storage will be crucial to bring more flexibility to the system.	The chemical sector is driving the development of novel types of **batteries** with a higher power density and longer life time (see mobility). **Large-scale batteries** may be developed by the chemical industry that smoothen production peaks and troughs of renewable electricity (e.g. wind and solar) that stabilize electricity networks and reduce required capacity.

5.4 Conclusion

Chemical products have the ability to ensure emission reductions throughout the entire value chain, contributing to the decarbonisation in other parts of the economy. Examples include the efficient use of fertilizers in the agrifood sector, improvement of batteries for energy storage and electric vehicles and the use of insulation material for buildings. The potential for avoided emissions in which the products of the Dutch chemical industry play a role can be roughly estimated at 50 $MtCO_2$ per annum in 2030. Therefore, as well as looking at the transition towards a low emissions chemical industry, it is important to consider the role that the chemical industry plays in broader society.

6 The road to 2050: enabling factors

The previous chapters have shown that actions taken by the Dutch chemical industry, together with its value chain partners, will contribute to emissions reduction in both the chemical industry and almost all other sectors of the economy. The reduction is technically feasible, even with a 1% per annum grow of the added value of the chemical industry. However, the implementation of the options will not happen automatically. This chapter investigates factors required to enable the transition.

Adequate pricing and financing to create the right incentive

The Dutch chemical industry operates in a globally competitive environment. CO_2 prices around the world do not yet enable the entire transition. In the longer term, an effective global carbon price would be the preferred route towards a level playing field. The Dutch government has, in absence of an effective carbon price, already implemented several policy instruments to accelerate the energy transition. Examples include: broadening the "SDE+" approach to incorporate energy efficiency and feedstock measures, organizing greenhouse gas tenders to attract technology independent least-cost investments for GHG emission reduction, and differentiating consumer taxes based on the CO_2 footprint of the products.

The investments mentioned in chapter 4 relate to the sector (and in the energy system). When these investments are made by chemical companies, each company will make its decision based on the company specific business case, which can (and often will) be quite different from the sector average (see for example the text below Figure 36). The viability of the investment thus depends on:

- The company's financial situation, as investments in abatement levers compete with other investments,
- The resulting impact on production costs – also in comparison with production (and transport) cost abroad, and
- The local situation.

Investment decisions are generally made at the international headquarters. The chemical industry is therefore keen to discuss new financial structures with the government, e.g. via loan guarantees and innovative financing.

Another vehicle for financing is investments are made by energy companies to provide services to the (chemical) industry clients in their efforts reduce CO_2 emissions. For ESCO's (energy service companies), these services are core-business, unlike chemical industries, whose core-business is the chemical process. The services comprise delivering the operational outcome of the use of energy (heating, lighting, transportation and so on) rather than the energy itself. There are two reasons to consider an ESCO-approach: (1) ESCO can consider longer-pay back periods for energy investments, as these do not have to compete with other investments; (2) substantial investments in the energy sector are required to facilitate the transition within the (chemical) industry, as shown by our analysis, and energy companies are at the driver's seat of these investments. Examples for such an approach have already been encountered as a result of earlier projects such as "Power to Products" [26] and "Electrification in the process industry" [51], and are illustrated by recent ideas at energy utilities to install electrical or hybrid boilers in the industry. It is recommended to explore these ideas further in order to bridge some of the gap between technical and economical pay-back times, and secure the link between the transition processes in the energy sector and large chemical companies.

Accelerating innovation and implementation is essential

Innovation is not only directed at technological developments but also at cost optimization. In addition, the investment costs of new technologies typically come down with the scale of installation and the installed capacity. Figure 6-1 illustrates a development perspective: invest now in technologies with a lower TRL to bring the investment costs down. In the preceding chapters, investment costs for technologies in the chemical industry have been assessed at current prices. With an increasing price for carbon emissions, the break-even point may come sooner than without these investments. This is an argument to accelerate technology development and implementation before 2030, as is assumed in the plausible pathway 2.

To achieve the far-reaching reduction of greenhouse gases described in this Roadmap, coherent, wide-scale implementation of existing and innovative solutions is required. Not all abatement technologies are commercially available yet. The TRL varies from very low to commercial. Even with a high TRL, implementation of the technology cannot be assumed. Other factors, such as regulation, financing, social acceptance, thorough (process) safety studies for the exact design and political willingness come into play. Solely focusing on reducing emissions in the short term brings the risks of being too late with new technologies or a lock-in with old technologies, which can impede the implementation of new technologies. Since 2050 is just one investment cycle away for many chemical processes, such a lock-in situation is a serious risk. This is a reason for not delaying the abatement of end-of-life emissions, as is assumed in plausible pathway 1.

Figure 6-2 gives an illustration of when which technologies are expected to be available to contribute to target reduction at different points in time. This shows that a fast implementation can be possible for biomass

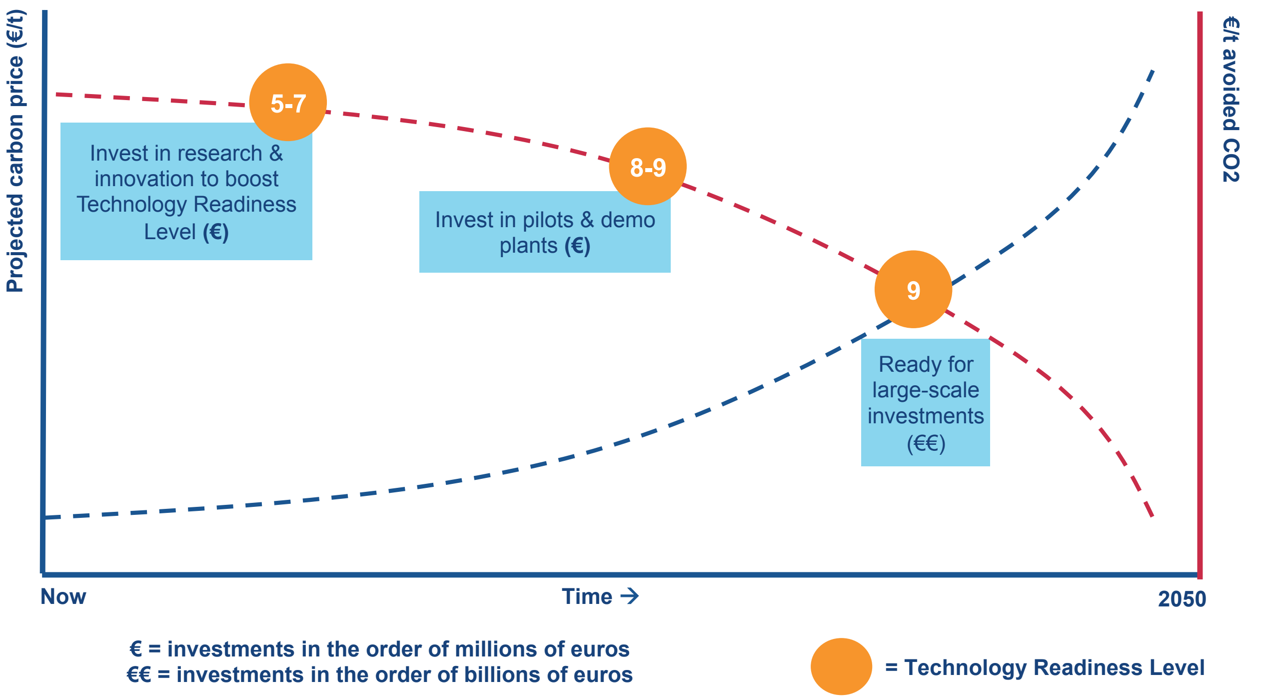

Figure 6-1 Development perspective: invest in pilot and demonstration phase while carbon price increases towards 2050

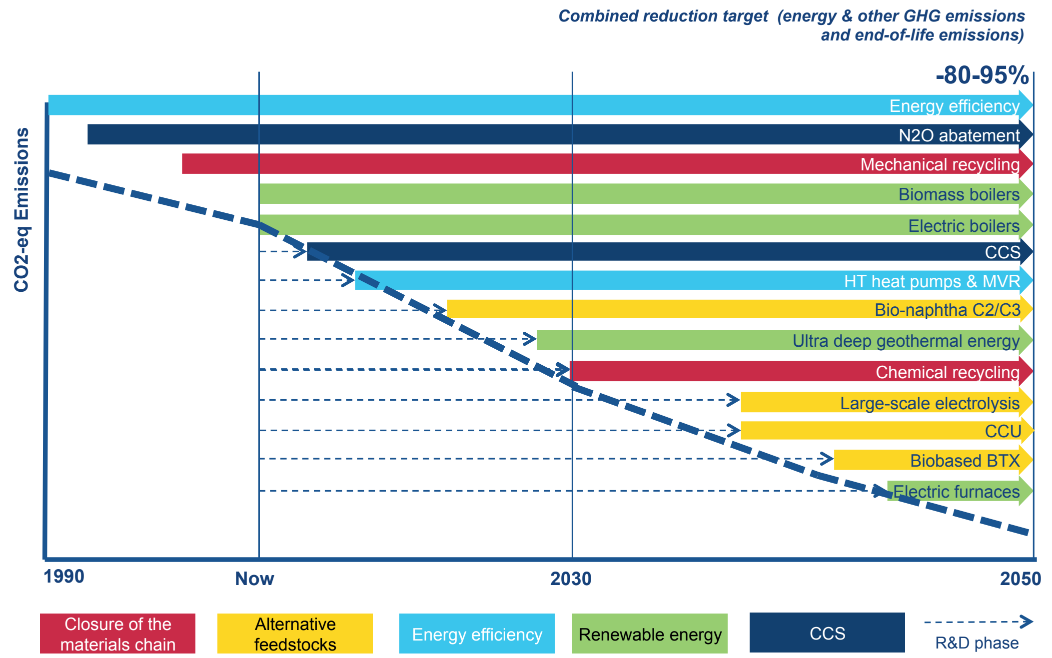

Figure 6-2 Expected availability of technologies towards 2050

boilers, electric boilers and CCS. Technologies such as high temperature heat pumps and geothermal energy require research and development, but can be available before 2030. This also accounts for biobased naphtha for C2/C3, and (to a lesser extent) for chemical recycling. Electrolysis, electric furnaces and biobased BTX are expected to require more innovation efforts before large scale implementation. Yet, for all of these technologies, research and development, as well as enabling factors, are required from now onwards, in order to reduce costs.

To be able to realise a deep emission reduction by 2050, it is essential that innovation and implementation is accelerated in the short term, with targeted programs that consider all these factors. These programs should be built on two pillars, which we will explain in more detail:

- Joint industry, government innovation and implementation programs to focus efforts, and
- Regional, long-term implementation programs to create strong partnerships.

1. Joint industry and government innovation and implementation programs

The chemical industry, together with the Dutch government and other partners, aims to develop innovation programs, referred to as mission-driven innovation programs in the Dutch Energy Agenda [2]. These programs are designed to strengthen innovation at a technological challenge and to arrange support on issues such as finance, training and education, research facilities, and regulatory constraints. The aim of these programs is to accelerate the development of technologies in a focussed program. Next to technology development, we see these innovation programs also as a means for implementing technologies that require non-technological innovations (i.e. regulations, logistics, infrastructure).

These innovation programmes should facilitate testing technology, economics and regulation. A dedicated geographical area to develop and test these innovations can accelerate these programmes. Figure 6.3 shows a range of innovation areas and technologies, which can be the focus of such programs. It also shows how technologies fit into these programs, based on our analysis of options in Chapter 4. It can be seen that by focusing on a specific innovation program, the related technologies gradually improve in TRL. Without such a focus, several key technologies would not be available in time to be able to contribute to emission reductions in the industry. Table 6-1 describes possible focus areas for each of the innovation areas that the chemical industry would like to work on. These include the following innovation programs, together with other stakeholders in the value chain, the energy sector, built environment, the transport sector and the waste management sector.

The final selection of the programs should be made in close cooperation with stakeholders and be aligned with existing and planned initiatives in the chemical and other sectors. The chemical industry can play a leading role in the set-up and roll out of these programs together with the Government, which can, for instance, give guarantees on financial and other support by committing on long-term arrangements.

Table 6-1 Suggestions for joint industry and government innovation programs

	Innovation area	Focus
1.	Recycling and circularity	Closing material loops by mechanical and chemical recycling, building up the logistic systems for recycling and investigating how value chains should be adapted with recycled materials.
2.	Biobased materials	Using biobased resources with the highest added value taking into a broad set of sustainability criteria. Focus areas can be the production of biodiesel / bio naphtha, understand the process and how costs can be reduced, and increasing the volumes of sustainable biomass.
3.	Efficiency and electrification	Production of hydrogen by electrolysis as building block for chemical product, combined with CCU. Understand the impact on existing value chains and build new value chains between the chemical industry and other sectors, like energy and steel. Increase process efficiency of chemical processes, e.g. by further process intensification.
4	Renewable heat	Heat generation using renewable electricity. Integration of electric boilers in current steam systems, and high-temperature heat pumps. Deep geothermal energy
5.	CCS	Building viable and reliable CCS infrastructure for transport and storage.

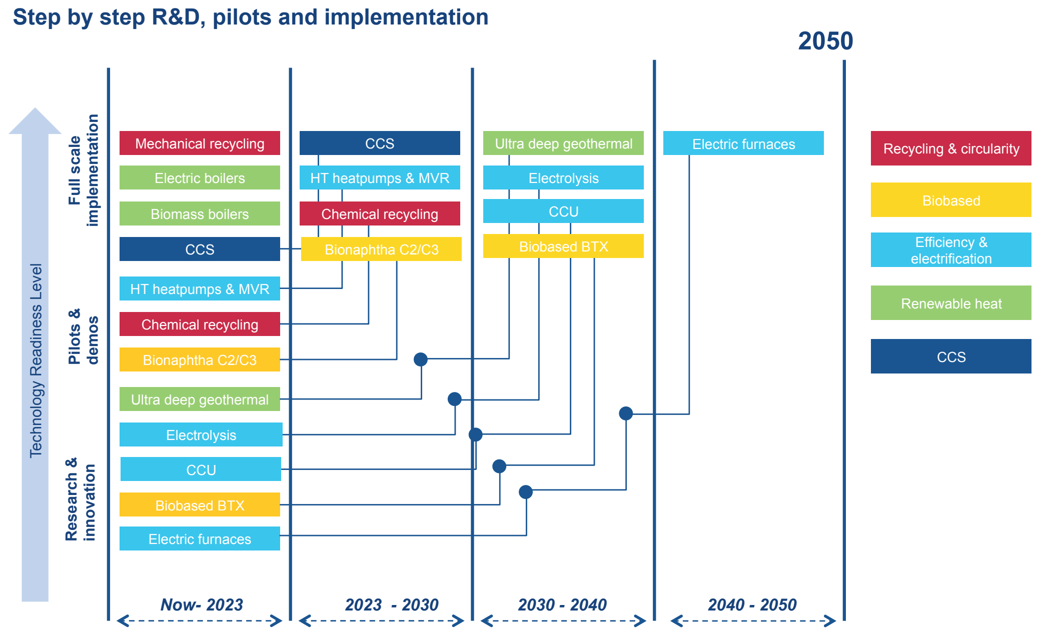

Figure 6-3 Step by step R&D, pilots and implementation, distributed over 5 suggested joint industry and government innovation programs.

2. Regional long-term implementation programs to create strong partnerships

The other pillar that the chemical industry uses to speed up implementation is regional long-term implementation programs. These programs involve reliable partnerships between individual chemical clusters, value chain partners, the power sector and the local and national government. All chemical clusters already have programs in place or under development to act in a low GHG emissions economy. Based on these programs, building on the strengths of the clusters, regional long-term development programs can be set up. These regional programs also require coordination at national level.

The aim of the programs is to assess with demo-plants the opportunities, challenges and phasing of large-scale implementation of sustainable technologies. Examples of these programs are:

- Optimize large-scale implementation of CCS, renewable hydrogen and bio-refineries
- Jointly design a system whereby collected products made from chemicals can be effectively recycled

Table 6-2 Snapshot of current initiatives and focus of the chemical clusters

	Rijnmond	Chemelot	Zeeland	Delfzijl & Emmen	Amsterdam
Circular economy	Focus area, already several running initiatives	Closing value chains and recycling	Several companies working on plastic recycling	Circular synergies and sustainable value chains	Closing value chains is focus CCU
Biobased	Pre is sea-harbour large market and inland connections Some biobased companies already active	Existing logistics for handling bulk fossil feedstocks can be used, new functionalities on the radar	Biobased Delta aims innovations for the chemical industry	Get maximum value out of biomass Sea-harbour is pre	New functionality biobased products
Electrification	Land connection off-shore wind	Large interest in H_2 as feedstock for e.g. fertilizer	Upgrade to robust and cost-effective electricity network. Power2H_2 in Delta region. Connection H_2 pipeline between Zeeland Refinery, Dow, Yara and Arcelor Mittal.	Land connection off-shore wind Strong interest in H_2	Land connection off-shore wind Extension of H_2 pipeline to Rotterdam
Energy efficiency	Remains relevant	Shift to electricity processes on the long term	Stimulation of heat pump technology	Remains relevant	
Sustainable heat	Heat carousel for cascading heat to industry, built environment and agriculture	Deep geothermal heat and electrification Cascading heat to build environment	Cascading waste heat with food companies. Geothermic potential at Bergen op Zoom	Power to heat	
CCS	Relatively close to off-shore storage and some large point sources Piping infrastructure present	Intermediate solution for crackers and fertilizers	In partnership with Rijnmond		
General	Havenbedrijf Rotterdam Plant One: innovation and testing area	In network with Northrhein Westfalen and Vlaanderen industrial areas. Strategy is to be the sustainable technology center	Synergies with Antwerp area. DOW and ArcelorMittal explore CCU	Groningen seaports	

Energy transition and industry transition go hand in hand, connected by infrastructure. Infrastructure will be a key factor, including an electricity grid for transportation of large capacities of renewable energy, as well as pipelines for hydrogen, CO_2 and heat, plus adequate waste handling and recycling infrastructure. This illustrates that the chemical industry transition will go hand in hand with the energy transition. Leveraging these synergies requires close co-operation with the energy sector (see Figure 64) and large-scale access to affordable and reliable renewable energy will be key for a lasting competitive position. For some chemical industries, especially those located close to the shore, an opportunity may arise to play a role as balancing hub to absorb volatilities in the power generated. A redesign of the tariff structure for electricity is needed to make this more attractive for the industry, focussing on a shift from capacity costs to usage costs with flexible tariffs.

In the longer run, investments will be needed in infrastructure to transport hydrogen from off-shore production locations to on-shore users. Strong infrastructure for transporting CO_2 over longer distances and storage offshore in empty gas fields will need to be developed.

In the pathways presented, the chemical industry will be reliant on the availability of sufficient amounts of sustainable biomass and a waste management system aimed at creating value from waste. Next to effective shipping, processing and distribution of biomass infrastructure, a widely accepted set of criteria for sustainable biomass should be developed. Also in boosting the amount of available sustainable biomass, the chemical industry will need to cooperate with the agricultural sector (both producing and processing industry), creating both higher available volumes (food) and added value (via feedstock chemicals) for the total production chain.

Figure 6-4 The chemical industry's transition requires a careful balancing of different constrained abatement options[17].

Stakeholder	Cooperation with the chemical industry
Topsectors Energy and Chemistry	- Align programs - Steer on innovation and set the agenda - Share expertise
Energy Sector	- Deals with wind parks - Masterplan hydrogen and green gas - Share investments in infrastructure
NGO's	- Engage public support - Connect stakeholders to the region
Government	- National: long-term guarantees for innovation programs - National: support in financing structures - Local: heat infrastructure & green deals - Local: help clusters to work together
Universities and research institutes	- cross-cluster and cross-sector innovation - Upscaling technologies through demo projects
Waste sector	- Masterplan waste management - Bring circular economy to EU level - CCS on waste incineration
Other industries	- Green deal on financing climate abatement - Together set industry agenda - Promote leaders and flagship projects - Development of energy saving options
Financial sector	- Innovative financial structures - Invest in overarching projects, like CCS-infrastructure
Agrifood	- Explore options to exchange CO_2 for greenhouses - Invest in innovative solutions (i.e. reduced packaging, efficient fertilizers)

Figure 6-5 Possible partnerships of the chemical industry

17) For an explanation of the term "sustainable CO_2" please refer to the end of paragraph 3.4.2.

The waste management system should be designed so that end-user waste is used for the highest value purpose. Plastic waste should, where possible, not be burned in a waste incinerator but recycled back into the chemical value chains. This requires development of, and investments in, new collection and separation systems and design products for recycling. Remaining waste incinerators should be equipped with CCS.

Partnerships are needed to achieve the ambition

To achieve the ambitions outlined in this document, the chemical industry needs to reach out to government, science, industry and other societal partners to work together to accelerate the transition to a low-GHG emission society. In interactive sessions with external stakeholders, many parties accepted the invitation of the chemical industry to realize the ambition of deep reduction of GHG emissions. Many suggestions for possible partnerships and subjects were brought forward; an overview is given in Figure 6-5.

The chemical industry will continue its cooperation with partners along the value chain to develop chemical solutions that can help to reduce GHG emissions along the value chain. Chemical products are used in a large range of applications that enable value chain partners to generate added value. Next to this, chemical products also provide solutions to help value chain partners to lower their GHG-emissions and will continue to do so. The impact of these solutions to avoid emissions can already be found in many end-use applications. The chemical industry is working on innovative solutions that are expected enhance this impact. In this way, the chemical industry contributes to a stronger economy and a lowering of emissions outside of the chemical sector.

Strong leadership is needed

Leadership of the top management of the chemical industry is required, as the business cases of many low-emission technologies are not yet sufficiently profitable to meet current investment thresholds. This was concluded in one of the stakeholder sessions. There are good reasons to lead this transition, as it opens new business models, it contributes to the attractiveness of employers and it demonstrates a company's societal and corporate responsibility. How can this leadership be shaped? It can, for instance, involve:

- Lobbying internally for a company-wide vision on reduction of GHG emissions and action plans;
- Leading visibly, thereby motivating the organization to work towards decarbonization;
- Planning and preparing, based on a company-wide vision on reduction of greenhouse gases, which includes adequate staffing, developing a pipeline of projects, ensuring resources are available, and making decisions
- Communicating about the contribution to the transition to society and internally;
- Partnering, cooperating intensely based on trust, and leading and communicating jointly with government (fair deals; public/private cooperation), NGO's and other sectors.

The government can help in shaping this leadership by creating a stable policy framework, with targets and support for a longer timeframe, aligned with EU and where possible global initiatives.

7 Key findings and implementation actions

Actions taken by the Dutch chemical industry, together with its value chain partners, will contribute to emission reductions in the chemical industry as well as in all other sectors of the economy. This requires a significant transition: not just in the way the chemical industry operates, but also in the way it interacts with other stakeholders in society.

In this Roadmap, Ecofys and Berenschot have explored viable pathways towards 80-95% reduction of greenhouse gases by 2050, covering the industry's own emissions and emissions occurring when products made from chemicals reach their end-of-life. It is concluded that, with innovation, it is technically possible to achieve the necessary emission reductions, while maintaining a growth in added value of 1% per year. This is based on an extensive analysis of options, including alternative feedstocks (e.g. biomass), electrification using renewable power, and closing the carbon cycle (e.g. recycling of plastics and Carbon Capture & Utilization (CCU)), and Carbon Capture & Storage (CCS).

After having explored different thematic pathways for achieving the objectives, each showing the possibilities in a defined direction, this report has focused on more integrated and optimized pathways with a mix of solutions. Based on this exercise, two plausible integrated pathways explore different routes to this emission reduction.

The first plausible pathway – *2030 compliance and least costs* – has a short-term focus, aiming at compliance with the target of the Dutch government to reduce the other GHG and energy related emissions by 49% in 2030 as compared to 1990. The chemical industry is well underway to achieve this target, as the emissions of N_2O have already been reduced significantly since 1990. The end-of-life emissions will increase by 25% in 2030 compared to 1990. This pathway also relies at the use of large volumes of biomass for heat generation (about 70 PJ in 2030). To achieve the 2050 goals, an acceleration is needed after 2030, doubling the amount of biobased heat. Alternative feedstocks are obtained via bio-diesel (up to 280 PJ), biobased materials and CCU. Besides these options, CCS on waste incineration will be needed to reduce end-of-life emissions by 8.5 Mtonne CO_2.

The investment required for this pathway is expected to be around EUR 40 billion, which is comprised of around EUR 15 billion to be invested in the chemical industry, and around EUR 25 billion in the energy system. In addition, the annual energy and feedstock cost for the industry would increase by approximately EUR 4 billion (65%), at present prices (of which EUR 400 million as a consequence of business-as-usual growth).

The second plausible pathway – *direct action and high value application* – aims at reducing both other GHG / energy and end-of-life related GHG emissions directly from the start, accelerating technology development and implementation. This pathway takes external constraints into account, such as using all energy and feedstock for the applications with the highest value for the society, considering a reasonable share of biomass, considering the required capacity for off-shore wind, and the capacity for storage of CO_2 in empty gas fields. This pathway will also reduce other GHG and energy related GHG emissions by 49% by 2030, and, as opposed to plausible pathway 1, will keep the end-of-life emissions in 2030 at a similar level to 1990. This pathway builds on emissions reduction due to the mechanical recycling of plastics and the use of bio-diesel for C2/C3 chemicals in order to reduce the end-of-life emissions up to 2030.

The second pathway is built on the knowledge that the challenges of climate change need direct action to ensure that technologies are developed and implemented and that costs come down on the longer term. Since 2050 is just one investment cycle away for many chemical processes, it is essential that these investments will result in emission reduction in the longer term. Accelerating implementation of the feedstock-related measures soon accelerates learning in the Netherlands and reduces the likeliness of optimizing (energy efficiency) processes that are later no longer required. The innovation and development needed still requires serious efforts and is too important to leave to actors outside the Dutch chemical industry.

The investments required up to 2050 for this pathway are expected to be around EUR 63 billion, which is comprised of around EUR 26 billion to be invested in the chemical industry, and around EUR 37 billion in the energy system. These costs are higher than for pathway 1, as this pathway is less reliant on biomass and more reliant on renewable electricity to produce hydrogen. This contrasts the annual energy and feedstock cost for the industry, which will be less in this pathway, and increase by approximately EUR 3 billion (50 percent), at present prices (of which EUR 400 million is a consequence of business-as-usual growth).

Average abatement costs for this pathway are approximately 140 €/tCO_2eq (excluding costs in the energy system; only accounting for investments in the chemical sector and effects on energy, and feedstock, use at current energy prices), with costs for individual measures of up to 300 €/tCO_2eq. While the abatement costs of several measures are significantly lower than those from many other Dutch sectors, many of the associated abatement measures are not profitable at a company level.

Other sources confirm that this order of magnitude of investments is needed for the energy transition. For comparison, McKinsey estimates that the capital investments for decarbonizing the Dutch industry by 95% by 2050 is EUR 24 billion, excluding costs for the energy sector and the switch to renewable feedstocks [52]. The European Parliament estimates the additional annual investments levels needed to make the European energy system ready for deep decarbonization to be EUR 70 billion for the period 2021-2050 [53]. Total investment costs for the whole period will add up to more than EUR 2 trillion. It should be noted that, due to differences is scope, one should exercise caution when comparing these figures on a one-to-one basis.

The industry transition would have to go hand-in-hand with an equally intensive energy transition. Large-scale access to affordable and reliable renewable energy carriers will be key for a lasting competitive position. In the second plausible pathway (“direct action and high-value applications”), the chemical industry will need 280 PJ of sustainable biomass and 170 PJ of renewable electricity, requiring about 11.4 GW of off-shore wind capacity by 2050. As hydrocarbons will remain the main building block for many chemical products, carbon loops will be closed (CCU amongst others), and renewable sources of carbon will be introduced. CCS would be applied to fossil carbon streams.

Infrastructure will be an important factor, including an appropriate electricity grid for the generation and transportation of large amounts of renewable energy, as well as appropriate pipelines for hydrogen, CO_2 and heat, plus adequate waste handling and recycling infrastructure. This illustrates that the chemical industry transition will go hand in hand with the energy transition; Leveraging synergies requires close co-operation with the energy sector.

Although the benefits of the pathways have not been quantified in this Roadmap, the transition required for the deep emission reduction will bring value to the society and the sector itself. Chapter 5 has illustrated how the chemical industry enables the GHG emission reduction needed for many other Dutch sectors.

One other benefit is the impact this transition can have on the Dutch economy. The Netherlands can be the international centre of excellence in the field of the climate transition. The geographical position, with strong logistic connections and large areas of suitable land, the presence of a strong industry, our globally renowned academia, and a highly-trained labour force are all elements that will contribute to this. New circular business models for the industry and its clients, including innovations in recycling, biorefining and CCU, offer a great opportunity to attract investments to the Netherlands, and to realize decarbonization in the wider Dutch economy. This will attract new businesses, resulting in job creation and increase the national GDP. Furthermore, the products of the chemical industry, both building blocks and finished products, will bring benefits for the value chain partners who aim to reduce their carbon footprints. Also, since the Dutch chemical industry is a large exporter of materials and products, the sustainable impact will not only be limited to the Netherlands be will also help our trade partners to reduce their GHG impact.

7.1 Actions for implementation

Although the investment costs are lowest for plausible pathway 1, we see a significant risk that the period from 2030 to 2050 is too short to realise the required transformation. The Dutch chemical industry and Dutch society will then not be able take the full advantage of the benefits the transition can bring. Plausible pathway 2 addresses the speed that is required to enable the transformation required to achieve the deep reduction by 2050.

Our analysis has identified that this pathway yields an overall emission reduction of approximately 90 percent by 2050, taking constraints in energy and feedstock resources into account, and aiming to use them at maximum value. To achieve the potential of this pathway, we recommend the following actions:

- *The government is asked to take an active role in reducing the current friction between achieving the entire transition and maintaining competitiveness*. Many of the investments to be made by the chemical industry are uneconomic under current circumstances, with the increase in energy and feedstock cost being of the same order of magnitude as the industry’s current overall profit. An active role from the Dutch government is therefore essential:
  - To work towards an EU and a global level playing field, which enables the transition on a long term basis, and
  - In its absence, to provide the necessary financial support for the Dutch chemical industry to enable it to invest in the development of as yet unprofitable (innovative) measures.

- *Establish a joint task force (government – industry – energy sector) to ensure that the energy system and the associated infrastructure is developed in a timely manner alongside the industry transition.*

- *This task force should also lead to a far-reaching joint industry/government innovation program, aiming to develop the necessary technologies to the point where they can be deployed reliably at full scale.* Such a program would reduce the required investments, as well as the cost of energy and feedstock, thus enabling the Dutch chemical industry to accelerate the required changes.

- *Continue and strengthen existing partnerships, establish new partnerships*. The chemical industry should reach out to government, science, industry and other societal partners to work together to accelerate the transition to a low-greenhouse gas emission society.

- *Speed up implementation via regional long-term implementation programs.* These programs require reliable partnerships between individual chemical clusters, value chain partners, the power sector, and the local and national governments.

Finally, we observe that the transition will require a fundamental overhaul in the industry’s production processes. Its capital-intensive nature means that there will be only one opportunity to get this right in the 32 years remaining until 2050. From now on, all major investments in production and innovation will need to consider the 2050 climate target.

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ANNEX 1: Assumptions

Energy Prices:

The current energy prices are used;
no future energy prices are projected.

	Price (€ / GJ):	Background:
Fossil gas	5	Eurostat (two semesters 2016, the Netherlands), band I5 (one but highest, the highest I6 has no data for the Netherlands), excluding VAT and other recoverable taxes and levies, converted from HHV in eurostat to LHV here.
Fossil oil	7.7	Average 2016 naphtha price was 384 $/tonne [54], with a petroleum naphtha LHV of 44.938 GJ/tonne and a conversion between $ and € of 0.904 in 2016 [55].
Electric	10	Expert opinion
Bio-wood	7.2	FOB RotterdamWood pellets: 26 Euro/MWh [56]
Bio-diesel	23.1	For FAME bio-diesel: ≈ 1000 $/metric tonne [56]; however, FAME bio-diesel would not be used to replace naphtha (due to its high oxygen content); HVO bio-diesel is much more apt, but its price is considerably less known; it is considered more valuable then FAME-biodiesel though. As alternatively to HVO bio-diesel, pyrolysis oil (which should, on the longer term, have a lower price than HVO bio-diesel) or bio-naphtha (with a lower price than HVO bio-diesel as well [57]), the price of FAME bio-diesel is taken as a proxy for the price of bio-diesel. With an LHV for bio-diesel of 37 GJ/ton (expert opinion) and converting between $ and € the bio-diesel price follows.
Bio-ethanol	28.5	600 €/m3 (PIX Nordic CIF [58]), with the ethanol density of 789 kg/m3 [59] and an LHV of 26.7 GJ/tonne [60].

No carbon price has been used, but the carbon price per tonne of avoided CO_2 has been calculated (see further on); the current carbon price is around 6 € / tonne CO_2.

Choices per pathway:

Thematic Pathway Bio-based and Circular

Background:

General:
Apply recycling and bio-based where possible.
Mechanical recycling (2030 and 2050):
0.9 Mton of plastics recycled[18], of which 74% corresponds to C2/C3 and 12% corresponds to BTX, with an efficiency of 72%.

Chemical recycling 2030:
Twice the NRK 2030 target to chemically recycle 144 kton. This is divided over C2/C3 and BTX according to their production ratio in the Netherlands (is 29% of the 2050 chemical recycling implementation).

Chemical recycling 2050:
In EU, 8 Mton of polymers can be chemically recycled [14]; we add the other inorganic chemical recycling potential (0.48 Mton). Total production of plastics in EU is 58 Mton. Taking the efficiency of the recycling into account, in total 11.3% (8.48/58/*75%) of plastics production can be chemically recycled. The Dutch plastics production is 6.6 Mton/year, so in the Netherlands 0.75 Mton of plastics can be made from chemical recycling. This is divided over C2/C3 and BTX according to their production ratio in the Netherlands.

Bio-based functional 2030:
50% of 2050 potential.

Bio-based functional 2050:
5% of the total production of C2/C3 in 2005, based on an interpretation of extrapolated 2030 projections (0.55 Mton).

Bio-based drop-in chemicals (2030):
2.6 Mton of C2/C3 bio-based
2.6 Mton of C2/C3 bio-based (to reach the 30% bio-feed goal); C2/C3 is preferred above ammonia and methanol as it can be processed in existing crackers, while C2/C3 is preferred above the bio-BTX route as this is still at relatively low TRL.

Bio-based drop-in chemicals (2050):
4.97 Mton of C2/C3, 3.2 Mton of BTX, and all ammonia (2.2 Mton) and methanol (0.62 Mton) bio-based, so that the fossil-based oil use becomes 0 PJ.

CCU functional 2030:
50% of 2050 potential.

CCU functional 2050:
Assumption is that all polyol production would become CO_2 based, with 1/3 of the mass being replaced by CO_2 [expert opinion]; with an average energy content of 35 GJ/ton for plastics [expert opinion], this translates to 0.2 Mton C2/C3. Functionality driven CCU could be applied to a few other (niche) chemicals as well.

H2-based (2030 and 2050):
Zero for ammonia, methanol, C2/C3 and BTX.

Energy efficiency:
0.5%/year after 2005, implying 12% improvement in 2030 and 20% in 2050.

Renewable energy:
- Geothermal: 15 PJ in 2030 and 30 PJ in 2050
- Biomass boilers: 12.5 PJ in 2030 and 105 PJ in 2050

CCS:
0

Requires in total:
- Biomass 2030: 214 PJ
- Biomass 2050: 709 PJ
- Additional H2 2030: 0 ton
- Additional H2 2050: 0 ton

18) This is based on EU data. In total, 12.6 Mton of polymer can be recycled [14] (based on communication with the authors; we have included around 20% of non polymers organics). Of this amount 4.7 Mton was already mechanically recycled in the base year 2005 (Plastics Europe – data for 2006). Remaining potential is thus 7.9 Mton. 11.4% of this amount in the Netherlands (based on the ration between the Dutch and the European plastics production) → 0.9 Mton.

Thematic Pathway Electrification

Background:

General:
Use electricity where possible.
Emission factor electricity is assumed to be zero already in 2030 (as it only makes sense to apply the deep electrification measures with renewable power). à For this reason, the 2030 decarbonisation has been modelled higher, to account for the almost 3 Mton CO_2 saving that results just from this assumption.

Mechanical recycling (2030 and 2050):
See Thematic Pathway Bio-based and Circular.

Chemical recycling 2030:
The NRK 2030 target to chemically recycle 144 kton. This is divided over C2/C3 and BTX according to their production ratio in the Netherlands (is 21% of the 2050 chemical recycling implementation).

Chemical recycling 2050:
2/3 of the implementation in Thematic Pathway Bio-based and Circular.

Bio-based functional 2030:
50% of 2050 potential.

Bio-based functional 2050:
5% of the total production of C2/C3 in 2005, based on an interpretation of extrapolated 2030 projections.

Bio-based drop-in chemicals (2030 and 2050):
0

CCU functional 2030:
50% of 2050 potential.

CCU functional 2050:
See Thematic Pathway Biobased and Circular

H2-based (2030 and 2050):
- In 2030: Partly for ammonia (1 Mton) as this one is the most cost effective.
- In 2050: Max for ammonia (2,2 Mton), methanol (0.62 Mton), C2/C3 (5.21 Mton) and BTX (3.2 Mton), so that fossil oil feed energy use becomes 0.
  - Note that for BTX production, the produced by-products have not been included in the pictures / in the economic calculations. Including this could improve the economics significantly (around 270 PJ, composition and value unknown) and could produce fuel which could potentially save around 15-20 Mton CO_2 when substituting fossil fuels).

Energy efficiency:
1.0%/year after 2005, implying 22% improvement in 2030 and 36% in 2050.

Renewable energy:
Electric boilers: 25 PJ in 2030 and 65 PJ in 2050
Biomass boilers: 0 PJ in 2030 and 42.7 PJ in 2050

CCS:
0

Requires in total:
- Biomass 2030: 45 PJ
- Biomass 2050: 103 PJ
- Additional H2 2030: 200 kton
- Additional H2 2050: 5,3 Mton

	Background:
Thematic Pathway CCS	**General:** Apply CCS where possible. **Mechanical recycling (2030 and 2050):** See Thematic Pathway Bio-based and Circular. **Chemical recycling 2030:** The NRK 2030 target to chemically recycle 144 kton. This is divided over C2/C3 and BTX according to their production ratio in the Netherlands (is 21% of the 2050 chemical recycling implementation). **Chemical recycling 2050:** 2/3 of the implementation in Thematic Pathway Bio-based and Circular. **Bio-based functional 2030:** 50% of 2050 potential. **Bio-based functional 2050:** 5% of the total production of C2/C3 in 2005, based on an interpretation of extrapolated 2030 projections. **Bio-based drop-in chemicals (2030 and 2050):** 0 **CCU functional 2030:** 50% of 2050 potential. **CCU functional 2050:** See Thematic Pathway Biobased and Circular H2-based (2030 and 2050): Zero for ammonia, methanol, C2/C3 and BTX. **Energy efficiency:** 0.5%/year after 2005, implying 12% improvement in 2030 and 20% in 2050. **Renewable energy:** 0 in 2030 and in 2050. **CCS:** • Process emissions captured: 2.7 Mton CO_2 (in 2030) and 2.6 Mton CO_2 (in 2050) • Energy-related emissions captured: 4.15 Mton CO_2 (in 2030) and 9.71 Mton CO_2 (in 2050) Note that with the approach followed, there would be scope to capture a further 2 Mton CO_2 in 2050 at comparable cost. • Waste incineration: CO_2 captured: 2 Mton CO_2 (in 2030) and 9.4 Mton CO_2 (in 2050) - The 2030 aim (-49% energy & process related emissions) is achieved by capturing around 2 Mton of CO_2 from waste incinerators. - For 2050, the starting point is that the Dutch chemical industry produces 6.6 Mton of plastics, of which 1.1 Mton C2/C3 and 0.33 Mton BTX are recycled. Furthermore, 0.55 Mton and 0.2 Mton C2/C3 are replaced by bio-based functional respectively CCU functional. This leaves 3.0 Mton C2/C3 for polymer production and 0.5 Mton BTX for polymer production. When this would be incinerated, 11.0 Mton of CO_2 is released, of which 9.4 Mton can be captured (efficiency 85%). **Requires in total:** • Biomass 2030: 46 PJ • Biomass 2050: 62 PJ • Additional H2 2030: 0 ton • Additional H2 2050: 0 ton

	Background:
Combination Pathway "2030 compliance at least costs"	**General:** Aim to be as cheap as possible, but with full mechanical recycling potential. **Mechanical recycling (2030 and 2050):** See Thematic Pathway Bio-based and Circular. **Chemical recycling (2030):** See Thematic Pathway Electrification **Chemical recycling (2050):** See Thematic Pathway Bio-based and Circular. **Bio-based functional 2030 and 2050:** Like Thematic Pathway Circular & Bio-based **Bio-based drop-in chemicals (2030):** 0 (not needed for -49% reduction aim for energy & process side); **Bio-based drop-in chemicals (2050):** 3.5 Mton of C2/C3; 2 Mton of BTX this amount is required to make the overall 2050 aim. **CCU functional 2030:** 50% of 2050 potential. **CCU functional 2050:** See Thematic Pathway Biobased and Circular H2-based (2030 and 2050): Zero for ammonia, methanol, C2/C3 and BTX. **Energy efficiency:** 1.0%/year after 2005, implying 22% improvement in 2030 and 36% in 2050. **Renewable energy:** • Electric boilers: 0 PJ in 2030 and 65 PJ in 2050 (full potential in 2050) • Biomass boilers: 26 PJ in 2030 and 67 PJ in 2050 (similar order of magnitude costs as electric boilers, slightly more expensive; nevertheless, in 2030 biomass boilers due to the current subsidy scheme). **CCS:** • No CCS in 2030. • In 2050: - Process emissions: 2.4 Mton CO_2 captured - Energy-related emissions: 1.2 Mton CO_2 captured - Waste incineration: 8.5 Mton CO_2 captured; the starting point is that the Dutch chemical industry produces 6.6 Mton of plastics, of which 0.9 Mton is recycled mechanically and 0.65 Mton C2/C3 and 0.33 Mton BTX is recycled chemically. Furthermore, 0.55 Mton and 0.2 Mton C2/C3 are replaced by bio-based functional respectively CCU functional. In total 2.8 Mton C2/C3 remains, and 0.35 Mton BTX. When this would be incinerated, 10.0 Mton of CO_2 is released, of which 8.5 Mton can be captured (efficiency 85%). **Requires in total:** • Biomass 2030: 71 PJ • Biomass 2050: 435 PJ • Additional H2 2030: 0 ton • Additional H2 2050: 0 ton

	Background:
Combination Pathway "Direct action and high-value applications"	**General:** Attempt to use a balanced mix of power, CCS, recycling and biomass, and make the best (most high-value) use of these scarce resources. Availability of biomass is limited to 140 PJ in 2030 and to 280 PJ in 2050[19]. **Mechanical recycling (2030 and 2050):** See Thematic Pathway Bio-based and Circular. **Chemical recycling (2030 and 2050):** See Thematic Pathway Bio-based and Circular. **Bio-based functional 2030:** 50% of 2050 potential. **Bio-based functional 2050:** 5% of the total production of C2/C3 in 2005, based on an interpretation of extrapolated 2030 projections. **Bio-based drop-in chemicals (2030):** 0.53 Mton of BTX (not the full potential, reflecting its relatively low current TRL), 1.2 Mton of C2/C3, the amount that can still be produced within the 140 PJ bio-mass use limit. **Bio-based drop-in chemicals (2050):** Almost all (3.4 Mton) BTX; on top of that 1.2 Mton of C2/C3, the amount that can still be produced within the 280 PJ bio-mass use limit. **CCU functional 2030:** 50% of 2050 potential. **CCU functional 2050:** See Thematic Pathway Biobased and Circular **H2-based:** • 2030: 0 • 2050: Max for methanol (0.62 Mton) and 1.12 for C2/C3 (needed to arrive at the target respecting the constraints). **Energy efficiency:** 1.0%/year after 2005, implying 22% improvement in 2030 and 36% in 2050. **Renewable energy:** • Electric boilers: 0 PJ in 2030 and 35 PJ in 2050 • Geothermal: 0 PJ in 2030 and 30 PJ in 2050 **CCS:** • Process emissions: 0,82 Mton CO_2 captured (in 2030) and 2.4 Mton CO_2 (in 2050) • Energy-related emissions: 0 Mton CO_2 captured (in 2030) and 5.1 Mton CO_2 (in 2050) • Waste incineration: 0 Mton CO_2 (in 2030) and 8.5 Mton CO_2 captured (in 2050) - See Combination Pathway "Lowest Cost" for calculation. Note that all the C2/C3 and BTX produced by the bio-based drop-in routes are included in this potential. **Requires in total:** • Biomass 2030: 140 PJ • Biomass 2050: 280 PJ • Additional H2 2030: 0 ton • Additional H2 2050: 600 kton

19) These are estimates, based on several insights: It is likely that such amounts require imports. The Commission Corbey has explored how a 25% bio-based chemicals goal could be achieved (this would correspond to 140 PJ), and saw no limitations in the availability. Other sources give various amounts of globally available sustainable biomass: 100 EJ in 2050 and perhaps 200 EJ in 2100 [81], 75-200 EJ, of which 2.3 EJ for the European chemical industry [7], a 2030 bio-based aim of 95 PJ a fair share of 140 PJ [88] and a total availability of 359 PJ (HHV- so conservative) biomass [89]. The amount of sustainable biomass available in 2050 is taken to be 2* the amount of biomass available in 2030; refer to the associated recommendation concerning the chemical industry's contribution to the increase of the global availability of sustainable biomass.

Characterization of measures[20]:

A few general remarks to start with:

- In crackers, for the reference process (fossil based naphtha), the naphtha converted to other substances than C2/C3, BTX and fuel, as well as the sales of the products generated with this naphtha (around 25%-35% of the total naphtha intake [expert opinion]); as on average the sales price of these products is higher than the naphtha costs, this leads to an underestimation of the abatement costs.

	Consequences[21]:	Annualized investment (€/ton CO_2 yearly avoided)	Energy cost savings (€/ton CO_2)	Cost Effectiveness (€/ton CO_2)[22]
Closing the loop: Mechanical Recycling	**For each ton of replaced C2/C3:** 14.9 GJ/ton fossil gas (production HVC), 46.7 GJ/ton fossil oil (LHV C2/C3), 5.2 GJ/ton electricity (production HVC + production polymers; the latter is determined on the basis of sector average [7]) **For each ton of replaced BTX:** 12.26 GJ/ton fossil gas (production BTX), 40.4 GJ/ton fossil oil (LHV C2/C3), 5.2 GJ/ton electricity (production HVC + production polymers; the latter is determined on the basis of sector average [7]) For the cost effectiveness, the energy required for recycling (23.8 GJ/tonne – assumed to be power) and the energy no longer produced during the alternative waste incineration (26% of the 46.7 respectively 40.4 GJ/tonne heat and 25% of the 46.7 respectively 40.4 GJ/tonne electricity) is taken into account. The composition of the polymers to be recycled has been determined on the basis of the most produced Dutch polymers: On that basis, 74% of these originates from C2/C3, 12% originates from BTX, and 14% originates from hetero-atoms [own analysis]. *Mechanical recycling of fertilizers has not been included in the modelling.*	42 (on the basis of [14][23], accounting for the composition mentioned in the column on the left).	11	31

20) Relative to 2050 conditions (in practice: emission factor power of 2050 (= 0)).
21) Positive values indicate savings, negative values indicate additional energy use.
22) Cost Effectiveness reflects the total effect of the annualized investment costs and the yearly additional energy costs, per ton of CO_2 saved; other effects are not considered. To annualize the investment costs, the following formula is used: Yearly costs = (Total Investment / 2) * WACC + Total Investment / Technical Lifetime. Across the board, a WACC of 17% and a lifetime of 25 years (8.7 years for investments in utilities ("renewable energy") are used. This boils down to taking the annualized investment costs as ≈ 1/8 of the total investment costs (a higher share for utilities).
23) In the absence of better data assuming the investment required to recycle one tonne of fertilizer is equal to the investment required to recycle one tonne of polymer.

	Consequences[21]:	Annualized investment (€/ton CO_2 yearly avoided)	Energy cost savings (€/ton CO_2)	Cost Effectiveness (€/ton CO_2)[22]
Closing the loop: Chemical Recycling	For chemical recycling, the production of pyrolysis oil has been taken as the proxy for the model. This allows transport of a high density fuel (no "transport of air") to large scale cracker installations. Relatively small pyrolysis oil production units should regionally process collected waste ("transport of air" only over relatively limited distances). The effect of chemical recycling on the chemical industry is modelled by assuming that the pyrolysis oil can be made on the basis of waste, and leads to (emission free) naphtha. For the cost effectiveness, it has been taken into account that the waste is no longer available for the production of electricity and heat in waste incinerators. For the cost effectiveness, the efficiency of the process is assumed to be 75%, and waste is assumed to be available at zero costs. Energy use for logistics is ignored, as is the value of any by-product (the remaining 25%). The energy no longer produced during the alternative waste incineration (26% of the 46.7/75% respectively 40.4/75% GJ/tonne heat and 25% of the 46.7/75% respectively 40.4/75% GJ/tonne electricity) is taken into account. The energy needed for the process originates from part of the waste. In case this would be fossil-based waste, some emissions would still take place (during the preparation of the pyrolysis oil), which could be abated with CCS. In most of the pathways, sufficient emission free chemicals are made (through bio-based / electricity based) to provide sufficient "emission free" waste though. Therefore, these costs have not been taken into account. We have not accounted for the presence of any hetero-atoms.	127 €/tonne recycled product → 180 €/tonne CO_2 [expert opinion]	50	130
Alternative Feedstocks: Functional bio-based	14.85 GJ/ton fossil gas and 46.7 GJ/ton fossil oil are replaced by similar amounts of bio-wood.	24.5[24]	-2.2	26.7
Alternative Feedstocks: Bio-based C2/C3	Bio-diesel route assumed, can be processed in existing crackers: 14.85 GJ/ton fossil gas and 46.7 GJ/ton fossil oil are replaced by 14.85 and 46.7 GJ/ton bio-diesel	0	-234	234
Alternative Feedstocks: Bio-based BTX	Bio-diesel fed Bio-BTX process assumed (still at a relatively low TRL now): 12.26 GJ/ton fossil gas, 0.96 GJ/ton electricity and 40.4 GJ/ton fossil oil are replaced by 7.575 and 40.4 GJ/ton bio-diesel.	24.1[25]	-200	224

24) Based on the assumption that the investment costs are more or less similar to the costs of a cracker.
25) Based on an rough estimate of 700 euro/(ton yearly produced BTX), which is amongst others informed by information received from BTX.

	Consequences[21]:	Annualized investment (€/ton CO_2 yearly avoided)	Energy cost savings (€/ton CO_2)	Cost Effectiveness (€/ton CO_2)[22]
Alternative Feedstocks: Bio-based Ammonia	Based on syngas route [25]: 15.7 GJ/ton fossil gas energy, 0.74 GJ/ton electricity and 18.6 GJ/ton fossil gas feed are replaced by 22 GJ/ton bio-wood energy, 0.6 GJ/ton electricity and 18.6 GJ/ton bio-wood feed.	225	-61	286
Alternative Feedstocks: Bio-based Methanol	Based on syngas route [25]: 11.9 GJ/ton fossil gas energy, 0.6 GJ/ton electricity and 25 GJ/ton fossil gas feed are replaced by 14.6 GJ/ton bio-wood energy and 25 GJ/ton bio-wood feed.	179	-45	224
Alternative Feedstocks: CCU Functionality Driven	With the assumption that all CO_2 replaces C2/C3, a saving of fossil oil feed of 46.7 GJ/tonne follows. Based on a conservative look at LCAs, one could also assume that half of this energy, 23.35 GJ/tonne, is saved as fossil gas use [expert opinion].	Not known, but small in the bigger picture	>0	Relatively cheap
Alternative Feedstocks: Ammonia based on renewable hydrogen	Based on renewable hydrogen route [25]: 15.7 GJ/ton fossil gas energy, 0.74 GJ/ton electricity and 18.6 GJ/ton fossil gas feed are replaced by 18.6 GJ/ton electricity energy and 18.6 GJ/ton electricity feed. Our calculation assumes total investment costs of euro 1065 / ton NH_3 produced yearly, consisting of: • Considerably lower hydrogen electrolyser investment costs (525 euro / kW [expert opinion] à 5880 euro / ton H2 produced yearly, assuming 4500 operating hours and thus 1038 euro / ton ammonia. • Furthermore, investments for the ASU are 27 euro / ton ammonia produced yearly [61] • For the ammonia synthesis reaction, the existing installations can be used (no investment required; no growth of ammonia production is assumed).	68	-99	168
Alternative Feedstocks: Methanol based on renewable hydrogen plus sustainable CO_2	Based on renewable hydrogen route [25]: 11.9 GJ/ton fossil gas energy and 25 GJ/ton fossil gas feed are replaced by 14.1 GJ/ton electricity energy and 25 GJ/ton electricity feed. Our calculation assumes total investment costs of euro 2535 / ton CH_3OH produced yearly, consisting of: • Hydrogen costs: Analogue to ammonia, and thus 1103 euro / ton methanol • A CAPEX of 714 euro / ton of CO_2 captured yearly for CO_2 capture (analogue to CCS), translating to 982 euro / ton of methanol (just capture, no transport or storage). • An investment costs of 451 euro / ton CH_3OH produced yearly for the synthesis of methanol from H_2 and CO_2 [62].	151	-99	250

	Consequences[21]):	Annualized investment (€/ton CO_2 yearly avoided)	Energy cost savings (€/ton CO_2)	Cost Effectiveness (€/ton CO_2)[22])
Alternative Feedstocks: C2/C3 based on renewable hydrogen plus sustainable CO_2	Based on renewable hydrogen route [25]: 14.85 GJ/ton fossil gas energy, 1.65 GJ/ton electricity and 46.7 GJ/ton fossil oil feed are replaced by 49.3 GJ/ton electricity energy and 46.7 GJ/ton electricity feed. No by products are formed at the assumed ratio between methanol and C2/C3. Investment costs are based on the assumption that 2.28 tonne of methanol is required for each tonne of C2/C3 + 300 euro / ton C2/C3 [24].	180	-121	300
Alternative Feedstocks: BTX based on renewable hydrogen plus sustainable CO_2	Based on renewable hydrogen route [25]: 12.26 GJ/ton fossil gas energy, 0.96 GJ/ton electricity and 40.44 GJ/ton fossil gas feed are replaced by 135.26 GJ/ton electricity energy and 40.44 GJ/ton electricity feed. In this case, by-products are formed at the assumed ration between methanol and BTX (4.3), as the overall BTX yield is around 56% [24]; we assume the mass of water is included in this number. To determine the value and carbon content of these by-products (44%; 1.9 ton by-product per ton of BTX) we assume it to be naphtha, with an LHV of 44.938 GJ / tonne thus has leading to 85 GJ naphtha, with a value at current energy prices of 655 euro / tonne of BTX, and "harvesting" 6.2 ton CO_2 (0.0725 ton CO_2 / GJ). Investment costs are based on the assumption that 4.3 tonne of methanol is required for each tonne of BTX + 300 euro / ton BTX [24]. Based on these uncertainties, this number comes with significant inaccuracy, and the approach to assume that the byproducts have the same value as naphtha might well be too optimistic. Therefore, this option has been used only limitedly in the modelling (just in the extreme electrolysis pathway in 2050).	143	-74	217
Energy Efficiency	0.5%/year – 1%/year	5 times the yearly energy saving	Positive	Negative
Renewable Energy: Electrical boilers	1:1 replaces fossil gas energy, applicable to 350°C [expert opinion]. Around 65 PJ of the chemical industry's heat use is necessary at or below these temperatures [expert opinion].	4 (3 for the fossil boiler)	-88	90
Renewable Energy: Geothermal Energy	Replaces fossil gas energy, applicable to 200°C [expert opinion]. Around 30 PJ of the chemical industry's heat use is necessary at or below these temperatures [expert opinion].	279 (3 for the fossil boiler)	88	187
Renewable Energy: Biomass	Replaces fossil gas energy 1:1 by bio-wood.	64 (3 for the fossil boiler)	-39	99

	Consequences[21]):	Annualized investment (€/ton CO_2 yearly avoided)	Energy cost savings (€/ton CO_2)	Cost Effectiveness (€/ton CO_2)[22])
CCS: Process emissions	Just compression, transport and storage: 0.4 GJ/tonne CO_2 captured power use. *SMR/ATR to produce hydrogen in combination with pre-combustion CCS has not been modelled.*	23 (excluding transport and storage)	-4	27
CCS: Energy-related emissions	Post combustion, transport and storage: 0.48 GJ/tonne CO_2 captured power use, plus 1.6 GJ/tonne CO_2 gas use (based on a total heat use of 3.2 GJ/tonne CO_2 of which 50% originates from waste heat). *SMR/ATR to produce hydrogen in combination with pre-combustion CCS has not been modelled.*	89 (excluding transport and storage)	-14	103
CCS: On waste incineration	Post combustion, transport and storage: 0.48 GJ/tonne CO_2 captured power use, plus 3.2 GJ/tonne CO_2 gas use (no use of waste heat). *SMR/ATR to produce hydrogen in combination with pre-combustion CCS has not been modelled.*	89 (excluding transport and storage)	-25	115

Energy Efficiency

The table below summarizes the energy efficiency improvements projected by other sources, which have informed the energy efficiency projections in this report.

Source:	Incremental (%/yr):	Game-changers (%/yr):
CEFIC Roadmap	0.5% (target year 2050)	1.6% (target year 2050)
Process Intensification Traxxys		0.6% (target year 2050)
ICF	0.3%	0.2%
BEIS	>0.2% (target year 2050)	
MEE	1.2% (historic)	
Dechema / ICCA	0.56% (no target year)	
JRC	0.4% (target year 2050)	
Turkenburg	14% *overall* (no target year)	

CCS:

General:
CCS is, at most, applied on 80% of the energy related emissions (not in the smallest installations) [expert opinion], and, at most, in 100% of the waste incinerators. The capture efficiency is 85% [7].

Investment costs:
Literature shows a wide range of CCS investment costs, but no detailed study of the investment costs for CCS applied to the chemical industry is available. Often, such studies do not publish how they annualized the investment costs, thus reducing the insight provided significantly. Nevertheless, here follows an overview of key sources:

- 465 UKpound / tonne of CO_2 (non annualized) [63];
- 714 €/ton CO_2, excluding transport and storage, for a 0.25 Mton stack [7]; investment costs for transport and storage are accounted for under the cost for energy system and infrastructure and are 140 €/ton CO_2 [7].
- 52 UKpound / tonne of CO_2 for an ethylene plant and 190-340 UKpound / tonne of CO_2 for CHPs of different sizes (all non annualized, just capture) [64];
- 130-370 €/ton CO_2, just capture, non-annualized [65];

ECN/PBL report total costs of 60-110 €/ton CO_2 [66], which corresponds reasonably well to the 714 €/ton CO_2 mentioned above.

Based on the above and on expert opinion, the numbers given in [7] are used in this report.

General:

The total amount of (2005) feedstock use cannot be explained just on the basis of the production of ethylene, propylene, methanol, ammonia and BTX. To compensate, the amount of produced ethylene, propylene, methanol and BTX has in the model been increased with a factor 1.24.

ANNEX 2: Thematic pathways

1 Circular & Biobased

Reduction potential
In the Circular & Biobased pathway, the largest share of emissions is abated by the change from fossil feedstock towards biobased streams and a strong focus on circularity of feedstocks through recycling. Figure A-1 shows the reduction potential of each of the solution themes in this pathway, for both energetic and other GHG emissions as end-of-life emissions. These reduction potentials are based on the full potentials for closure of the materials chain, and moderate developments for other solution themes. The largest abatement potential for this transition pathway concerns the use of biobased as alternative feedstock. This requires a 100% switch from naphtha to bio-feed for the production of ethylene and propylene, a 100% syngas based shift for ammonia and methanol, as well as a 100% glycerin based BTX route ('bio-btx').

Another large abatement measure for this pathway concerns the closure of the materials chain. Through mechanical and chemical recycling, an emission reduc-

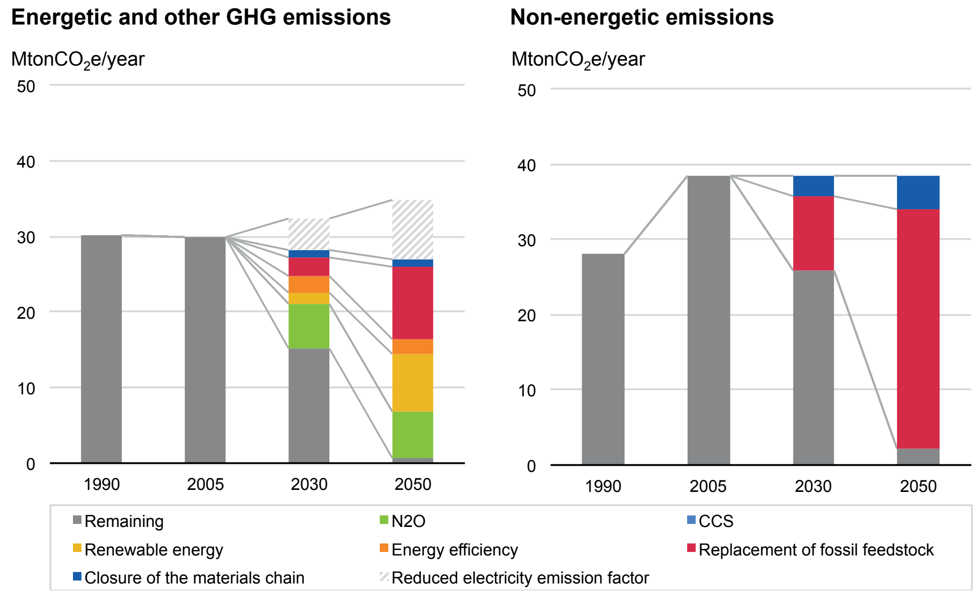

Figure A1 Potential for emission reduction by 2030 and 2050 in the Circular & Biobased pathway

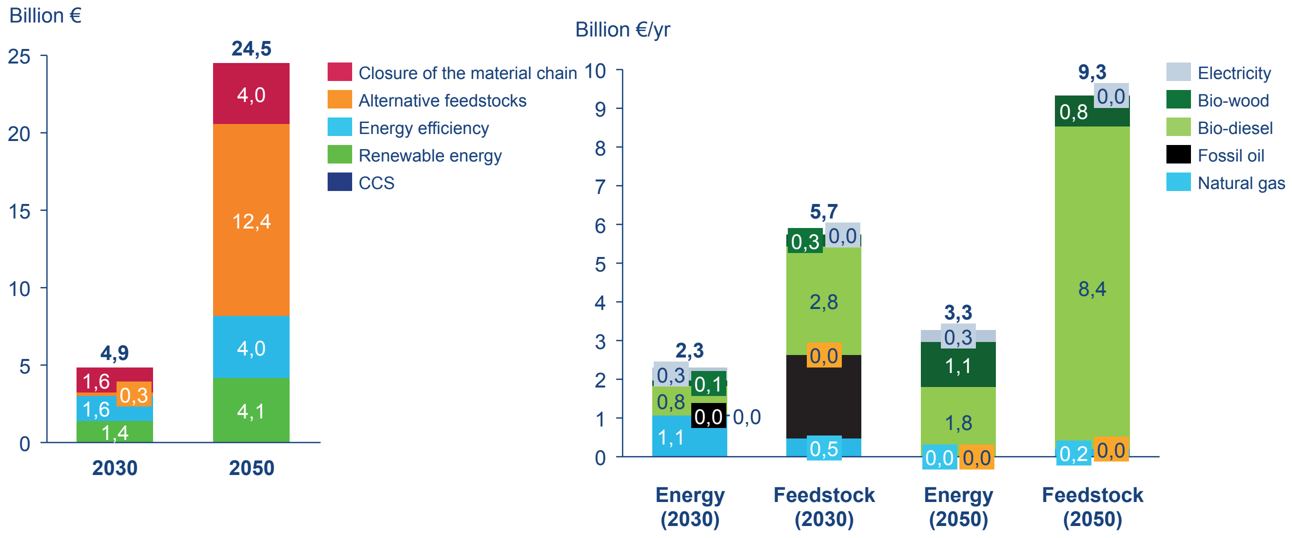

Figure A2 Projected investment costs (left, billion Euro) and energy and feedstock costs (right, billion Euro/year) in the chemical sector up to 2030 and 2050 for the pathway "Circular and Biomass" (for the investment costs: about EUR 0.8 billion is assumed to have already been invested in energy efficiency up to now). Energy and feedstock costs are calculated with 2017 prices. All costs are relative to the current situation.

tion of 5.3 Mton CO_2 is technologically feasible, of which 2.3 Mton from mechanical recycling and 3 Mton from chemical recycling (in 2050). Although energy efficiency plays a limited role in this transition pathway, another share of abatement potential comes from the use of renewable heat. In this pathway, energetic heat demand is fully covered by the use of (ultradeep) geothermal energy up to 200°C and biomass boilers, leading to emission reductions of 7.7 Mton.

Investments for the chemical sector

When looking at necessary investments for the transition pathway Circular & Biobased for the chemical sector, the total capital investments are estimated at EUR 4.9 billion up to 2030 and EUR 24.5 billion up to 2050. The largest share of capital investments is expected for the use of alternative feedstocks (12.4 billion euros towards 2050). Moreover, around 4.0 billion euros are required for the full deployment of mechanical and chemical recycling, of which around EUR 3.3 billion for chemical recycling. Mechanical recycling of plastics seems to be a 'no-regret' option. For renewable energy, investments of EUR 2.3 billion are required for the use of geothermal energy and EUR 1.8 billion for the installation of biomass boilers.

Energy and feedstock costs for the sector are expected to increase as a result of a large share of biomass use. Considering current energy prices, annual energy and feedstock costs are expected to nearly double to EUR 12.6 billion / year in 2050, mainly as a result of biodiesel use (EUR 400 million of the increase is due to the assumed business as usual growth of energy use).

Energy system investments

Figure A2 shows the estimated total investments for the energy system, with regard to the 2050 Circular & Biobased pathway. These investments are accounted for by the energy sector, and as such they can impact energy prices for the chemical sector. Yet, it shows the implications of the Circular & Biobased pathway for the Dutch energy system as a whole.

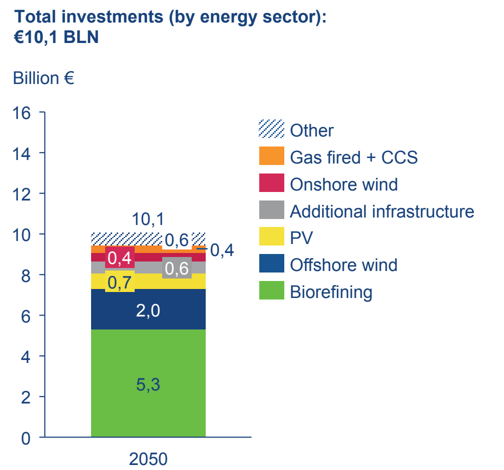

Figure A3 Investments in the energy sector in the pathway "Circular and Biomass" for 2050.

Largest investment costs for the energy sector are expected for refining of biodiesel through pyrolysis (5.3 billion Euro). Moreover, the use of renewable electricity through offshore wind requires capital investments of around 2 billion Euro. Total system costs for the pathway Circular & Biobased add up to 10.1 billion euros towards 2050.

Conclusion

The pathway Circular & Biobased shows many opportunities for the creation of new business models for the chemical industry. Looking at circularity, the emphasis on recycling and reuse would require the invention of new products that enhance the feasibility of recycling molecules. Yet, this pathway requires around 700 PJ of sustainable biomass, which puts pressure on available (sustainable) sources and seriously affects the competition with other sectors. Moreover, moving towards a circular economy requires a complete value chain turnaround, including more intensive clustering, increased flexibility of plants and processes to deal with 'waste' and bio-materials and significant logistical developments. Considering the innovation agenda, an emphasis on chemical recycling would be needed, including a focus on the availability and logistics of the collection of apt waste streams.

2 Electrification

Figure A4 shows the reduction potential of each of the solution themes in the Electrification pathway, for both energetic and other GHG emissions as end-of-life emissions. A precondition for emission reduction in this pathway is that it is in 2030 all electricity is already from renewable sources.

In the electrification pathway, the largest share of emissions is abated by the use of hydrogen from electrolysis in combination with CCU as alternative feedstock. This leads to CO_2 emission reductions of 1.9 Mton in 2030 and 39.2 Mton in 2050. For the energetic and other GHG emissions, the potential of electric boilers is fully deployed, leading to around 3.7 Mton CO_2 reductions in 2050.

With regard to other solution themes, the Electrification pathway foresees a minimal deployment of mechanical recycling as a 'no-regret' solution and chemical recycling (2.3 Mton and 2.0 Mton CO_2 reductions respectively), a 1.0% per year energy efficiency improvement leading to 3.5 Mton reduction in 2050, approximately 2.4 Mton reduction through the use of biomass boilers and 65 PJ of heat delivered by electric boilers, corresponding to 3.7 Mton CO_2 reduction.

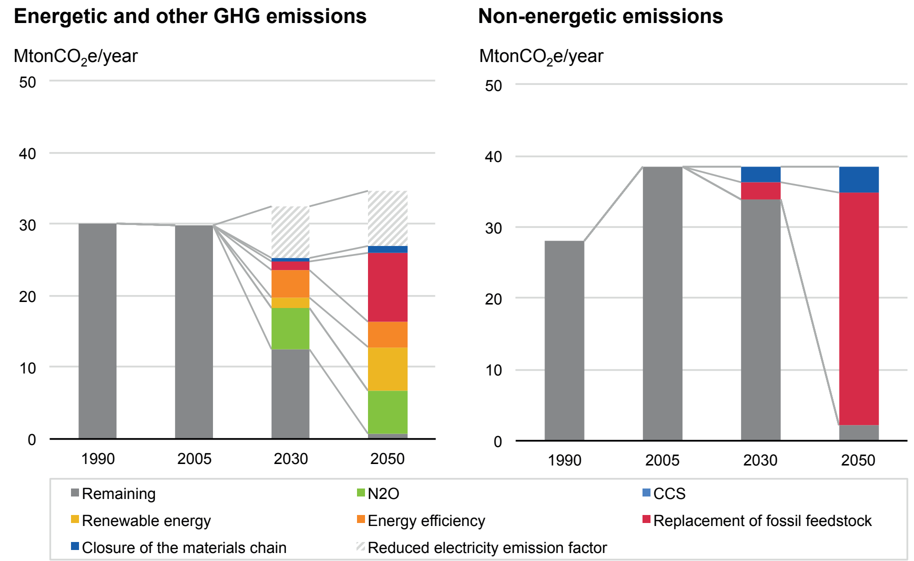

Figure A4 Potential for emission reduction by 2030 and 2050 in the Electrification pathway

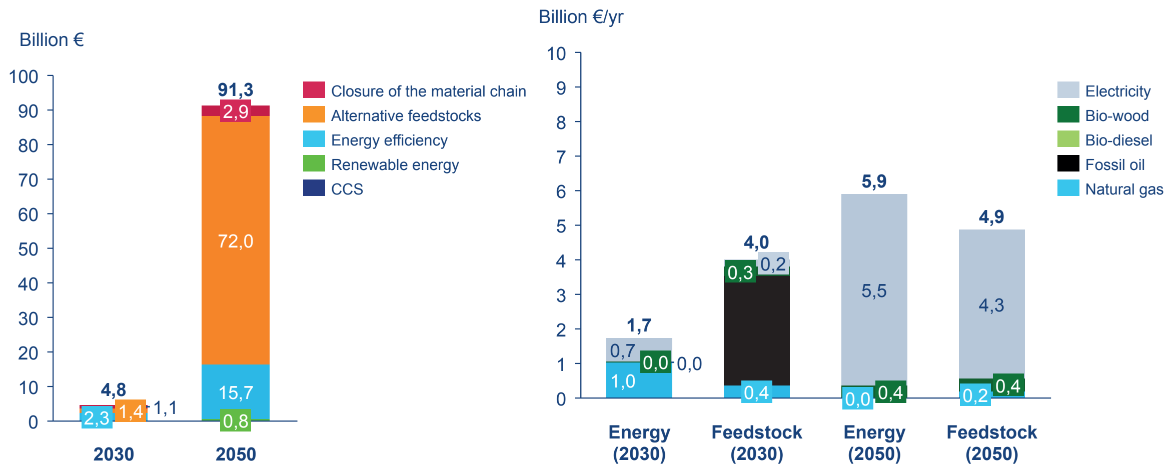

Figure A5 Projected investment costs (left, billion Euro) and energy and feedstock costs (right, billion Euro/year) in the chemical sector up to 2030 and 2050 for the pathway "Electrification" (for the investment costs: about EUR 1.2 billion is assumed to have already been invested in energy efficiency up to now). Energy and feedstock costs are calculated with 2017 prices. All costs are relative to the current situation.

Economic implications
Looking at the economic implications of the Electrification pathway, large investments are required for the replacement of fossil feedstock for hydrogen. This is mainly due to high costs for electrolysis. Yet, these costs are expected to decrease rapidly after 2030, potentially using other technologies such as PEM or SOE. In our modelling we assume that investments for electrolysis are assumed to be carried by the chemical industry, although other options for the direct supply of hydrogen are conceivable, as mentioned earlier.

Energy costs for the sector are expected to increase because of a large electricity usage. Considering current energy prices, annual energy and feedstock costs are expected to rise by about 80% to EUR 10.8 billion / year, mainly for the use of electricity (at current prices) (EUR 400 million of the increase is due to the assumed business as usual growth of energy use)..

Energy system investments
Figure A6 shows the estimated total investments for the energy system, with regard to the 2050 Electrification pathway. These investments are accounted for by the energy sector, and as such can impact energy prices for the chemical sector. Yet, it shows the implications of this pathway for the Dutch energy system as a whole.

Large investment costs for the energy sector are expected for offshore wind for the use of renewable electricity, adding up to EUR 110 billion towards 2050. Transporting these extra amounts of offshore wind electricity requires another EUR 35 billion in infrastructure costs. Total system costs for the pathway Electrification are estimated at to 152,4 billion euros towards 2050.

Conclusion
The Electrification pathway shows large potential for the chemical industry in terms of carbon neutral production processes, while simultaneously benefiting a competitive advantage when electricity prices are competitive. The Dutch chemical industry is uniquely positioned with its clustered geography close to the seashore, and benefits by origin from its close ties with the energy sector. These conditions provide the right basis to successfully deploy electrification opportunities. Yet, the demand for large volumes of hydrogen (from electrolysis) and energetic electrification requires around 980 PJ of electricity, equalling around 62 GW of offshore wind development[26]. This requirement brings about significant costs, both for the chemical sector and the energy sector. In order for such a transition pathway to succeed, large developments in the energy sector and cooperation between the sectors are necessary.

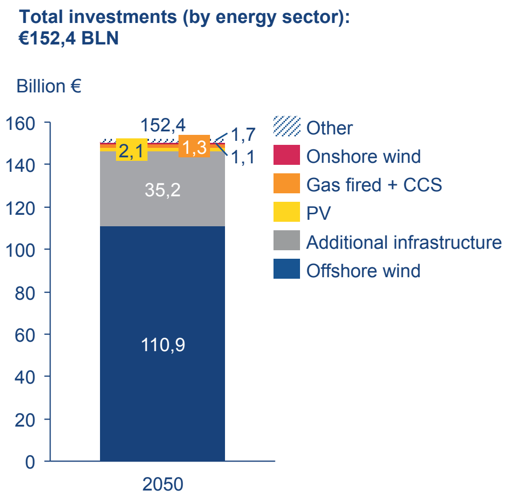

Figure A6 Investments in the energy sector in the pathway Electrification for 2050.

26) Solely considering offshore wind, with 4500 full load hours for hydrogen / electrolysis windfarms and 3500 full load hours for remaining wind farms (see Annex 3 for more details)

3 CCS

The CCS pathway emphasizes the reduction of emissions through Carbon Capture and Storage possibilities. Figure A7 shows the reduction potential of each of the solution themes in this pathway, for both energetic and other GHG emissions and end-of-life emissions.

In the CCS pathway, the largest share of emissions from energy and processes is abated by CCS, adding up to around 11.4 Mton per year.[27] Apart from CCS, the CCS pathway includes a minimal deployment of reductions in other solution themes, of which 2.3 Mton for mechanical recycling (as a 'no-regret' solution), a 0.5% per year energy efficiency improvement and a small (2.3 Mton) reduction as a result of functionality driven biobased feedstock*

When looking at the direct influence of the chemical industry, the CCS pathway remains limited to the

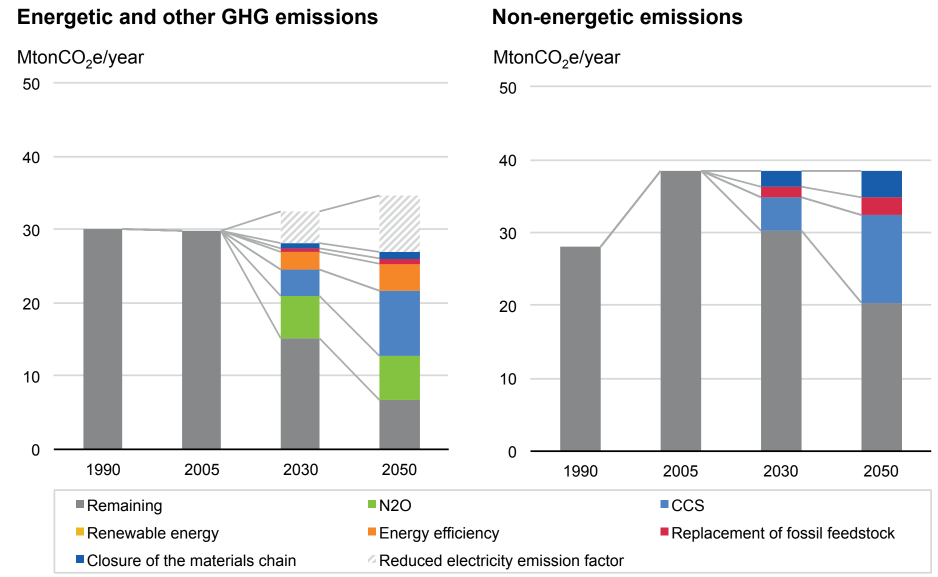

Figure A7 Potential for emission reduction by 2030 and 2050 in the CCS pathway

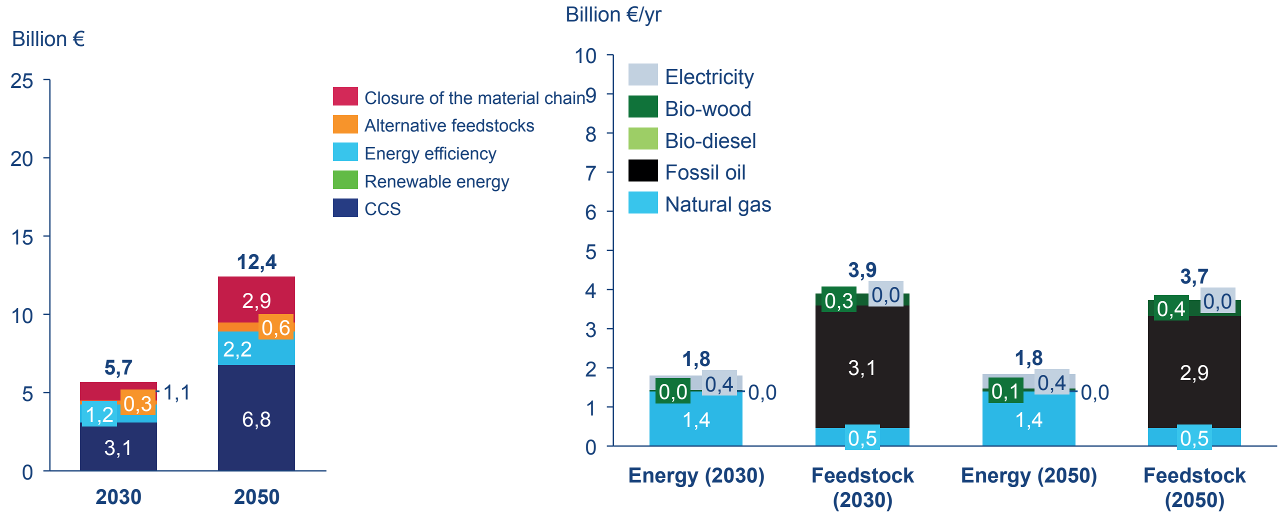

Figure A8 Projected investment costs (left, in billion Euro) and energy and feedstock costs (right, in billion Euro/year) in the chemical sector up to 2030 and 2050 for the pathway "CCS" (for the investment costs: about EUR 0.6 billion is assumed to have already been invested in energy efficiency up to now). Energy and feedstock costs are calculated with 2017 prices. All costs are relative to the current situation.

27) In this pathway, 12,3 Mton of CO_2 is actually captured and stored. The lower abatement figure includes emissions from the capturing process.

abatement of CO_2 from energetic and other GHG emissions. The largest part however, is accounted for in end-of-life emissions. To reduce emissions on that end, CCS on waste incinerators is necessary and included in our analysis. The maximum potential for CCS on waste incinerations is estimated at 9.4 Mtonne in 2050 (with 2 Mtonne already captured in waste incinerators in 2030). This will come with an additional energy use of 0.48 GJ electricity and 3.2 GJ heat per tonne of CO_2.

Economic implications

Generally, investments in the CCS pathway are lowest compared to the Circular & Biobased and Electrification pathways. Yet, these investments only include abatement for energetic and other GHG emissions, since CCS on waste incinerators is regarded as outside sector costs. Investment costs for CCS are 180 €/t for capturing process emissions of ammonia production and 714 €/t for other processes, excluding transport and storage.

Energy costs for the sector are expected to remain relatively constant. Considering current energy prices, annual energy and feedstock costs are projected to be EUR 5.5 billion / year in 2050, almost equal to the current cost (despite the EUR 400 million increase due to the assumed business as usual growth).

Energy system investments

Figure A9 shows the estimated total investments for the energy system, with regard to the 2050 CCS pathway. These investments are accounted for by the energy sector, and can impact the energy prices for the chemical sector. Yet, it shows the implications of this pathway for the Dutch energy system as a whole.

Largest investment costs are for CCS on waste incinerators, estimated at EUR 9.7 billion, including costs for capture, transport and storage. Investment cost for offshore wind re EUR 2.5 billion towards 2050.Total system costs for the pathway CCS are estimated at EUR 15.9 billion towards 2050.

Total investments (by energy sector): €15,9 BLN

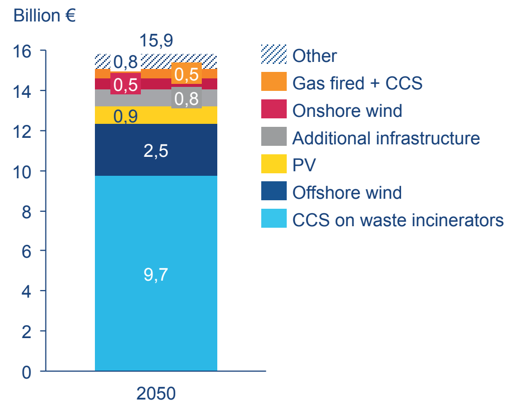

Figure A9 Investments in the energy sector in the pathway CCS for 2050.

Conclusion

The CCS pathway is by far the pathway that involves the least modifications in business models and production processes. This pathway emphasizes the possibility of business as usual, where CO_2 is efficiently captured and stored. This line of thinking does however require a strong infrastructure grid for CO_2 for transport and storage. As such, PBL states that on the short term, the roll out of CCS accounts for a delaying factor as the application of the technology requires many infrastructural developments. Moreover, public acceptance remains a barrier towards the large-scale implementation of CCS.

ANNEX 3: System costs based on the ETM Model

The understanding of the economic system implications of each transition pathway and combination pathway is done using the Energy Transition Model (ETM). The ETM, developed by strategic consultancy Quintel, is an open source tool which allows users to understand present and future energy systems in stringent detail, as well as the effect of policy and industry choices on the energy system. The ETM calculates environmental and economic effects of technology choices and infrastructure for electricity, gas, and heat. The ETM describes the entire energy system by distinguishing various sectors, such as households, transport, industry, and allowing the user to make choices regarding energy supply and demand in each sector. Further, the model includes hundreds of technologies with up-to-date financial and technical parameters. By using the ETM, the user can test technical and financial feasibility of established energy scenarios.

The feasibility and effects of each transition pathway and combination of pathways for the chemical sector was determined by the ETM. Each transition pathway encompasses technology choices and scenario conditions which served as input for the ETM. As a basis for parameters outside the chemical sector, the 95% scenario for 2050 made for the Raad voor de Leefomgeving (RLI, 2015) was used. However, to complete the scenarios, values had to be determined for the present and future costs of chosen technologies, resources, and infrastructure. Cost assumptions for the year 2050 were made by analyzing and comparing the cost values established in a variety of national and international sources.

In the following table, costs are assumed for investments and maintenance of the relevant ETM parameters.

Technologies	Unit	Start value (ETM 2015)	Value 2050	Value change	Sources
Combustion plant costs – investment					
Gas plant	k€/Mwe	535	508	-17%	IEA World Energy Investment Outlook 2015
Coal plant	k€/Mwe	1400	1330	8%	IEA World Energy Investment Outlook 2015
Biomass plant	k€/Mwe	1400	1330	38%	IEA World Energy Investment Outlook 2015
Combustion plant costs – operations and maintenance					
Gas plant	€/kW/jaar	9.97	9,47	78%	[67]
Coal plant	€/kW/jaar	33,62	31,94	14%	[67]
Biomass plant	€/kW/jaar	33,62	31,94	101%	[67]
Wind power costs - investment					
Onshore	k€/Mwe	1391	1224	3%	[67]
Offshore	k€/Mwe	3902	1912	-51%	[67]
Wind power costs – operations and maintenance					
Onshore	k€/Mwe/jaar	49,19	36,89	-20%	[67]
Offshore	k€/Mwe/jaar	142,96	85,78	-31%	[67]
Hydro-electric					
Investment	k€/Mwe	3600	3600	-1%	[67]
Operations and Maintenance	k€/Mwe/jaar	32	32	94%	[68]
Solar power costs - investment	€/kW/jaar	980	196	-42%	[68]

Technologies	Unit	Start value (ETM 2015)	Value 2050	Value change	Sources
Geothermal electricity costs					
Investment	k€/Mwe	12923	7107	-39%	[69]
Operations and maintenance	k€/Mwe/jaar	200	200	-7%	[69]

The output of the ETM includes total investments for the energy sector for energetic purposes per transition pathway. These investments are explicitly not accounted for by the chemical industry, but give insights into the economic implications of each of the transition pathways for the energy sector.

The economic energy system analysis also contains calculations made outside the ETM. This applies to two parameters not included in or not suited for the model:

Energy requirements for hydrogen use: this parameter was calculated outside the ETM, as feedstock use is not an input parameter in the model. Calculations are based on the installation of offshore wind, as this technology is assumed to be most effective for large-scale renewable demand. Assumptions include a capacity of 3 MW per wind turbine, with 4.500 full load hours per year. This figure differs from the full load hours as used for 'the regular windfarm generation' as simulated in the ETM, featuring a fixed number for operational hours of 3500 per year average. This a sound estimate based on operational experience and also keeping in mind the future possibility for more curtailment to avoid negative income at negative prices. The windfarm generation utilized for hydrogen production through electrolysis however takes into account several enhancing factors: investments in a later stage with bigger and more advanced wind turbines, at more windy locations farther offshore, and also without curtailment; thus with a higher estimated number of operational hours of 4500 per year average.

- **Biofuel plants:** Investments for biofuel plants are not included in the ETM and therefore calculated separately. The calculations are based on the production of pyrolysis oil in biorefineries, considering a caloric value of pyrolysis oil of 18.5 GJ/m3 and a density of 1.200 kg/m3 [70]. Investments and yields for a pyrolysis plant are derived from Jahirul et. Al (2012) [71].

ANNEX 4: Establishing a 1990 baseline

The Roadmap 2030 used 2005 as the baseline for target setting. The CO_2 emissions of the chemical industry in 2005 were determined by ECN in a separate study [ECN]. This study explains some of the complexities of determining the emissions related to the use of CHP and non-energetic use of fuels.

To estimate the CO_{2e}-emissions for 1990, we follow a bottom-up analysis based on the energy use of the sector and corrected for the share of CHP. The final energy use as given by CBS for 1990 and 2005 are shown in Table A1.

Table A1 Final energy use chemical and pharmaceutical industry in 1990 and 2005 (PJ)

Energy carrier	1990	2005
Total final energy use	290.9	326.5
Coal and coal products	10	
Oil and oil products	65.7	82.4
Natural gas	92.7	65.5
Renewable energy		0.1
Waste	2.5	1.8
Electricity	37.8	45.5
Heat	82.2	131.3

Source: http://statline.cbs.nl/Statweb/publication/?DM=SLNL&PA=83140NED&D1=26,53&D2=0-1,11,35-50&D3=0-15,l&HDR=G2,G1&STB=T&VW=T

Electricity and heat is partially delivered by CHP. Since between 1990 and 2005 many CHP-plants have been installed, the share of CHP in 2005 is larger than in 1990.

From ECN we learn that the fuel input in CHP was 149 PJ in 2005. With this fuel, 42 PJe of electricity and 75 PJ of heat was produced. Relating this to the final electricity use in 2005 of 45.5 PJ (see Table A1), it can be calculated that 92% of the electricity demand in the sector was produced by CHP in 2005. For our calculation we allocate all CO_2 emissions to electricity, resulting in an emission factor of 198 kg CO_2/GJe. Consequently, to avoid double counting the emission factor of heat was set to 0 kg/GJ.

We use a 2005 power to heat ratio of 0.57 to estimate how much electricity and heat were produced by CHP in 1990. Based on expert judgement on the development of CHP in the sector, we assume that in 1990 20% of the electricity was delivered by CHP and 80% was provided by the national grid. The electricity produced by CHP would then be 7.6 PJe and heat 13.2 PJ in 1990. Using the 2005 CHP emission factor, the emissions associated with CHP in 1990 were 1.5 millon kg.

To calculate the CO_2 emissions for the remainder of the heat and electricity we use the emission factors reported by ECN (56.1 resp. 173.3 kg CO_2/GJ).

We did the same exercise for 2005 to test the method against the emissions reported in the ECN-study. The emissions calculated for 2005 along the lines of this method were 9% lower than the emission reported by ECN. The reason might have to do with sector definitions or other statistical differences. To bring the 1990 data in line, we corrected our results also by 9%.

Table A2 shows that the resulting CO_2 emissions due to the use of energy are estimated to be 23.7 Mtonne in 1990. The other GHG emissions and the non-energetic emissions are taken from CBS[28]. The total emissions in 1990 are estimated to be 59.1 Mtonne.

Table A2 Emissions for 1990 and 2005 (Mtonne CO_2e) estimated according the approach described in this appendix.

Energetic emissions	1990	2005
Fossil fuels	11,1	9,7
CHP - electricity	1,5	8,6
CHP – heat*	0,0	0,0
Other electricity	5,3	0,4
Other heat	3,9	3,1
Total	21,7	21,8
Scale to fit ECN emissions	23,0	23,1
Other GHG emissions	7,1	6,7
Energetic and other GHG emissions	30,1	29,8
Non-energetic emissions	28,0	38,4
Total emissions	58,0	68,2

* All emissions of CO_2 are allocated to electricity.

In other statistics CBS[29] reports the direct CO_2 emissions of the chemical industry related to Dutch activities. These emissions were 21.6 Mtonne in 1990 and 16.0 Mtonne in 2005. Since these emissions only include direct

28) http://statline.cbs.nl/Statweb/publication/?DM=SLNL&PA=83140NED&D1=26,53&D2=0-1,11,35-50&D3=0-15,l&HDR=G2,G1&STB=T&VW=T
29) http://statline.cbs.nl/Statweb/publication/?DM=SLNL&PA=83300NED&D1=0-3&D2=17-18,20&D3=0,5,10,15,20,25-26&HDR=G2&STB=G1,T&VW=T

emissions, and not the emissions due to the generation of electricity or heat off-site, there is a mismatch with the bottom-up calculated data in Table A2. The reason for this mismatch might be due to differences in the definitions of activities included in both statistics, but cannot be explained without further study. Since an accurate assessment of the 1990 emissions is relevant for the ambition in absolute terms, we strongly recommend improving the energy and emission statistics of the Dutch chemical industry.

ANNEX 5: The stakeholder process

To realise a well-supported roadmap, stakeholder involvement has been a focal point throughout the development of this roadmap. Stakeholders, both internal (VNCI members) and external (NGO's, government, network operators etc.) have been included in the development process, inter alia, through several steps on the way. A Steering Group with representatives of the chemical industry, Ministry of Economic Affairs and Climate Policy and the Topsector Chemie (now Holland Chemistry) reflected on intermediate results and provide valuable feedback on process, assumptions and content during several occasions.

Kick-off event — The Roadmap 2050 was first announced at the annual VNCI event in June 2016. The event provided a great opportunity to discuss the roadmap, the underlying goals and possible solution themes with a broad range of stakeholders.

Online tool — An interactive online tool was sent to all VNCI members to inform them about the Roadmap and to collect their valuable input.

Workshop VNCI policy groups — An interactive workshop with two VNCI policy groups (Energy and Climate & Sustainability) was organised to acquire visions on the roadmap, collect input on the different transition pathways and to discuss the solution themes and conditions in more depth.

Workshop Topteam Chemie — A workshop with the Topteam Chemie was organised to discuss the roadmap and collect input on the required innovation-agenda for the different transition pathways and solutions directions.

Internal validation session — The (preliminary) outcomes of the roadmap where presented to and validated with VNCI members. In an interactive session the results and implications of the different transition pathways were discussed as well as the next (short term) steps to be taken.

External validation session — The (preliminary) outcomes were also presented to and validated with external stakeholders, such as governmental parties, NGO's, grid operators etc. In an interactive session the implications of the different transition pathways were discussed and possibilities for cooperation were explored.

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