Reaching Net-Zero in the Chemical Industry

- A study of roadmaps for reducing greenhouse gas emissions

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Nå nettonollutsläpp i kemiindustrin - En studie av färdplaner för att minska växthusgasutsläpp

Sammandrag

Som en följd av EU-beslutet om ett nettonollutsläppsmål till 2050 har flera industrier utvecklat färdplaner för hur dessa utsläppsminskningar ska uppnås. Det här examensarbetet undersöker kemiindustrins färdplaner i syfte att bedöma hur de ser på sin roll i att nå EU:s utsläppsmål. Teknikerna och strategierna som används i färdplanerna för att nå utsläppsminskningar varierar stort. Ofta antas att en blandning av mekanisk och kemisk återvinning, byten av råmaterial till biomassa och CO_2, samt elektrifiering, och CCS kan komma att utnyttjas. Industrins omställning är dessutom beroende av olika förutsättningar i samhället i övrigt, framför allt kopplat till politik och energi.

Tydliga signaler om hur kemiindustrin ser på sina egna möjligheter till agerande saknas dock ofta i färdplanerna. Medan färdplanerna ofta indikerar hur omsällningen skulle kunna ske modellerat i intervall fram till 2050 så saknas planering och rekommendationer till industrin på kort sikt. Därmed underlättar heller inte färdplanerna för tidiga åtgärder. Vilka utsläpp som inkluderas och hur de beräknas är heller inte konsekvent färdplaner emellan, i synnerhet vad gäller utsläpp som inte är under kemiindustrins direkta kontroll. För att kunna bedöma potentialen för lösningar som involverar hela produkternas värdekedja och cirkulära lösningar bör utsläppen från produktens hela livscykel inkluderas och bedömas mer i detalj. Trots EU:s mål om nettonollutsläpp illustrerar färdplanerna varierade och ofta mindre ambitiösa mål för utsläppsminskning. Om industrier följer vägar som inte leder till nettonollutsläpp äventyras EU:s möjligheter att nå sitt mål. Likaså äventyras Parisavtalet och i slutändan den framtida stabiliteten av planetens klimat.

Nyckelord

Kemiindustri, färdplaner, scenarier, nettonollutsläpp, återvinning, biobaserad råvara, CCU, CCS, elektrifiering, effektivitetsförbättringar, förutsättningar

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Abstract

Following the decision set by the EU of a net-zero greenhouse gas emission target for 2050, several industries have made roadmaps for how these reductions will be achieved. This thesis investigates the chemical industry roadmaps in order to assess how they envision their role in reaching the EU target. The technologies and strategies used in the roadmaps to reach the reduction targets vary widely, often showing a mix of mechanical and chemical recycling, feedstock switches to biomass and CO_2, electrification and CCS. The industry's transition is furthermore seen as heavily dependent on the surrounding framework, mainly in regard to policy and energy.

Clear signals to indicate the industry's own agency is on the other hand often lacking in the roadmaps. While the roadmaps often indicate how the transition is modelled to progress in intervals until 2050, more short term planning and recommendations for industry is generally lacking, thus not facilitating early action. What emissions are included and how they are accounted for is not consistent across the different roadmaps, and this is especially the case for emissions that are not under the direct control of the chemical industry. To better assess the potential of solutions involving the entire value chain and circular economy solutions, the full life cycle emissions of products should be more carefully assessed and calculated. Despite the EU target of net-zero, the pathways illustrated in the roadmaps show varying and often less ambitious reduction targets. If industries follow paths that do not achieve net-zero emissions, this jeopardizes the EU's ability to reach its target, as well as the Paris agreement and ultimately the future stability of the planet's climate.

Keywords

Chemical industry, roadmaps, scenarios, net-zero emissions, recycling, biobased feedstock, CCU, CCS, electrification, efficiency improvements, framework conditions

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Preface

This master thesis is the result of a degree project in Environmental Engineering at Lund University, Faculty of Engineering, LTH. The project was performed from December 2021 to May 2022 at the division of Environmental and Energy Systems Studies in collaboration with the Wuppertal Institute in Germany.

Here we are at last! After a complete change of plans when the original idea of performing a degree project abroad had to be canceled due to the global pandemic, my Swedish supervisor Lars J Nilsson helped me find a new path. Together with my German new supervisor Clemens Schneider and Stefan Lechtenböhmer from the Wuppertal Institute, the idea for this project took form. I would like to thank all these people for their great help especially during that turbulent winter.

To my supervisors Lars and Clemens I would like to direct my sincerest gratitude. Without your continued guidance, input and great discussions along this journey, this work would not have been possible. I would also like to thank Ellen Palm, for your wisdom, thorough inputs on drafts, and tips on where to find the information that I needed. When I have felt lost and not knowing where to go next, you all have helped me find direction once again. The forest of roadmaps can be very confusing, and I would like to express a thank you also to Elliot Mari at ADAME for helping me understand and navigate it a little better.

Lastly I would like to thank my friends and family, and the W-guild at LTH for filling my life and time here in Lund with so much inspiration and joy. And to my poor laptop who is still “going strong” after almost 9 years of service, thank you for (almost) keeping up with me and all my files and tabs.

Ylva Kloo
Lund, May 2022

Contents

1 Introduction

The year 2015 set a spark for climate ambitions around the world. The signing of the Paris Agreement in December 2015 was the catalyst for new legislation and goals, and four years later, the EU had set a target for net-zero greenhouse gas emissions by 2050 (COM/2019/640 final). Such a target requires deep transformation of all sectors of society. It is also a long-term goal, and reaching it requires planning, coordination and clear communication. Roadmaps are useful tools for this, and the development of roadmaps can also function as a structured analysis of scenarios, technology options, opportunities and challenges as well as timeframes. In fact, already in 2011 the European Comission expressed a need for sector-specific roadmaps, made in cooperation with each industrial sector (COM/2011/0112 final). However, while carbon neutral solutions in sectors like energy and transport are fully commercialized and being expanded, heavy industry sectors like chemicals, cement and steel are considered hard-to-abate. Solutions for full decarbonization of these sectors are still in a development phase. At the same time, since the assets in these industries have long lifetimes and 2050 is only one investment cycle away, the net-zero target risk being missed if early action is not taken.

The chemical industry has a fundamental challenge compared to other sectors, since the fossil input is not only used for energy, but constitutes the material itself. Fossil input is used to produce petrochemicals and plastics, and fertilizers are produced with hydrogen from fossil sources. Yet, since 1990, the chemical industry in Europe has managed to decreased its direct greenhouse gas emissions by 69%. However, this decrease has largely been the result of efforts to reduce N_2O emissions between the mid 1990s and early 2010s. Today N_2O emissions correspond to about 5% of the sectors direct emissions, and the sectors GHG emissions consists mainly of CO_2. The sector has not seen significant changes in emissions since 2013 (Cefic, 2022).

To be in line with the net-zero targets by 2050 the chemical industry must find ways to eliminate their emissions completely. From a holistic perspective, this also includes the emissions caused by the products carbon content at their end-of-life. The work of developing roadmaps for reducing the sector's emissions has begun, and several roadmaps have thus far been published. In this thesis, these will be investigated with the focus of understanding how the industry envisions itself in a future carbon neutral society and the road to reach it.

1.1 Aim

Investigating how the European chemical industry envisions its role in reaching the EU net-zero emissions targets for 2050, by evaluating and comparing roadmaps for the chemical industry in Europe in terms of

- Technologies and feedstocks
- Investment needs
- Dependency on other actors and stakeholders
- Concretion and timeline

1.2 Scope

17 documents have been chosen that address the transition of the chemical industry within the current half century. Of these are nine considered to be by or for the industry associations or clusters, two are related to government authorities, two are scientifically published academic articles and three are documents by chemical industry companies. The selection was made as described in Methods. While the focus is on the European chemical industry and European countries or country regions, company roadmaps and scientific articles have a global scope.

Although no part of the chemical industry has been deliberately excluded, the investigated pathways themselves do not always include the total chemical industry. They can be limited geographically, and/or to a subset of products. The incompleteness is reflected in this paper, where the main focus is on plastics as well as fertilizers to a lesser extent. Globally, plastics and fertilizers make up 75-80% of all greenhouse gas emissions from the chemical sector (Dell et al., 2022). This thesis takes the full life cycle greenhouse gas emissions from the chemical industry products into consideration. The included documents however vary in this regard as well, and the scope of each document is clarified in this thesis.

The documents included show ways for the chemical industry or parts of the chemical industry to reduce its emissions, but not all referred to themselves as “roadmaps”. Some instead used terms like “pathways” or “scenarios”, and were still included in this comparison as they described the transition and were considered roadmap-like. This is further discussed in 2.3. As many roadmap-like documents as could be found from European chemical industries were included, provided they were written in English or had an English summary. Roadmap-like documents in other languages were found which had a national or local scope, but it cannot be said how these excluded roadmaps compare to the included ones.

1.3 Overview

Chapter 2 presents the background. In it, the context of the chemical sector as a whole is briefly explained in terms of its products, current and historical emissions and its global nature. It also gives some background on where emissions appear in the life cycle of chemical products. The concept of roadmaps is discussed and how the term will be used in this thesis is explained. Finally, technologies and strategies for reducing the sectors emissions are explained.

Chapter 3 presents the methods used in this thesis, both explaining how roadmaps were selected for evaluation, how the evaluations were structured and how the calculations were made.

Chapter 4 contains the results and analysis of the evaluations. An overview of the roadmaps is first presented, followed by sections for each of the evaluation points of the aim. A shorter assessment of roadmaps from individual companies is also given, and this chapter ends with a summary.

Chapter 5 discusses some of the points that were noted in the analysis more in depth, points out gaps and broadens the discussion to put these roadmaps into the context of global climate change efforts.

Lastly, Chapter 6 presents conclusions and take-home messages from this thesis.

2 Background

2.1 Current state: emissions, volumes, global competition

The chemical industry in Europe produces a wide range of products and intermediates, ranging from petrochemicals to fertilizers and specialty chemicals like paints, inks and glue. In terms of sales, the biggest products from the industry are petrochemicals, plastics and various auxiliaries for industry (e.g. glues, essential oils and gelatin) (Cefic, 2022), but globally, over 85 000 compounds are produced commercially (Pöyry, 2020). It is thus a very heterogeneous and complex industry with a large variety of material flows (see Figure 2.1), and the complexity of the full material chain for the chemical industry is something that sets it apart from other manufacturing industries like cement and steel. Despite the myriad of compounds however, only a smaller number of products and processes are responsible for a large share of the chemical industry's emissions. The process of steam cracking, ammonia, chlorine, hydrogen/syngas/methanol and aromatics production together made up around 70 % of greenhouse gas emissions from the chemical industry in 2013 (Boulamanti & Moya, 2017).

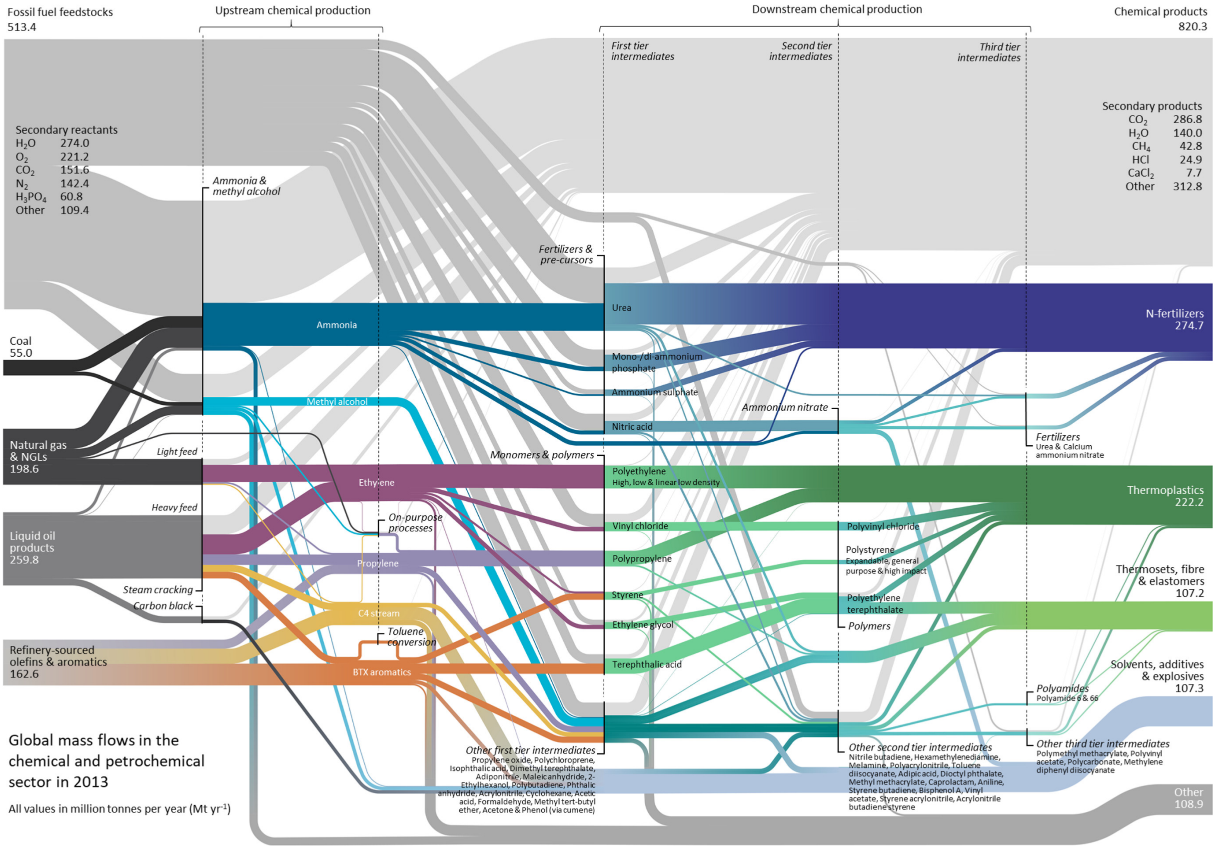

Figure 2.1 – Global material flows of chemicals from raw materials to products. Image by Levi and Cullen (2018), used with permission from ACS.

In terms of direct greenhouse gas (GHG) emissions, the chemical industry accounted for 3.1% of the EU total, or 5.9% of the total industry emissions in 2017, which is 135 Mt CO_2eq in absolute terms (EEA, 2020). This is however only a portion of the emissions resulting from the produced products since it does not include indirect emissions from energy consumption or upstream and downstream emissions like waste management. For plastics and ammonia, the annual emissions for the whole life cycle is 217 Mt CO_2eq, i.e larger than the direct emissions from the whole chemical industry (Material Economics, 2019).

It is often pointed out that the chemical industry exists on a global market, and faces strong competition from other parts of the world. The stage is dominated by China, who is the worlds largest chemical producer in terms of sales. The second largest is the EU, but while the EU sales has increased since 2000, its market share in the world has declined from about 25% to 14% in 2020, and this development is expected to continue (Cefic, 2022). Still, the EU is a net exporter, and 34% of the sales are from exports (Cefic, 2022).

The strong global competition means that economic disadvantages from local conditions and regulation risk making the industry noncompetitive compared to other global actors who do not face the same conditions. In order to level this playing field and avoid carbon leakage, the industry receives some free allocation of EU ETS emission allowances. The amount is decided by a benchmark value for each product, where the benchmark is set as the average emissions per amount product from the 10% best installations in the EU (Boulamanti & Moya, 2017).

2.2 Emission scopes and where emissions appear

A product can cause emissions in several different stages of its life cycle, from the extraction of raw material until its end-of-life treatment. The full life cycle emissions are not always accounted for when calculating emissions, and thus it is important to indicate what emissions are included in the scope and not. In the context of industry emissions, the terminology of The Greenhouse Gas Protocol (WBCSD & WRI, 2004) is commonly used. This standard defines the life cycle emissions in three scopes accordingly:

- Scope 1: Direct greenhouse gas emissions from sources that are owned or controlled by the company. (Emissions from biomass combustion are however excluded and should be reported seperately.)
- Scope 2: Greenhouse gas emissions from the generation of purchased electricity, steam, and heating/cooling consumed by the company.
- Scope 3: All other indirect emissions resulting from the company's activity. This is for example production of purchased materials, transportation of products and fuels, outsourced activities, use of sold products/services, and waste disposal.

As an example, a plastic products life cycle (see Figure 2.2) begins with extraction of the feedstock (e.g. oil), followed by refining, cracking and other processes, polymerization and blending. Electricity and energy is also produced and used throughout these processes. Then it is turned into plastic products, is used by consumers and finally enters end-of-life treatment (Material Economics, 2019). The scope 1 emissions of a the chemical industry would typically include the steps from cracking to polymerization and blending. The electricity, heat and steam for these processes would be included in scope 2. The other steps: feedstock extraction, refining, processing into products, use phase and end-of-life treatment are all scope 3 emissions. These scope 3 emissions are not directly under the company's control, yet, they account for $\sim$60% of the emissions during the products life cycle, with end-of-life treatment being the most significant part today (Material Economics, 2019). These emissions depend on how the product is treated and today, this consists of $\sim$60% incineration (directly releasing the bound carbon to the atmosphere), ~20% landfill (potentially postponing emissions depending on circumstances), recycling (~10%) and export (Material Economics, 2019).

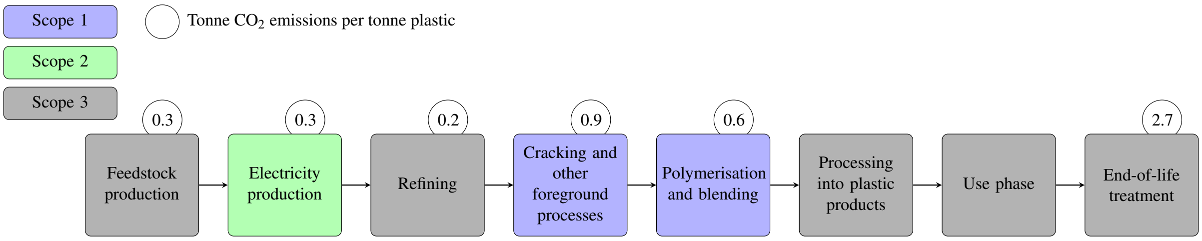

Figure 2.2 – The life cycle of plastics and the corresponding CO_2 emissions per tonne plastic based on Material Economics (2019), and approximate scopes for chemical industry (however the scope depends on the company)

Looking at the chemical industry's own emissions, the production of petrochemicals is the main emitter, but ammonia and methanol production via H_2/syngas production, as well as processes to produce heat generates large emissions as well (BCG, 2021b; Boulamanti & Moya, 2017). The steam cracking process is responsible for the largest emissions in the petrochemical industry, and is used to break down longer chains of hydrocarbons into shorter chains at high temperatures (BCG, 2021b). The emissions mainly arise due to the combustion of fuel to provide heat, and decoking of the cracker furnace tubes (Falcke et al., 2017). In order to produce ammonia and methanol, H_2 is produced as an intermediate product via steam reforming of natural gas, where CO_2 is released from combustion of fuel to supply heat, while process-generated emissions are primarily recovered (Boulamanti & Moya, 2017). Nitric acid and chlorine production are also among the more emission intensive processes in the chemical industry. Nitric acid, which is mainly used for the production of fertilizers, can give rise to emissions of the greenhouse gas N_2O during oxidation of ammonia, and chlorine production causes indirect emissions via the high use of electricity for electrolysis (Boulamanti & Moya, 2017).

2.3 The concept of roadmaps

What is and is not called a roadmap is not always coherent or precise, and there is no universally agreed upon methodology for how they are made (Mari & Chony, 2022). One definition by Johnson et al. (2021) describes roadmaps as: "*long-range strategic plans setting out actionable measures on innovation, policy, public–private partnership, and finance required to transform industries*", but for the purposes of this thesis, such a definition can be too limiting. In this section, the concept of roadmaps in a broader sense is explored, as well as the process of making them.

2.3.1 The purpose of roadmaps

In an industry transition, the choice of pathways can create different winners and losers and is thus deeply political (Johnson et al., 2021). Making a roadmap, suggesting a preferred path or even exploring the realm of considered possible options thus adds to a political discussion and can be seen as a political statement. It can therefore be worth noting who has made the roadmap and for what purpose.

The purposes can range from simply exploring and illustrating a possible future to functioning as a basis for discussion with stakeholders or communication with the public. One way to view the purpose of roadmaps is by what is gained through the roadmap making process itself. Although the roadmaps in this thesis does not include their work, Fossil Free Sweden (Fossilfritt Sverige) describe the purpose of roadmaps as a way to bring out the opportunities that the climate transition can provide for the industries, companies and Sweden (Fossil Free Sweden, n.d.). They state that roadmaps are a way to identify necessary technology shifts, potential obstacles and present ways to remove those obstacles. Roadmaps also serve a purpose by showing a preferred narrative by the roadmap makers. Mari and Chony (2022) explore this in detail, pointing out that roadmaps would not be made public if they were only for internal reflection. Rather, as they state, they can be used to present and sell in the roadmap makers side of a dialogue which may involve companies, governments, NGOs etc. Thus, they often include recommendations usually directed at governments. Roadmaps can in other words be a way to facilitate the discussion, but this depends on how well it addresses and answers some of the more practical questions that stakeholders need to know. However, with roadmaps being public, companies making them may be reluctant to include more detailed information about the business strategy, and especially large actors can for the same reason be hesitant to take part in collective roadmapping projects (Mari & Chony, 2022).

Who makes the roadmap is a relevant aspect as the result can mirror the makers priorities (Mari & Chony, 2022). The roadmaps in this thesis are made by a range of different actors: industry organisations and companies (although company roadmaps are evaluated to a lesser extent in this thesis), as well as third party actors like consultants and institutes, other expert groups and researchers. Many of the roadmaps are commissioned by industry actors but performed by others. On the one hand, the industry itself has the most detailed knowledge of it's operation, technologies and business, and on the other hand, third parties can function as a counterweight to the industry and could help improve the roadmap's credibility (Mari & Chony, 2022).

2.3.2 The process of making roadmaps

While there is no general definition of what roadmaps should entail, Fossil Free Sweden has a proposed work process and set criteria for quality and concretion. They for example encourage using seminars, workshops and reference groups for the industries as well as other actors and stakeholders to present views and give broad perspectives for the roadmaps (Fossil Free Sweden, n.d.). The process of making a roadmap can also sometimes be more useful than the roadmap itself. Mari and Chony (2022) points out that the construction phase provides the opportunity for people to come together, share visions and experiences, build trust and form connections. It thus opens up for more collaboration and action later. Furthermore, they describe the process as a chance to gain new interdisciplinary expertise and knowledge from the range of topic areas and actors involved.

In a broader sense, roadmaps and the process of making them is about thinking about the future, and with a more academic lens, Dreborg (2004) describes three different modes for this: the predictive mode, the eventualities mode and the visionary mode. The predictive mode of thinking relates to finding and explaining patterns, which can be used to predict the most likely future events. The eventualities mode of thinking is used for managing the possibilities of several different developments. For this, explorative scenarios and scenario planning can be used. Both these approaches are ways of forecasting to understand and plan for the future. The visionary mode of thinking, on the other hand, begins by envisioning how the future society or a part of it could be designed in a better way. The approach is then to use backcasting to explore paths leading to the envisioned goal. While these three different approaches can be and are used in their pure forms, they can also be combined and used complementary. All these modes of thinking, forecasting as well as backcasting, can be found in the roadmaps covered in this thesis, and combinations are sometimes used as well.

2.3.3 Roadmaps in this thesis

While a definition of roadmaps by Johnson et al. (2021) was given at the beginning of this section, they also note that other terms such as "pathways" have been used to refer to similar things. The same observation was made when working with this thesis. Both the wide range of things that are referred to as a "roadmap" and the variety of terms used to describe similar things. In this thesis, "roadmap" is used as a catch-all term for the documents investigated and the paths therein. However when it is deemed necessary to be more specific, "roadmap", "scenarios" and "pathways" are used depending on the word choice of the source material, since the nuance that may be intended by those authors may differ. For example, a scenario can be interpreted as a future context unrelated to any choices by the industry, a pathway could be seen as one option for the industry's future development, while a roadmap shows the chosen option. This thesis also uses a somewhat wider scope than the definition described by Johnson et al. (2021) since the documents found have a varying degree of actionability and not all the aspects specified by Johnson et al. (2021) are brought up in all documents. Instead, how well the documents live up to this definition is evaluated and analyzed.

2.4 Technologies and strategies for decarbonization

In this section, the strategies and technologies for decarbonization of the chemical industry are described. They have been divided into strategies targeting the feedstock use, those aimed at switching energy sources and finally measures that reduce the emissions to the atmosphere in other ways.

2.4.1 Feedstock

The material input to the chemical industry is largely of fossil origin. Figure 2.1 shows that for ammonia, the largest primary input globally is natural gas followed by coal, while oil is the main input for olefins and aromatics. The carbon input is partly released in the processing steps (for example that of natural gas in ammonia production), but often the material is bound in the products until the products end-of-life, as in the case of polymers. As previously discussed however, depending on the end-of-life treatment, this carbon content causes large emissions at the end of the products life cycle. To avoid or compensate these emissions other feedstocks can be used, where recycled material, biomass, captured carbon and renewable hydrogen are the considered alternatives.

Recycled plastic

Enabling post-consumer plastics to be re-processed into new products achieves a higher rate of circularity and can avoid the use of new raw material. Yet, today, this potential is not reached. About 35% of the plastic waste in the EU 2020 was collected for recycling and sent to recycling facilities (Plastics Europe, 2021). This is lower than the overall recycling rate of 48% in the EU in 2016 (EEA, 2019). Furthermore, heterogeneity, problematic films and contaminants in the collected fraction prevents some of the plastic sent to recycling from being turned back into new material (Antonopoulos et al., 2021). Of the plastic packaging sent to recycling, an estimated roughly 35% of the separately collected plastic ends up in new material, meaning that overall, about 14% of all the plastic waste is returned to the cycle (Antonopoulos et al., 2021).

The methods for recycling can be broadly divided into **mechanical recycling** and **chemical recycling**. Thus far, almost all (>99 %) plastic recycling is done through mechanical recycling (Plastics Europe, 2021). In mechanical recycling, collected plastic waste is sorted with the help of IR technology, washed with water and chemicals depending on how dirty the material is, and is then granulated to be used for new plastics (Lätt et al., 2020). These steps are not necessarily in the same location, and intermediate packing and transport is then necessary. In chemical recycling on the other hand, the plastic is broken down further into its chemical constituents. This can be done to different degrees depending on the type of process, which can be solvolysis, pyrolysis or low or high temperature gasification (Stork et al., 2018). Chemical recycling through solvolysis only seperates different polymers into the pure compounds, pyrolysis breaks the material down more into pyrolysis oil which can be returned as cracker feedstock, and in low and high temperature gasification the plastic is broken down into monomers and syngas respectively (Stork et al., 2018). Chemical recycling methods like pyrolysis and gasification currently suffer from high energy intensity due to the highly endothermic reactions, but catalysts and alternative processes are being explored (Huang et al., 2022).

Biomass as feedstock

If fossil input is to be avoided and recycled material is not sufficient or preferred, other sources of carbon will be needed as feedstock. This can be provided either from biomass or from captured CO_2 (see below). If biomass is used, various sources could potentially be of interest, e.g. agricultural or forestry residues, other woody biomass, starch, sugar or oil crops, or food waste. These can be processed starting with gasification, pyrolysis or fermentation (of sugar crops). Gasification produces syngas which is subsequently converted into methanol. The methanol can then be processed into olefins via the methanol-to-olefins (MTO) route, where methanol is converted into small olefins like ethylene and propylene (IEA, 2013). Syngas could also be processed via Fischer-Tropsch reactions to produce liquid hydrocarbons (Bazzanella & Ausfelder, 2017). Pyrolysis gives pyrolysis oil (also called e.g. bio-crude or bio-naphtha). Fermentation yields ethanol which can then be converted into ethylene (IEA, 2013).

The processes described above are processes that can transform the biomass into conventional polymers. Converting biomass to secondary feedstock (methanol, ethanol, etc) is energy intensive and consumes substantially more energy compared to conventional fossil production (IEA, 2013). Another option, which could possibly also be less energy intensive, is to make polymers that is closer to and utilize the molecular structure of the biomaterial. These types of biopolymers would then have different structures and characteristics from conventional polymers.

CCU

CO_2 captured from other processes, industries, or from direct air capture (DAC) is another potential source of new feedstock. This is referred to as Carbon Capture and Utilization (CCU). The methods for capturing CO_2 from combustion processes can be classified into pre-combustion, post-combustion and oxyfuel combustion methods, as described by Rissman et al.

(2020). In pre-combustion, the fuel is only partly combusted to form CO, which is then converted into a CO_2 and H_2 mix through the use of steam. The CO_2 is then separated out by using ad- or absorbents. In post-combustion, sorbents are used to pull out CO_2 from a combustion exhaust. The CO_2 can then be regenerated from the sorbent for example through heating. Oxyfuel combustion refers to a combustion process in which pure O_2 is used. Since there is no N_2 or other gases present, oxyfuel combustion allows for pure CO_2 streams to be extracted. CO_2 can also be captured directly from ambient air as described by Yuan et al. (2016), although this provides challenges due to the dilute concentrations of CO_2. Similarly to post-combustion methods, direct air capture methods typically utilize sorbents, but membrane-based technologies have also been considered (these are however still in a very early stage of development). Once pure CO_2 has been obtained through one of these processes, it can be compressed and transported for subsequent use (or storage in the case of CCS, see below).

CO_2 capture technologies is currently used in certain industries. For example, captured CO_2 is combined with ammonia in the production of urea (although this CO_2 is released to the atmosphere once the urea fertilizer has been applied to the soil) (Saygin & Gielen, 2021). It is also used in oil refining and natural gas industry, for example for enhanced oil recovery (EOR) (Rissman et al., 2020; Saygin & Gielen, 2021). In these cases, however, the CO_2 remains close to its original form. The use of CO_2 in new fuels or materials requires first conversion into intermediate products, e.g. methanol, ethanol or syngas (Yuan et al., 2016). These can then be converted into fuels, aromtics, olefins or oxygenates. Since these intermediates and final products have much higher energy content than CO_2, the conversion processes need to provide this energy as efficiently as possible, and hydrogen must be added. Such conversion routes however are still not economic and are for the most part at a development stage (Yuan et al., 2016).

Hydrogen for feedstock

Hydrogen gas, H_2, is needed for some of the previously described processes for producing decarbonized chemicals. It is required in the methanol based processes and in chemical recycling (Samadi & Barthel, 2020), as well as in the production of ammonia as mentioned earlier.

The key aspect of H_2 for decarbonization is how it is produced. An overview of the terminology used in the EU hydrogen strategy (COM/2020/301 final) is seen in Figure 2.3. The H_2 can either be produced through a fossil based route where the hydrogen is obtained from natural gas via methane reforming, or from coal via gasification. This causes fossil emissions, and is often referred to as “gray” hydrogen. However, if the process is equipped with carbon capture, emissions are avoided and this is referred to as “blue” hydrogen. Another way to produce H_2 is through water electrolysis, where water is split up into H_2 and O_2 with the use of electricity. Depending on the source of electricity, this may or may not cause indirect emissions from electricity production. The colours “green” and “pink” are used to refer respectively to H_2 from renewable electricity and electricity with significantly lower emissions compared to conventional production. Renewable H_2 can also be produced from biogas similarily to reforming of natural gas, or it can be produced biochemically from biomass. Blue, green and pink production routes are all considered low-carbon technologies.

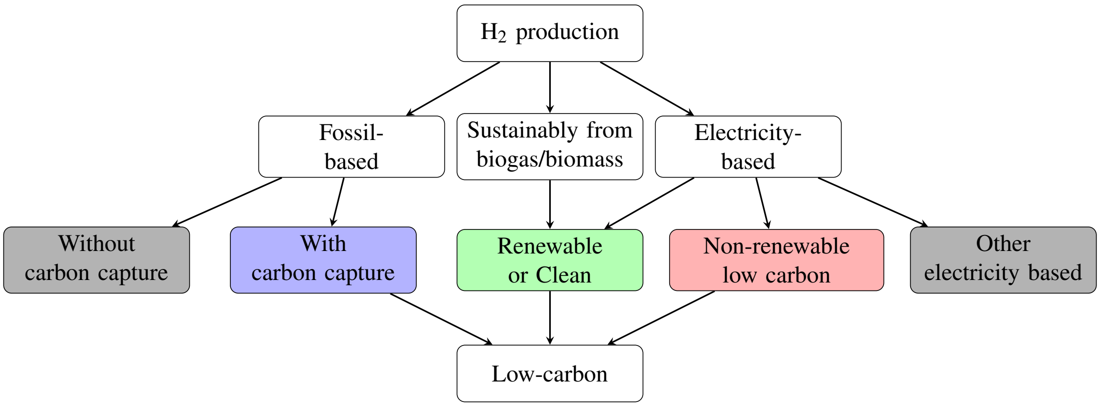

Figure 2.3 – Different categories of H_2 productions, based on the terminology in the EU hydrogen strategy (COM/2020/301 final).

2.4.2 Energy

The emissions from the chemical industry by and large has its origin from the use of fossil fuels for heat and electricity. Thus, switching the fuel and energy sources, or using less energy results in lower emissions, and there are different options for doing this. Here, the switches of energy sources will be described, while decreased energy use through energy efficiency measures will be described further down in section 2.4.3.

Primary heat sources

Heat is produced through combustion in for example boilers and combined heat and power plants, giving steam and hot water (Fleiter et al., 2016). A main energy carrier is steam, which is used in the chemical industry for example in cracking, distillation, evaporation, hydrogen generation and as a carrier of heat (Fleiter et al., 2016). Production of heat for the chemical industry processes is dominated by fossil fuels, mainly natural gas and oil (Cefic, 2013). One strategy for reducing emissions from energy use is therefore switching fuels to biomass and biofuels, which can be done with technologies that are used today. Natural gas fired boilers can easily switch to biogas, and biomass boilers and biomass fueled combined heat and power plants (CHPs) are used to a small extent in Europe today (Fleiter et al., 2016).

Other renewable heat sources are geothermal and solar heat. Both can provide process heat up to around 250 °C (Cefic, 2013; Kalogirou, 2003). In the chemical industry, these temperatures can be used for production of soaps and synthetic rubber, processing heat and for preheating (Kalogirou, 2003). However, these temperatures can often be provided by using cascaded waste heat from high temperature processes, and both solar heat and geothermal have geographic limitations (Cefic, 2013).

Electricity and electrification

The use of electricity and the emission intensity of that electricity is another focus which reduces scope 2 emissions. Of the total energy use in the chemical industry, about 28% is in the form of electricity (Cefic, 2022). This is used in the production processes of several chemicals, with chlorine production being by far the dominating one (Boulamanti & Moya, 2017). Electricity is used in chlorine production for electrolysis to extract chlorine from a chloride salt solution (Boulamanti & Moya, 2017). Electricity is also used in the industry to drive for example fans, compressors and pumps (Cefic, 2013). Switching the energy source from fossil fuels to electricity (i.e. electrification) in more processes can further reduce emissions if the emission intensity of the electricity is low enough. Electrification options includes power-to-heat technologies such as low and high temperature heat pumps, mechanical vapour recompression, electric steam generation and electric furnaces for steam cracking electrification. Other electrification measures are switching to direct electro-catalytic processes, membrane separation and chemical production via water electrolysis for syngas, ammonia and methanol (Wiertzema et al., 2020). Thus electricity is also a vital enabler for many of the previously mentioned strategies. Of course, essential for these technologies to function as emission reduction strategies is that the electricity used is from a low-carbon source.

2.4.3 CCS and system measures

Apart from measures directly related to feedstock and energy, a number of other strategies could be pursued. CCS could be applied where emissions are not avoided through other measures, efficiency can be improved which reduces overall resource and energy needs, and circular economy concepts that function on a system level can be applied.

CCS

An alternative to using the captured CO_2 as in CCU (method described above) could be to permanently store it, thus preventing it from reentering the atmosphere. It is then referred to as Carbon Capture and Storage (CCS).

The captured carbon can be injected and stored in saline formations or potentially in depleted oil and gas fields, and CCS is also used today to store CO_2 for enhanced oil recovery (EOR). As of 2018, there were 17 commercial-scale CCS projects, 13 of which were for EOR. While CCS is technically mature, commercial and political barriers remain. Several attempts and programmes have been made around the world to develop commercially viable CCS, but have failed despite government support. A key issue is the need for integrated infrastructure and storage sites, which is unlikely to be developed by private actors due to the high risks involved. While it is a technology that can be applied broadly across all carbon emitting sectors, it is relatively new and has received less political attention compared to others like renewable and nuclear energy, and biofuels. Oil and gas companies have been the main supporters of CCS while the view from environmentalists has been that it may have a role to play but should not divert attention and investments away from renewables and efficiency measures. (Bui et al., 2018)

Another issue is the public perception of CCS, where percieved benefits, risks and trust are the most important predictors for acceptance (L'Orange Seigo et al., 2014). Some public concerns are that CCS is seen as an end-of-pipe solution that might displace other solutions, as well as perceived risks of leakage and overpressurization. However, local protests may pose a larger barrier to CCS projects than general societal perception, and the social context of the community is important. Previous experiences, trust (especially considering that project developers are often energy companies which tend to be the least trusted actors) and perceived benefits need to be considered. (L'Orange Seigo et al., 2014)

Efficiency measures in chemical industry processes

Efficiency measures allow lower amounts new input to be used for the same (or higher) output, where the input can be in terms of both material and energy. Efficiency can be achieved both through incremental changes and implementations of best performing technologies, but also through more fundamental changes by switching process technologies and production routes (IEA, 2018). On a unit or process scale, measures include for example retrofits, using new catalysts or techniques (e.g. membrane separation), heat integration, and other process optimizations (Vooradi et al., 2019). Higher efficiencies can also be obtained through system scale measures going beyond the individual process such through industrial symbiosis discussed below.

Implementation of efficiency measures is driven by return-on-investments, and a mature industry like the chemical industry generally has made these kinds of improvements over the years where economically feasible. IEA (2018) state that conversion losses are close to minimal in the major chemical production processes. Thus, the potential for any significant energy efficiency improvements is regarded as low.

Industrial symbiosis and other system measures

A number of measures to reduce emissions are imaginable that function on a scale beyond just the chemical industry. While recycling was discussed above, other circular economy concepts like industrial symbiosis, relocation, efforts across the supply chain, reduced demand and offsetting are briefly considered here.

Industrial symbiosis, i.e. "*industrial activities where a waste or by-product of one actor becomes a resource for another actor*", is typically a collaboration between co-located companies where they exchange e.g. materials, energy, water or by-products (Nilsson, 2016). It can thus be seen as a form of efficiency measure which reduces waste and the demand for additional resources, and in turn can reduce costs. While economic profitability and competitiveness is the primary driver, establishment of industrial symbiosis is facilitated by a number of factors such as a mapping of flows, trust and shared ideology between the symbiotic partners, aid through public incentives and cluster organisations that can provide assistance (Nilsson, 2016). Establishing this kind of business models also requires time, resources and expertise (Nilsson, 2016).

Related to this is the measure of relocation, i.e. moving the industries geographically to better make use of local conditions. Where clusters are placed is related to the conditions that applied when they were built, for example being close to the raw material resources, transportation infrastructure and vicinity to other relevant industries. However, transition means that fossil resources will likely be less important, and for example electricity price, bioresources, knowledge and regulatory conditions may become more important. Gielen et al. (2020) identified that relocation of iron-reduction processes to places like Australia with high potential for cheap renewable energy can enable the use of more sustainable processes and reduce global emissions, and also stated that the approach can be expanded to other industries.

Parts of the emissions from the life cycle of chemical industry products are not under its direct influence, which raises the question of measures across the supply chain. Such can include selection of suppliers based on environmental performance, engagement and cooperation downstream (CDP, 2019). Measures downstream the value chain for improving the material efficiency of the system can also be explored, which requires understanding of the sector's complex downstream supply chain and material flows (Levi & Cullen, 2018). Losses along the value chain can also be avoided for example by recycling in-house scrap (IEA, 2018).

Apart from reduced demand through industrial measures as described above, the environmental impact of the chemical industry would also decrease if demand was reduced on a societal level. In the case of plastics, demand could be reduced through the design of products (e.g. to be used longer and more intensively), re-use, substituting for other materials, changing habits, and avoiding certain uses altogether (Bauer et al., 2018; IEA, 2018). There is a risk that these types of measures may have undesirable side-effects like substituting for materials with a larger environmental impact or missing out on environmental benefits that the use of the material achieves (Bauer et al., 2018). It is thus important to ensure that such measures are aimed at reducing the use in a way that results in an overall positive environmental effect.

If the chemical industry does not reach net-zero in their own scope 1, 2 and 3 emissions, the European target can only be reached if the remaining emissions are compensated via negative emissions obtained outside the industry. One way this could be done with the use of carbon credits, or "offsetting", where the company's purchase of a carbon credit results in reduced, avoided or sequestered greenhouse gases via projects elsewhere with an approved carbon credit methodology. In its guidance on carbon credits, WWF acknowledges this as a temporary bridging step when few other direct abatement measures are available (WWF, 2019). They however advise caution and transparency stating that reducing scope 1, 2 and 3 emissions should be the priority, adherence to the GHG Protocol when it comes to carbon accounting, and avoiding misleading statements in the company's environmental claims. They also provide guidance for ensuring that the purchased carbon credits are high-quality.

3 Methods

3.1 Selection of roadmaps

A number of priorities were made in the selection of roadmaps. First, as the aim is to investigate the industry's own perspective on their contribution to reaching net-zero, documents directly from or for industry actors (industry organisations, industrial clusters and companies) were prioritized. A smaller number of documents with pathways from other actors were chosen as well, with the goal of finding a breadth of representation. As recent documents as possible were chosen, in order to best represent the current industry's view. A total of nine roadmaps from the industry were chosen as well as five roadmaps from other actors (the chosen roadmaps can be seen further down in Table 4.1).

A number of roadmap-like documents that were found during the search were thus excluded from evaluation in this thesis. These were exclusively made by non-industry actors, and were excluded due to their lower specificity, absence of timeframe and/or limited geographical scope. Roadmaps written in languages other than English were also excluded, unless there was an English summary. In those cases the English summary was used as the main base for evaluation, but graphs, values and translated sections of the original text were used as complement. Google Translate was used for these translations.

3.2 Evaluation

In order to facilitate the evaluation and comparison, three different kinds of evaluation tables were set up, in which notes were made for each roadmap document. The first table focused on qualitative aspects and contained notes on:

- specific technologies mentioned,
- existence and level of detail of timelines,
- calls for other actions and requirements,
- assumptions and other especially important information,
- reflections on specificity,
- reflections on how it addresses the own responsibility and dependency on other actors.

The second table specified the extent to which different types of technologies were used, how much they contributed to the goal of emission reductions and in the supply of feedstock or energy. This was made for each scenario/pathway in all documents. The technologies were categorized into the following strategies (the original terminology used in each roadmap can be seen in Table A.1 in Appendix A):

- Recycling
- Biomass (for feedstock if specified)
- CCU and H_2
- CCS
- Electrification
- Electricity emission factor

- Renewable energy (non-electricity)
- Industrial symbiosis
- Other

The goal of using this table was to find qualitative basis for comparison. It also contained notes on overall energy amounts as well as the geographical, product and emission scope. Lastly, tables of investment and production costs were made where notes on this were collected and compared.

The selected documents were read in full once (but if a section was obviously irrelevant for the evaluation, it was skipped), passages and information relevant for the evaluation were marked and the evaluation tables were filled in. If information was still missing in the evaluation table, the document was revisited and skimmed if necessary, relevant words, tables and similar were searched for to fill in the missing information.

The notes in the evaluation tables form the basis of the analysis, and condensed results are presented in this thesis and in Appendix C.

3.2.1 Calculations for technologies and feedstock

Many roadmaps has made calculations for each of their considered technologies or strategies and has presented quantitative assessments of how much these are assumed to contribute to the emission reduction in their pathway. In this thesis, such results were compiled for comparison. As the names used in the roadmaps for the strategies, feedstocks and energy sources varied, they were first reclassified into broader categories according to Tables A.1, A.2 and A.3 in Appendix A.

In many cases, however, the values were not clearly stated, but rather for example presented in a figure from which the data had to be extracted. Furthermore, the roadmaps' calculated values could be referring to slightly different things in different roadmaps and in order to make them comparable, some choices had to be made to recalculate and compile the data. More precisely, in the roadmap documents, a strategy's relative contribution to emission reduction could be presented as share of the total reduction effort (note that not all pathways reach net-zero emissions), be compared to the emissions in a reference scenario for 2050, or in a reference year (e.g 2015). For this thesis, it was decided that a comparison to the reference year was most appropriate, and separately showing the emission increase expected in a reference scenario. This was considered the best way to reflect the effort taken, and also showing different expectations of production development. The year used as reference in each document is specified, or if missing, the closest basis for comparison is specified. An illustrative made-up Example scenario shows how calculations were made, for the strategy CCS (see Figure 3.1).

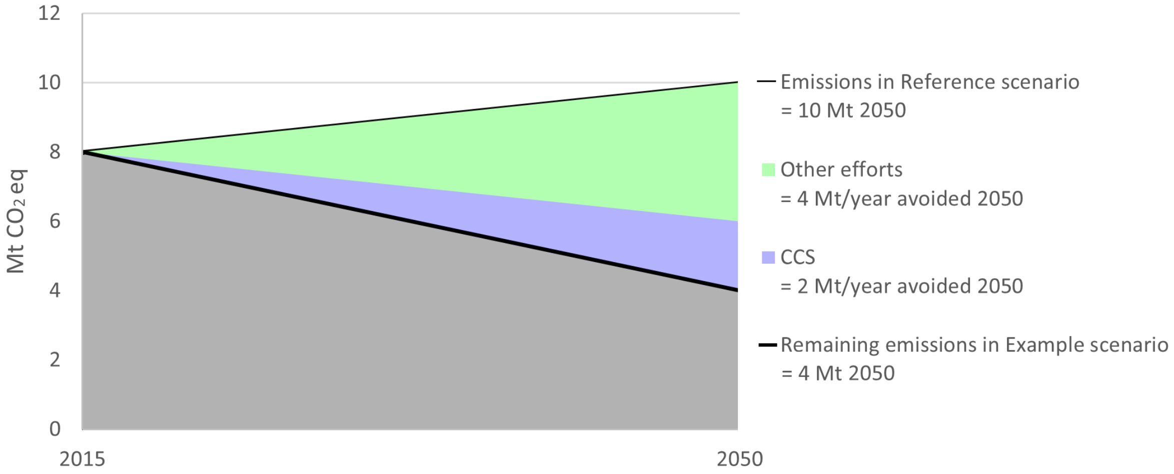

Figure 3.1 – A sketch of an Example scenario to illustrate how emission reductions for the strategy CCS were calculated from a figure.

Information given in the document about Example scenario:

- Emissions in reference year 2015: 8 Mt CO_2eq
- Emissions in Example scenario 2050: 4 Mt CO_2eq
- Reference scenario emissions for 2050: 10 Mt CO_2eq
- Reduction due to CCS compared to 2050 reference: 2 Mt CO_2eq

Calculations for information that would be presented in this thesis:

- Emission reduction for Example pathway compared to 2015 $= \frac{8-4}{8} \cdot 100\% = 50\%$
- CCS % of contribution $= \frac{2}{8} \cdot 100 = 25\%$[1]
- Increase from reference scenario $= \frac{10-8}{8} \cdot 100\% = 25\%$

When the values were not clearly stated as in this example, but instead for instance available in graphs such as Figure 3.1, measurements on graphs were made using a ruler to calculate the desired values.

Note that this work compiled and in some cases recalculated the findings of other works. How each roadmap calculated their results and attributed values to each strategy has not been studied in further detail, but is something that requires its own method and assumptions and which the different roadmaps may have done in different ways. This means that the results from the different roadmaps are not fully comparable and caution should be taken before comparing and drawing more specific conclusions for each value. The results in this thesis should be first and foremost be seen as giving a broad overview.

3.2.2 Evaluation of costs

Information on investments and other costs were collected for each scenario/pathway in the previously mentioned tables. The numbers could be presented as a total sum for the whole period until 2050, as a yearly average or if more specified for each time interval. To enable comparison, annual values were preferred and calculated if not directly stated, by dividing the total sum

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[1] Note that other methods of calculation could have shown CCS share of efforts as 20% (if comparing to 2050 reference emissions), as 33% (as share of the total reduction compared to 2050 reference), or even 17% (if we consider that CCS represented a third of the effort, but compare to 2015 reference instead).

with the number of years the roadmap spanned. However, since the documents typically used different scopes, direct comparison of these numbers would still largely be pointless. Thus, the percentage increase in costs compared to the starting year or baseline scenario was also calculated (if not already stated in the document). This was done by dividing the cost difference between the decarbonisation scenario and the reference case with the cost in the reference case. Costs could also be presented in the documents either as total or additional (i.e. only including the added costs for following the pathway), and note was taken of which was presented. Note was also taken which two types of costs that were stated to contribute the most to the total, and in what time period the investments were expected to peak.

3.2.3 Evaluation of dependencies

The first evaluation table, containing qualitative notes on calls for action, requirements and reflections on the own role and dependencies were used as a basis for this evaluation. All these notes were collected in a separate document (see Appendix C) and read through once to find general patterns in requirements and dependencies e.g. policy/governments, energy, research etc. After that, more specific needs and recommendations in the documents were identified and categorized under the general trends. This was done by skimming through the notes and searching for relevant words. If the notes were unclear or vague, the original roadmap document was revisited for clarification. Dependencies or descriptions of agency that stood out were noted.

3.2.4 Evaluation of concretion and timeline

When evaluating concretion and timeline, the notes in the first evaluation table were once again used. The notes regarding timeline and reflections on specificity were gathered in a separate document and read through to get an overall view. Eight evaluation aspects were then set up to enable a more precise comparison. These were divided into three categories accordingly:

Timeline

- 1. Timeplanning the next coming years (until 2030)
- 2. Interval-based modelling
- 3. Statements about when technologies are assumed to be available

Strategies and technologies

- 4. Specificity in technology option descriptions, e.g. specified process route, type of chemical recycling, type of biomass, etc.
- 5. Specificity in which technologies are used in the scenarios/pathways
- 6. Identification of uncertainties and challenges for technological choices

Recommendations

- 7. Concrete actions for chemical industry actors
- 8. Concrete suggestions for government agencies

With these aspects in mind, the previous evaluation notes were read, the roadmap documents were looked through, relevant words were searched for and related passages were skimmed.

Scores for each aspect were then given on a 5-grade scale and colour graded accordingly, depending on how much the aspect was explored:

- White: Not at all
- Light yellow: Very minor indications
- Yellow: To a small degree, with low specificity
- Lime green: To a larger degree, but with some vagueness
- Green: To a higher degree

Clarifying comments are also written down for each category and roadmap, which can be seen in Appendix D.

4 Analysis

4.1 Overview of roadmaps

The roadmaps evaluated in this thesis are of different origins with different scopes and purposes. Each roadmap is briefly presented here to give an overview and illustrate the variety. The documents commissioned by industry actors are presented first, followed by non-industry roadmaps. Table 4.1 summarizes the titles, authors and commissioners of the roadmaps together with their document codenames which will be used in the rest of the thesis to refer to the roadmaps. The codenames show the year of the roadmap and the actor or type of actor that commissioned it in a concise manner.[1]

Table 4.1 – Overview of the roadmaps evaluated in this thesis.

Document codename	**Name of document**	**Made by**	**Made for**	**Reference**
Industry roadmaps				
CEFIC17	Low carbon energy and feedstock for the European chemical industry	Dechema	Cefic	(Bazzanella & Ausfelder, 2017)
NCHEM18	Chemistry for Climate: Acting on the need for speed Roadmap for the Dutch Chemical Industry towards 2050	Ecofys and Berenschot	VNCI	(Stork et al., 2018)
PORT18	Deep decarbonisation pathways for the industrial cluster of the Port of Rotterdam	Wuppertal Institute	Port of Rotterdam	(Samadi et al., 2018) (Samadi et al., 2016)
CHEME18	We have more than just a plan!	Chemelot	Chemelot	(Chemelot, 2018)
CEFIC19	Molecular managers A journey into the Future of Europe with the European Chemical Industry	Cefic	Cefic	(Cefic, 2019)
GCHEM19	Working towards a greenhouse gas neutral chemical industry in Germany	Dechema and FutureCamp	VCI	(Verband der Chemischen Industrie e. V. (VCI), 2019) (Geres et al., 2019)
FCHEM20	Roadmap to Reach Carbon Neutral Industry by 2045	Pöyry	Kemianteollisuus	(Pöyry, 2020)
CEFIC21	iC2050 PROJECT REPORT Shining a light on the EU27 chemical sector's journey toward climate neutrality	Deloitte	Cefic	(Deloitte, 2021)
GIND21	Climate Paths 2.0: A Program for Climate and Germany's Future Development	BCG	BDI	(BCG, 2021a) (BCG, 2021b)
Non-industry roadmaps				
EC17	Energy efficiency and GHG emissions: Prospective scenarios for the Chemical and Petrochemical Industry	JRC	European Comission	(Boulamanti & Moya, 2017)
NGOV18	Transition agenda Plastics	(a Transition Team)	Government of the Netherlands	(*Transition agenda Plastics*, 2018)
ECF19	Industrial Transformation 2050 Pathways to Net-Zero Emissions from EU Heavy Industry	Material economics in collaboration with VUB-IES and Wuppertal Institute	European Climate Foundation	(Material Economics, 2019)
ACA21a	Achieving net-zero greenhouse gas emission plastics by a circular carbon economy	Meys et. al	(Published in Science)	(Meys et al., 2021)
ACA21b	Zero-Emission Pathway for the Global Chemical and Petrochemical Sector	Deger Saygin and Dolf Gielen (IRENA)	(Published in Energies)	(Saygin & Gielen, 2021)

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[1] For example, a roadmap from a country's chemical association published 2022 would get the codename XCHEM22 where X is the first letter of the countrys name. ACA is used for academically published articles with no industry association.

Caution should be taken when comparing these roadmaps as many of them differ widely in their scopes and assumptions. It is especially important to note whether scope 3 emissions are included or not, since excluding those excludes the large emissions from incineration of the products. The use of biofeedstock is also affected by this, as the negative emissions occur upstream from the chemical industry. However, even if they are not calculated to the same extent, scope 3 emissions and choices of feedstock can still be considered and be part of the story.

4.1.1 Industry roadmaps

CEFIC17:
Low carbon energy and feedstock for the European chemical industry
(Bazzanella & Ausfelder, 2017)
This technology study was commissioned by Cefic and written by Alexis Michael Bazzanella and Florian Ausfelder at Dechema (the German Society for Chemical Engineering and Biotechnology), with the stated objective of exploring options to reach carbon-neutrality for the European chemical industry. It presents three scenarios with varying levels of effort and emission reductions: intermediate, ambitious and maximum, as well as the reference business-as-usual (BAU) scenario. Compared to this BAU scenario in 2050, the emission reductions reached are 59% 84% and 175% (the maximum scenario reaching negative emissions). The scope is emissions from the chemical industry's nine largest products (accounting for >50% of the emissions), using a cradle-to-gate perspective. Thus upstream emissions from feedstock production are also considered. Large negative emissions as in the maximum scenario are enabled since the full life-cycle emissions, including end-of-life treatment, are not accounted for.

NCHEM18:
Chemistry for Climate: Acting on the need for speed; Roadmap for the Dutch Chemical Industry towards 2050
(Stork et al., 2018)
The purpose of this roadmap is to investigate possible pathways for the Dutch chemical industry to reduce emissions by 80-95%, identify opportunities and required conditions, as well as recommending actions for the chemical industry and other stakeholders to speed up the transition. It is made for the Association of the Dutch Chemical Industry (VNCI). In it are illustrated three "thematic pathways": Circular & Biobased, Electrification and CCS. These are meant to explore the boundaries of different strategies rather than being plausible options. Additionally, two "plausible combination pathways" are described called Pathway 1: 2030 compliance at least cost, and Pathway 2: direct action and high-value applications. The pathways all reach emission reductions of about 95% compared to 1990 emission levels, except for the CCS pathway which reaches about 55% reduction. The scope of these emissions are scope 1 and 2 as well as end-of-life emissions from carbon in sold products. Petrochemical and fertilizer routes were considered, whereas the routes where salt is the feedstock were left out.

PORT18:
Deep decarbonisation pathways for the industrial cluster of the Port of Rotterdam
(Samadi et al., 2018)
This paper, commissioned by the Port of Rotterdam Authority, aims to illustrate and discuss possible industry clusters for the future of the Port of Rotterdam under various sociopolitical and regulatory environments. In this way, it hopes to give support to policymakers, investors and the involved companies to take appropriate actions for decarbonization and embrace the future

policy and market potentials. Three decarbonization scenarios are presented, Technical Progress (TP), Biomass and CCS (BIO), Closed Carbon Cycle (CYC), as well as a BAU scenario. The main scanarios BIO and CYC both reach 98% emission reductions compared to 2015 and TP reaches 74% reduction. Here, the only included emissions are those directly emitted from the electricity generation, waste incineration and the petrochemical cluster in the Rotterdam Port area. The paper is based on the longer report "Decarbonization Pathways for the Industrial Cluster of the Port of Rotterdam" (Samadi et al., 2016), and both were used for the assessment in this thesis.

CHEME18:
We have more than just a plan!
(Chemelot, 2018)
This document is a brochure from the chemical cluster Chemelot in the Netherlands. It announces the clusters ambitions to become carbon neutral by 2050 and the purpose is also to show what conditions are needed for the goals to be accomplished. Being a brochure, it does not go into detail regarding the transformation, but gives an overview with some of the technologies, a list of planned projects and a list of requests for the government. A slightly longer Dutch version exists but was only very rarely consulted for this thesis.

CEFIC19:
Molecular managers; A journey into the Future of Europe with the European Chemical Industry
(Cefic, 2019)
Cefic, or the European Chemical Industry Council, made this vision statement meant to be realistic and usable, with an intention to stimulate dialogue and discussion about business, political and societal decisions-making around the European chemical industry. In this vision, the European chemical industry reach a 50% reduction of scope 1 and 2 emissions in 2050 compared to 2015, and raises various questions, aspects and technologies that could be relevant in such a future. The vision is based on the Delphi study report (Hatzack & Saunders, 2018) by CIFS (Copenhagen Institute of Futures Studies) on behalf of Cefic. The Delphi study report consists of the input of experts from the chemical industry (68%), other industries, academia and the public sector. It is worth noting that in the Delphi study, the experts were asked (among other things) what reduction they expected the chemical industry to be able reach by 2050, and about 2/3 expected reductions by more than 60%, including the 18% that answered 80-95% reduction. The rest pointed to a plateau towards 60%. Thus, the 50% reduction assumption in Molecular Managers is more conservative than the answers in the Delphi study. Like the Chemelot brochure, the Molecular Managers vision statement is of a different kind than many of the other roadmap documents in this thesis, and has less quantitative focus. However, being the only roadmap-like document found that was released by Cefic in recent years, it is an important addition in this thesis.

GCHEM19:
Working towards a greenhouse gas neutral chemical industry in Germany
(Verband der Chemischen Industrie e. V. (VCI), 2019)
The English summary of the German report Roadmap Chemie 2050 (Auf dem Weg zu einer treibhausgasneutralen chemischen Industrie in Deutschland) (Geres et al., 2019) is evaluated in this thesis. Written by Dechema and FutureCamp for the German chemical industry association (VCI), the study investigates a possible path for transformation, measures, technologies and investments needed and how far towards carbon neutrality the industry can progress. It sets

up a reference pathway, a technical progress pathway and a greenhouse gas neutrality pathway reaching 27%, 61% and 97% reduction respectively compared to 2020. The emissions included are scope 1, 2 and end-of-life emissions for six major basic chemical products (said to represent 2/3 of the sectors greenhouse gas emissions) from the German chemical industry. For this thesis, values and some details were obtained from the original German version.

FCHEM20:
Roadmap to Reach Carbon Neutral Industry by 2045
(Pöyry, 2020)
This roadmap was made by the consulting and engineering firm Pöyry for the trade association Chemical Industry Federation of Finland (Kemianteollisuus). It illustrates what technologies and potential the Finnish chemical industry strives for in order to reach carbon neutrality. It includes scope 1 and 2 emissions as well as upstream scope 3 (called feedstock in the report), however, the feedstock scenarios are presented separately from 1 and 2. Note that only upstream scope 3 emissions are quantified, i.e. end-of-life emissions are not. For scope 1 and 2, the scenarios Fast development and Carbon neutral chemistry reach 60% and 99% reduction respectively, and for the feedstock scenarios 62% and 159% emission reductions are reached compared to 2015.

CEFIC21:
iC2050 PROJECT REPORT; Shining a light on the EU27 chemical sector's journey toward climate neutrality
(Deloitte, 2021)
This document was written by Deloitte for Cefic. It is the report for the iC2050 project which had the objective of understanding enabling conditions of innovation, capacity deployment and resources for the EU27 chemical industry to reach climate neutrality by 2050. The objective was also to help inform stakeholders and decision makers of the implications of such a transition, and provide a tool for Cefic to help them identify and analyse possible pathways. Four scenarios with different focuses are presented: High electrification, Fostering circularity, Sustainable biomass and CO_2 capture. These all reach net-zero emissions, using a cradle-to-gate scope. This report has not been released publicly but is available upon request.

GIND21:
Climate Paths 2.0: A Program for Climate and Germany's Future Development
(BCG, 2021a)
BCG made the study "Klimapfade 2.0 (Ein Wirtschaftsprogramm für Klima und Zukunft) for the Federation of German industries (BDI) (BCG, 2021b). In this thesis, the English summary is evaluated. The study considers the full German industry but at times discusses sectors including the chemical industry more specifically. It proposes a program to reach 65% greenhouse gas emission reduction by 2030 compared to 1990 for all sectors and sets up a path for carbon neutrality by 2045. The path is also meant to maintain the competitiveness and balance the distribution of costs. Emissions from all sectors are considered which occur within Germany. The full German version was consulted in this thesis for values and details.

4.1.2 Non-industry roadmaps

EC17:

Energy efficiency and GHG emissions: Prospective scenarios for the Chemical and Petrochemical Industry

(Boulamanti & Moya, 2017)

Made by the JRC (Joint Research Center) for the European Commission, this report shows what energy efficiency improvements and greenhouse gas emission reductions can be achieved for the chemical sector with cost-effective measures. The purpose is to give scientific support to the EU policymaking process. Measures are only employed if they have a payback time of up to 2 years. The emissions included are scope 1 and 2 emissions for 26 chemical compounds, accounting for >90% of the sectors emissions. An emission reduction decrease of 14.7% are reached in 2050 compared to 2013.

NGOV18:

Transition agenda Plastics

(*Transition agenda Plastics*, 2018)

As a part of the Circular Economy Implementation Programme by the Dutch government, transition agendas for five different parts of the Dutch economy has been made of which one is for plastics. It was made by a Transition Team consisting of experts from the business, knowledge institutions, NGOs and governments. It is meant to act as a travel guide for reaching a circular plastic economy. It does not present the targeted reduction of emissions but shows goals for 2030 for plastic material flows.

ECF19:

Industrial Transformation 2050 Pathways to Net-Zero Emissions from EU Heavy Industry

(Material Economics, 2019)

This report is made as part of an initiative by the European Climate Foundation. It aims to provide understanding of what choices and actions are needed to reach net-zero, both for business leaders and policy makers, and to enable discussion and engagement. It presents three pathways: New Processes, Circular Economy, and Carbon Capture, all reaching net-zero by 2050 for plastics, whereas for ammonia only the first two reach net-zero. For ammonia, the Carbon Capture pathway reaches 95% reduction compared to 2015. The report as a whole includes steel, chemicals (i.e. plastics and ammonia) and cement industry in the EU, but only the overall assessment and the assessment for chemicals is considered here. The emissions included in the report are for plastics: Direct emissions from refining to polymerization, electricity, and end-of-life (see Figure 2.2 for a sketch of life cycle steps and emission scopes). For ammonia, the emissions included are: electricity, H_2 production and ammonia synthesis (not use phase). Only CO_2 emissions are included, i.e. not for example NO_2 from applied fertilizer.

ACA21a:

Achieving net-zero greenhouse gas emission plastics by a circular carbon economy

(Meys et al., 2021)

This scientific article shows that with a combinations of low-carbon technologies, net-zero emissions can be reached with lower operational cost and energy demand than if current production was equipped with CCS to achieve net-zero. The emissions included are the full cradle-to-grave life cycle emissions on a global scale for plastics, plastic waste and chemicals needed for their production. It represented 90% of the global plastic production volume. It presented four pathways: Recycling, Biomass, CCU and the combination pathway Circular Carbon which combines the three before. These are compared with a linear carbon pathway which uses only CCS to reach net-zero emissions. The four pathways reach emission reductions of 64%, 95%, 94% and >100% respectively, compared to the linear pathway prior to CCS, in 2050. However, only the Circular carbon pathway has been included in this thesis as it was the only pathway illustrated in sufficient detail. Being global, it assumes a higher volume growth rate that varies between 1.2-5% per year, reaching a total growth from 2015 to 2050 of 255%.[2]

ACA21b:
Zero-Emission Pathway for the Global Chemical and Petrochemical Sector
(Saygin & Gielen, 2021)
This second scientific article is written by Saygin and Gielen as a part of IRENA's global energy system optimisation model, and was published in Energies. It aims to find how net-zero CO_2 emissions can be achieved from a life cycle perspective and the potential contribution of solution based on renewables. It draws out a such a net-zero state by 2050 for the global chemical and petrochemical sector called "1.5 °C case", and compares to the Planned Energy Scenario (PES). Like ACA21a, it assumes a higher growth rate than most other roadmaps, 2% for the 1.5 °C case and 3% for the PES scenario.

4.2 Technologies/strategies

In this section, the technologies and strategies used and discussed in the roadmaps will be reviewed. First, the use of changed feedstock to reach lower emissions is summarized and analyzed. Then the utilisation of different energy sources is reviewed, followed by the use of CCS and system measures. The analysis aims to outline general trends and note some exceptional examples and comparisons. The overall emission reductions achieved through the different strategies is presented in Table 4.2, which will be referred to throughout.

4.2.1 Feedstock

The environmental benefit of changed feedstock is mainly in decreasing scope 3 emissions, either by avoiding emissions from end-of life treatment or by binding CO_2 from the atmosphere or industrial sources. The scope 1 and 2 emissions are less affected and can in theory increase. This can make the effect of feedstock strategies difficult to assess. As can be seen in Table 4.3, almost all quantified pathways utilize alternative feedstocks to some extent but many still assume significant fossil feedstock use.

Recycled feedstock

Almost all pathways utilize recycling to some extent, the only exceptions being CEFIC17, and the TP and BIO scenario from PORT18. CEFIC17 did not include recycling since quantifying the CO_2 reduction potential had not been quantified in the source material and it would require a thorough life cycle investigation. As mechanical recycling is already deployed today, it is not very surprising that recycling is utilized in most scenarios. However, the extent of the recycling varies between the pathways from 7% to 63% of the feedstock, but the corresponding emission reductions are not quantified. Recycled feedstock is used to a larger extent in the non-industry

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[2] In the other roadmaps, a growth rate around 0.5-1%/year is typically assumed.

Table 4.2 – Greenhouse gas emission reduction strategies by share. Numbers are presented as percentage of emissions during reference year. Emission reductions are given a green colour and remaining or increased emission are given a red colour. A deeper colour corresponds to a larger absolute value. Gray is used if the value is zero or if the strategy is not mentioned (“nm”), and yellow is used if the strategy is mentioned but not quantified (“nq”).

Document codename	**Scenario**	**Remaining emissions by 2050**	**Recycling**	**Biomass**	**CCU/H_2**	**CCS**	**Electrification**	**Electricity emission factor**	**Renewable energy (non-electricity)**	**Efficiency improvements**	**Industrial symbiosis**	**Other**	**Effect from BAU**	**Reference year or total reduction**
CEFIC17	Intermediate	**58%**	0%	11%	26%	0%	27%	nq[1]	nq	12%	nq	9%[2]	-41%	2015
	Ambitious	**23%**	0%	13%	53%	0%	24%	nq[1]	nq	8%	nq	19%[2]	-41%	2015
	Maximum	**-106%**	0%	25%	145%	0%	25%	nq[1]	nq	2%	nq	49%[2]	-41%	2015
NCHEM18	Circular & biobased	**4%**	8%	59%	1%	0%	0%	12%	11%	3%	nq	9%[4]	-7%	2005
	Electrification	**4%**	7%	3%	58%	0%	nq[3]	11%	9%	5%	nq	9%[4]	-7%	2005
	CCS	**40%**	7%	3%	1%	30%	0%	11%	0%	5%	nq	9%[4]	-7%	2005
	2030 compliance at least cost	**4%**	8%	37%	1%	18%	nq[3]	11%	11%	7%	nq	9%[4]	-7%	2005
	direct action & high-value applications	**5%**	7%	28%	11%	23%		11%	5%	7%	nq	9%[4]	-7%	2005
PORT18	Technical progress (TP)	**26%**	0%	0%	0%	nq	nq	nq	nq	nq	nm	-	nq	2015
	Biomass and CCS (BIO)	**2%**	0%	nq	0%	nq	nq	nq	nq	nm	nm	-	nq	2015
	Closed carbon cycle (CYC)	**2%**	nq	0%	0%	0%	nq	nq	nq	nm	nq	-	nq	2015
CHEME18	Propsed plan	**0%**	nq	nq	nq	nq	nq	nq	nq	nq	nq	-	nq	-
CEFIC19	Plausible estimate	**50%**	nq	nq	nq	nq	nq	nq	nm	nm	nq	-	nq	2015
GCHEM19	Technology pathway	**39%**	nq	nq	nq	0%	nq	nq	nq	nq	nm	-	nq	2020
	Greenhouse gas neutrality pathway	**3%**	nq	nq	nq	0%	nq	nq	nq	nq	nm	-	nq	2020
FCHEM20	Fast development scope 1&2	**40%**	0%	0%	15%	6%[5]	12%	29%	13%	17%	nq[6]	-	-31%	2015
	Carbon neutral chemistry scope 1&2	**1%**	3%		25%	15%[5]	27%	27%	19%	16%	nq[6]	-	-31%	2015
	Fast development feedstock	**38%**	nq	nq	nq	nm	nm	nm	nm	nm	nm	-	nq	2015
	Carbon neutral chemistry feedstock	**-59%**	nq	nq	nq	nm	nm	nm	nm	nm	nq	-	nq	2015
CEFIC21	High electrification	**0%**	nq	31%[7]	2%	6%	nq	16%	nq[8]	nq	nm	28% & 16%[9]	-	total effort
	Fostering circularity	**0%**	nq	19%[7]	3%	17%	nq	13%	nq[8]	nq	nm	30% & 17%[9]	-	total effort
	Sustainable biomass	**0%**	nq	27%[7]	2%	17%	nq	13%	nq[8]	nq	nm	28% & 13%[9]	-	total effort
	CO_2 capture	**0%**	nq	31%[7]	0%	45%	0%	12%	nq[8]	nq	nm	0% & 12%[9]	-	total effort
GIND21	Proposed path	**0%**	nq	nq	0%?	0%	nq	nq	nq	nq	nq	-	nq	-
EC17	Prospective scenario	**85%**	nq	0%	nm	nq	nm	nm	nm	nq	nm	-	nq	2013
NGOV18	Transition agenda	**nq**	nq	nq	nq	nm	nm	nm	nm	nm	nm	-	nq	2020
ECF19	Pla. New processes	**0%**	nq	nq	0%	0%	nq	nq	nq	nq	nq	-	-11%	2015
	Pla. Circular economy	**0%**	nq	nq	0%	0%	nq	nq	nq	nq	nq	-	-11%	2015
	Pla. Carbon capture	**0%**	nq	nq	0%	34%	nq	nq	nq	nq	nq	-	-11%	2015
	Amm. New processes	**0%**	2%	0%	-	0%	61%[10]	nq	nq	9%	nq	-	27%	2015
	Amm. Circular economy	**0%**	5%	0%	-	0%	50%[10]	nq	nq	18%	nq	-	27%	2015
	Amm. Carbon capture	**5%**	2%	0%	-	39%	18%[10]	nq	nq	9%	nq	-	27%	2015
ACA21a	Circular carbon pathway (combo)	nq	nq	nq	nq	nq	nm	nq	nq	nm	nm	-	nq	-
ACA21b	1.5 °C case	**0%**	11%	6%	25%[11]	68%	nq	33%	7%	70%	nq	-	-115%	2017

[1] Included in electrification
[2] H_2 for ammonia/urea
[3] Included in renewable energy
[4] N_2O
[5] All carbon capture
[6] Included in other categories
[7] All biogenic carbon removal, i.e both for feedstock and energy
[8] Included in biomass
[9] Reductions of other direct emissions & upstream and imported emissions
[10] Includes H_2 via water electrolysis
[11] H_2 feedstocks including ammonia

Table 4.3 – Feedstock used used in the pathways, as shares of total feedstock base for the products specified in the roadmaps. Note that this may vary between roadmaps so the values may not be fully comparable. For roadmaps presenting mechanical and chemical recycling separately, this table shows mechanical recycling as the first value and chemical as the second. Alternative feedstocks are given a green colour and fossil feedstocks are given a red colour. A deeper colour corresponds to a larger share. Gray is used if the value is zero, and yellow is used if the the feedstock source is mentioned but not quantified ("nq").

Document codename	**Scenario**	**Fossil**	**Recycling**	**Biomass**	**H_2 and/or CCU**
CEFIC17	Intermediate	75%	0%	3%	23%
	Ambitious	53%	0%	4%	43%
	Maximum	4%	0%	4%	92%
NCHEM18	Circular & biobased	nq	nq	nq	nq
	Electrification	nq	nq	nq	nq
	CCS	nq	nq	nq	nq
	2030 compliance at least cost	nq	nq	nq	nq
	direct action & high-value applications	nq	nq	nq	nq
PORT18	Technical progress (TP)	nq	0%	0%	0%
	Biomass and CCS (BIO)	nq	0%	nq	0%
	Closed carbon cycle (CYC)	0%	nq	nq	0%
CHEME18	Propsed plan	0%	nq	nq	nq
CEFIC19	Plausible estimate	nq	nq	nq	nq
GCHEM19	Technology pathway	46%	12%	29%	14%
	Greenhouse gas neutrality pathway	6%	11%	28%	55%
FCHEM20	Fast development scope 1&2	nq	nq	nq	nq
	Carbon neutral chemistry scope 1&2	nm	nq	nq	nq
	Fast development feedstock	44%	27%	27%	2%
	Carbon neutral chemistry feedstock	9%	41%	42%	8%
CEFIC21	High electrification	60%	8%	27%	5%
	Fostering circularity	54%	19%	17%	10%
	Sustainable biomass	53%	7%	35%	5%
	CO2 capture	88%	11%	1%	0%
GIND21	Proposed path	0%	18%+12%	70%	0(?)
EC17	Prospective scenario	100%	nq	0%	nq
NGOV18	Transition agenda	44%	31%+10%	15%	0%
ECF19	Pla. New processes	0%	15%+47%	38%	0%
	Pla. Circular economy	0%	25%+38%	37%	0%
	Pla. Carbon capture	38%	15%+14%	33%	0%
ACA21a	Circular carbon pathway	1%	19%+25%	38%	17%
ACA21b	1.5 C case	36%	nq	25%	39%

roadmaps. For those that quantify the emission reduction from recycling, its effect is generally low compared to other strategies, between 3 and 11% of the reference year emissions.

The recycling technologies used is almost always both mechanical and chemical, and which is used more varies. Some roadmaps, e.g. GCHEM19 specify that chemical recycling will be used only after 2030. EC17 did not consider chemical recycling arguing that only mechanical recycling uses PVC of high enough quality to replace virgin feedstock (they also did not consider recycling for other plastic types than PVC). Several types of chemical recycling are typically mentioned, but there is a slight preference for pyrolysis and gasification (although CEFIC21 mainly uses PET solvolysis).

Recycling, or the concept of circularity is one of the key conceptual strategies in the roadmaps. When creating multiple pathways, it is common that one of them focus on circularity with a large focus on recycling. When discussing circularity and recycling, several of the studies note the need for improved collection rates, waste and recycling infrastructure as well as markets for the end-of-life material. This is further discussed in 4.4.

Biomass as feedstock

Biomass is used as feedstock in all roadmaps except EC17 and the TP and CYC scenarios in PORT18. The biomass is also sometimes used for energy, which is discussed in 4.2.2. The main exception EC17 mentions the use of biomass for various processes, but those are not included due to lack of information or not used since they do not become cost-effective. The use of biomass as feedstock contributes between <3% and 59% to the reduction of emissions and is used for 1 up to 70% of the feedstock, although most often in a range around 30%. CEFIC17 however uses exceptionally low amounts of around 4% even in the most ambitious scenario. This is explained by stating that the routes to produce olefins and aromatics from biomass requires large amounts of feedstock and are expensive compared to the CO_2 avoidance, and is thus an inefficient use of biomass. Overall however, biomass for feedstock is one of the main strategies considered. When different types of pathways are developed, one typically focuses on the use of biomass, sometimes as a combined path with recycling.

The types of feedstocks considered vary: from wood, agricultural residues, sugar crops to algal oil, but wood and other lignocellulosic biomass like biomass residues are mentioned more commonly, and sugar crops for the (less common) instances where bioethanol is produced. The biomass is most commonly expected to be processed through gasification followed by Fischer-Tropsch or methanol-to-olefins. Overall the preference is thus for biomass use that can be integrated as drop-in solutions, but there are also instances of biomass use for bio-specific polymers, for example NCHEM18 and ECF19.

There is also a high awareness and emphasis of the risk of unsustainable use of biomass. Estimations of available sustainable amounts are often used for comparison. Regional differences in how biomass use is viewed and assumed would be conceivable, although only PORT18 and CEFIC21 note regional opportunities in this regard.

CCU and hydrogen as feedstock

Capturing CO_2 to use the carbon for new feedstock is used in a majority of the roadmaps. However, there is an overlap of the CCU strategy with the hydrogen strategy, since transforming the CO_2 to olefins requires addition of hydrogen. Hydrogen is however also used as feedstock for ammonia, where no carbon is needed, which complicates the distinction of the two strategies. Their contribution to emission reduction when used is very varying, and multiple examples exist both of a few percent and of more than 50% of emission reduction. It similarly varies largely as share of feedstock.

A few roadmaps explicitly avoid CCU as a mitigation strategy/source of feedstock, and interesting to note is the discussion around if captured carbon should be used (CCU) or stored (CCS) in the roadmaps. FCHEM20 and CEFIC17 consider CCU a better alternative since it closes the carbon cycle and that the deployment of CCU making the chemical industry a net importer of CO_2 makes CCS counterproductive. On the other hand, both ECF19 and GIND21 reason that net-zero puts stronger restrictions on which technologies can be used, and for short-lived products CCU might only delay the emissions rather than avoid them. PORT18 similarily note that CCU is only carbon neutral as long as the captured carbon remains in a cycle of use and recycling.

Various sources of CO_2 are used in the different roadmaps with more or less specific examples. CO_2 is assumed to be taken from various industrial sources, e.g. refineries, steel, cement, power plants and biomethane production, and is thus not modelled as restricted to the chemical sector. It is furthermore not obvious how these flows are accounted for in terms of emission reductions. For example, CEFIC21 counts CO_2 captured from the chemical industry as neutral or slightly positive if it is of fossil origin and negative it is biogenic, whereas CO_2 captured from other industries is counted as negative. GCHEM19 on the other hand counts all CCU as negative regardless of whether the origin is biogenic or fossil. In relation to carbon capture, calls are often made for the need of CO_2 infrastructure and sometimes integration with other industries.

H_2 is needed for several of the processes but is especially necessary for CCU. The H_2 is often specified as electricity-based and green/pink in some cases. A few, e.g. NCHEM18 and ECF19 also open up for blue H_2, i.e. fossil-based production like steam methane reactors with carbon capture. In NCHEM18, such a solution is used initially as a kick-start. More unabated fossil-based H_2 is likely assumed in the pathways with lower emission targets. The use of electrolytic H_2 requires large amounts of low-carbon electricity, and CCU thus becomes a significant contributor to the use of electricity. Electricity use is discussed more in section 4.2.2.

Fossil feedstock

Most roadmaps assume a significant use of fossil feedstock, often in the scale of 50% especially for the pathways that are not aimed at carbon neutrality. There are however multiple examples of roadmaps where 0 or <10% of the feedstock is fossil. The continued use of fossil feedstock either means that lower emission reductions are reached, and/or that strategies like CCS are used to a larger extent (as in both CEFIC21 and ECF19). Net-zero emissions are however still reached in the case of CEFIC21, ECF19 and ACA21b, despite continued use of fossil feedstock.

4.2.2 Energy use

The scope 1 and 2 emissions are mitigated by switching energy sources from fossil to alternative sources, but also through the decreased emission factor of the electricity that is used. It includes electrification of processes, alternative heat sources including electricity, geothermal, solar or biomass energy. It also relates to H_2 through the electricity needed for production through electrolysis. The use of H_2 for feedstock was discussed in the previous section, but the electricity demand this implies is elaborated on here. These strategies often account for large shares of the emission reductions. Which sources of energy are used can be seen in Table 4.4. Almost all roadmaps that quantify energy sources use electricity to a large extent, often accounting for >50% of the energy use, but biomass is also sometimes used as an energy source. Note that some roadmaps only show the total energy use for both energy and feedstock purposes, which complicates the comparison.

Electricity and H_2

Much of the current emissions originate in the use of energy, both energy within and without of the chemical industry (scope 1 and 2), thus large portions of the emission reductions are gained through electrification of processes and the energy sectors transition to low-carbon. Electrification is one of the central themes and is commonly the main focus of a thematic pathway. Electricity consumption is expected to increase in almost all roadmaps (EC17 being the exception) and often makes up the majority of the energy use. How much the electricity use increases varies widely, but the increases are often dramatic. The roadmaps often show a 5-fold increase, but even 10-fold increases are expected in some cases (e.g. PORT18 CYC scenario, GCHEM18 and FCHEM20 neutrality pathways, and ACA21b). The absolute most important factor for electricity demand increase is H_2 production via water electrolysis, which often requires around 80% of the electricity in the most demanding scenarios. More ambitious scenarios tend to have higher electricity demands.

Other electrification measures mentioned include heat pumps, electric steam recompression, electric steam production and electric crackers. These are all commonly mentioned and appear in several of the roadmaps although not necessarily in one and the same. The effect these have on electricity use is not as dramatic as water electrolysis for H_2. Carbon capture also requires electricity but is likewise seldom a large factor.

The pathways assume that the electricity comes from low emission intensity sources, and the emission intensity is sometimes assumed as zero since renewable electricity production does not cause any emissions during operation. The high demands of low-carbon electricity put on the energy sector is often pointed out. Furthermore, the assumption of zero-emissions electricity production is less valid when the full life cycle emissions of electricity are included since even the most low-carbon sources today still cause some small emissions during its life cycle. Vattenfall for example report a carbon footprint of 27 g CO_2eq/kWh for PV, and in the range of 4-7 g CO_2eq/kWh for wind, water and nuclear (Vattenfall, n.d.-a, n.d.-b, 2019, 2021), although it should be noted that these values can change with time depending on the energy source used in the life cycles of these constructions. ACA21a show that the best choice of strategy from a climate perspective can vary depending on this emission intensity, where CCU strategies are especially sensitive.

Table 4.4 – Energy sources used in the pathways, as shares of total energy use. Alternative energy sources are given a green colour and fossil energy sources are given a red colour. A deeper colour corresponds to a larger share. Gray is used if the value is zero or if the energy source is not mentioned (“nm”), and yellow is used if the the energy source is mentioned but not quantified (“nq”).

Document codename	**Scenario**	**Fossil**	**Waste material**	**Biomass**	**H_2**	**Electricity**	**Other/ Non-separable**	**Note**
CEFIC17	Intermediate	65%	0%	5%	nq[1]	30%	nq	Energy+feedstock
	Ambitious	44%	0%	7%	nq[1]	50%	nq	Energy+feedstock
	Maximum	3%	0%	7%	nq[1]	90%	nq	Energy+feedstock
NCHEM18	Circular & biobased	nq	nq	nq	0%	nq	nq	
	Electrification	nq	nq	nq	nq	nq	nq	
	CCS	nq	nq	nq	0%	nq	nq	
	2030 compliance at least cost	nq	nq	nq	0%	nq	nq	
	direct action & high-value applications	nq	nq	nq	nq	nq	nq	
PORT18	Technical progress (TP)	76%	0%	0%	nq[1]	24%	nm	Energy
	Biomass and CCS (BIO)	21%	7%	7%	nq[1]	64%	nq	Energy
	Closed carbon cycle (CYC)	5%	nq	0%	nq[1]	80%	15%[2]	Energy
CHEME18	Propsed plan	0%	nm	nq	nq	nq	nq	
CEFIC19	Plausible estimate	nq	nm	nq	nq	nq	nq	
GCHEM19	Technology pathway	21%	4%	21%	nq[1]	48%	5%[3]	Energy+feedstock
	Greenhouse gas neutrality pathway	2%	2%	11%	nq[1]	81%	3%[3]	Energy+feedstock
FCHEM20	Fast development scope 1&2	nq	nm	nq	nq	55%	nm	Electricity+heat
	Carbon neutral chemistry scope 1&2	nq	nm	nq	nq	74%	nm	Electricity+heat
	Fast development feedstock	nm	nm	nm	nm	nq	nm	Electricity+heat
	Carbon neutral chemistry feedstock	nm	nm	nm	nm	nq	nm	Electricity+heat
CEFIC21	High electrification	12%	nm	0%	nq[1]	88%	nm	Energy
	Fostering circularity	9%	nm	1%	36%[4]	55%	nm	Energy
	Sustainable biomass	10%	nm	2%	34%[4]	54%	nm	Energy
	CO2 capture	19%	nm	41%	9%[4]	31%	nm	Energy
GIND21	Proposed path	0%	2%	11%	2%	76%	8%[5]	Energy
EC17	Prospective scenario	88%	nm	0%	nq	12%	nm	Energy
NGOV18	Transition agenda	nm	nq	nm	nm	nm	nm	
ECF19	Pla. New processes	0%	45%	29%	nq[1]	29%	nm	Energy+feedstock
	Pla. Circular economy	0%	46%	29%	nq[1]	26%	nm	Energy+feedstock
	Pla. Carbon capture	33%	20%	22%	nq[1]	26%	nm	Energy+feedstock
	Amm. New processes	nq	nm	nm	nq	nq	nm	
	Amm. Circular economy	nq	nm	nm	nq	nq	nm	
	Amm. Carbon capture	nq	nm	nm	nq	nq	nm	
ACA21a	Circular carbon pathway	0%	nq	35%[6]	nq[1]	65%[6]	nm	Energy+feedstock
ACA21b	1.5 °C case	24%	nq	28%	19%	20%[7]	9%[8]	Energy

[1] Included in electricity

[2] Other is steam from undefinable and mixed sources

[3] Energy from district heating

[4] H_2 is from market, own H_2 production counted in electricity. Electricity also includes electricity for H_2 from market production

[5] 7% district heating +1% ambient heat

[6] Two alternatives are given in the roadmap, the values here correspond to the given feedstock values, but the second alternative representing a "feasibility point" relating to available resources would mean 81% and 19% for biomass and electricity respectively)

[7] Excluding electricity for H_2

[8] 2% solar thermal, 7% district heating

Biomass and other renewable energy sources

Apart from electricity, other renewable heat sources are used in some roadmaps, contributing to reduced emissions of around 10%. Using biomass and biofuels for heat and steam is the main contributer, but solar and geothermal heat are mentioned as well. The largest quantified use of biomass for energy is seen in the CEFIC21 CO_2 capture scenario, where it makes up 40% of the use. In this case and in a few other, the material is used in biomass boilers for steam and heat. Other examples exist where it is used in combined heat and power generation, and the use of biomass as heat via district heating also appears in a few roadmaps. While these types of uses are more mature and sometimes used today, the use of biomass for energy is modest in the roadmaps for 2050, where its uses as feedstock is prioritized instead. ECF21 puts this clearly:

> "*Bioenergy can provide a drop-in solution via wood pellets or biogas. This can provide valuable early emissions cuts, but switching a large amount of industrial energy to biomass rapidly starts to make large claims and electricity can often be an alternative.* [...] *Instead, the main use of biomass in the pathways is as a feedstock and source of non-fossil carbon in industrial processes. Whereas today's discussion and scenarios focus on 'bioenergy', in fact we will also need 'bio-feedstock'.*"
> (Material Economics, 2019)

A few roadmaps mention other renewable energy sources, mainly geothermal and solar heat. These are used to provide process heat up to around 200°C and contribute a few percent to the total emission reduction and energy supply.

Use of fossil energy

Like with fossil feedstock, fossil resources for energy remains in many of the roadmaps, often in the scale of 10-30% of the energy (Table 4.4). In some cases, e.g. FCHEM20, emissions are still reduced by switching to less emission intensive variants, the main example being switches to natural gas. Again, less ambitious scenarios and CCS-type scenarios (where emissions remain low as the fossil carbon is captured) tend to have higher amounts of fossil energy sources left, but fossils remain in net-zero pathways as well.

4.2.3 CCS and system measures

Some strategies do not directly change either the feedstock or energy, but reduce emissions in other ways. CCS and efficiency improvements are quantified most often although other measures like industrial symbiosis can be mentioned in the roadmaps (see Table 4.2). CCS is one of the most commonly mentioned and quantified strategies, and its use ranges widely. Efficiency improvements generally shows a more limited range of reduction potential. System measures can be a way to show a greater sense of maturity and system awareness, especially when it comes to measures that go beyond the own industry.

CCS

CCS is one of the main emission reduction strategies considered. In roadmaps where different pathways focus on different themes, CCS is usually one of them similarily to biomass, circularity, and electrification. Despite this however, there are about as many pathways that avoid using CCS than there are that use it. In many roadmaps the strategy is limited to the pathway that specifically fosuses on it, and some roadmaps avoid it altogether. In CEFIC17, CCS is avoided as CCU is seen as a better option for captured carbon. GCHEM19 see it as an option but have still not included it. In GIND21, it is considered for other sectors but not the chemical industry. Thus, the reasons for exclusion vary. In the cases where CCS is used, it contributes to emission reductions in the range of 6 to 68%, often around 20%.

While the use of CCU was more focused on capturing emissions from various parts of the industry (for use in the chemical industry), CCS here only refers to capture in the chemical value chain. The technology is applied to a variety of CO_2 sources. The roadmaps identify that the cheapest and easiest application of CCS is to process emissions (mainly on crackers, but also on other higher purity processes like (fossil) methane reforming and ammonia production), but other emission sources may have larger total potential. Some apply CCS to waste incinerators at the products end-of-life, which reduces scope 3 emissions rather than scope 1. As explained in section 2.2, a majority of the emissions from the life cycle of plastics appear at this stage. Applying CCS to waste incinerators is however more difficult that applying it to industry, since waste incineration is typically more distributed, lower concentration and smaller scale compared to industrial emission point sources. The responsibility may then also be shifted to, or shared with the waste management sector.

As pointed out previously, CCS-type pathways tend to allow larger amounts of fossil resources to remain in use, and more of the existing production units can remain more or less intact. This type of pathway is also often estimated to be cheaper, as described in section 4.3.

Energy efficiency

Efficiency improvements includes many different kinds of measures, from small scale optimization measures of process steps to reconfigurations of the plant to better utilize waste heat flows. In the roadmaps, it is often not specified which efficiency measures are taken, rather continuous improvements are expressed as assumptions of e.g. 0.5% improvement per year. It is sometimes assumed that there will be less efficiency improvements in scenarios that do more other transformations (e.g. CEFIC17). This is because the existing processes will be replaced instead of receiving the regular continuous improvements. Table 4.2 shows the assumed emission reductions from efficiency improvements in the scale of around 10% of reference year emissions, these mainly being due to energy efficiency. ACA21b is the exception, where energy efficiency, demand reduction and industry relocation together make up 70% of the emission reduction compared to the reference year, of which 30% is due to energy efficiency. This roadmap uses a global scope, so both the assumed demand increase and potential for energy efficiency improvements is assumed higher.

Material efficiency and lower production

Material efficiency is addressed in most of the roadmaps, in terms of process improvements and/or through product material efficiency aimed at increasing use intensity. Process improvement measures are more commonly mentioned than the latter. Product material efficiency measures mentioned in industry roadmaps include circular business models (e.g. paying for function), reuse, designing for circularity and measures to enable transfer of materials for reuse (NCHEM18 and CEFIC19). The non-industry roadmaps ECF19 and NGOV18 explore these types of measures in more detail but overall point to the same types of measures. How much these types of measures contribute to emission reductions could not be quantified specifically.

Only ECF19 and ACA21b assume or explore decreased production in their roadmaps. The general assumptions of demand are typically made as annual growth rates, often 0.5%-1% per year. The effect of this increase partly corresponds to the emission increase seen in column "Effect from BAU" in Table 4.2. The increase in demand is justified by referring to literature and e.g. NCHEM18 also discusses the demand in more detail. They assume that the overall demand will increase by about 34% between 2019 and 2050, but demand for different chemicals was adjusted based on trends in different sectors. While they find that some indicators point to increased demand (e.g. lightweight vehicle material and construction), they mention conflicting trends for packaging material regarding social and political concerns as well as increased demand for recycled materials. That decreased emissions through demand reductions is not more thoroughly explored is thus motivated given that global demand is expected to increase in all projections. The roadmaps from industry also intend to show how the industry can keep and adapt their production to fit into a net-zero future, so reaching the goal by reducing production could in a way be seen as "cheating". Exploring the options for decreased use should however still be encouraged, especially from a societal perspective.

Industrial symbiosis and relocation

Utilization of other industries' waste flows is already done today to some extent and depending on location. An expansion of industrial symbiosis is often mentioned or implied as a strategy in the roadmaps, but its contribution to emission reduction is never quantified. The measures discussed include integration of heat (often via district heating), CO_2, CO and H_2, where heat and CO_2 are most commonly mentioned. Some roadmaps also discuss how an electrified chemical sector could provide demand side response services to the energy sector (e.g. FCHEM20). Local conditions are discussed by some, CEFIC21 (as mentioned earlier), as well as the cluster roadmaps that highlight their specific oppurtunities. A few other also mention the benefits of clustering (e.g. NCHEM18, FCHEM20, ECF19), but only ACA21b discusses relocation, which there contributes 2% to emission reduction.[3]

Since strategies like industrial symbiosis and relocation are almost never considered more than qualitatively, there could be an untapped potential worth investigating quantitatively. Displaying the size of the potential in the roadmaps could motivate the industries and clusters to find solutions. The process of making a quantitative assessment and cooperating with possible partners to find the potential could itself trigger development. This may hold more true for more local roadmaps where the potential partner are more given.

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[3] Included in Efficiency improvements in Table 4.2.

4.3 Investments and costs

No detailed analysis of costs will be given in this thesis, but since the costs are often estimated to be multiples higher than is typical for the industry, it will be addressed, both in terms of investment costs and production costs.

Investments

Most roadmaps give estimations for investment costs and an overview is shown in Table B.1 in Appendix B, but keep in mind that the geographical and product scopes vary. Investments are needed for deploying new production processes (which are often more complex), but also for one-off costs for pilots and demonstrations as well as conversion of existing processes. Compared to baseline investments, the typical increase in investment is 100-200%[4]. The estimations do however vary widely between roadmaps, from CEFIC17 showing investments in the range of 700-1200% higher to CEFIC21 and GCHEM19 with increases in the range of 11-60% depending on pathway. How the roadmaps account for investments made within as opposed to outside the industry's own operation may differ (for instance if investments for water electrolysis is included or if the cost of H_2 is counted as a production cost), which could be one factor to explain the widely varying results. Furthermore, EC17 do not display investment costs and only includes measures with a pay-back period of 2 years, which is typical for efficiency projects but too short for strategic projects. What requirements are set for the profitability of an investment is thus another factor that can vary greatly between roadmaps. When different pathways are compared in the same document, the carbon capture type pathways typically turn out to have the lowest investment costs[5], and more ambitious scenarios have higher investment costs.

Investments into biobased feedstock technologies (e.g. gasification and Fischer-Tropsch processes) and H_2 technologies typically rank high on the list of most significant investments. The largest investments are always expected to be needed after 2030, but the investment peak ranges from around 2035 to after 2050 depending on roadmap and pathway. A few put these numbers into perspective, for example GIND21. They compare the investment sums for the total German transition (including energy, transport, buildings and industry sectors) to the country's GDP:

> "*Implementing climate protection measures requires additional investments of about €860 billion by 2030, or about €100 billion a year—almost 2.5 percent of Germany's gross domestic product (GDP).*" (BCG, 2021a)

GIND21 also state that the government spending for this total German transition would be 0.9% of the GDP, which would be similar to the Marshall plan spending after World War II or just under half of the Reconstruction East program after the fall of the Berlin Wall.

Another aspect of investments and economic feasibility are risks, which can affect both readiness to invest in new technology as well re-investments in current processes. The future is veiled

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[4] Even though it is not clear from the table, this includes ECF19 and FCHEM20 as well, if, for ECF19 the investments for plastic and ammonia are summed, and for FCHEM20 if the scope 1& 2 scenarios and feedstock scenarios are summed. This is not completely accurate for FCHEM20, which states that the investments in different scopes sometimes overlap and are not additive, so the sum should in this case show a upper estimate.

[5] In the case of NCHEM18, however, the CCS pathway does not reach the same emission reduction as the others.

in uncertainty for example in terms of resource availability and regulatory conditions as pointed out by several roadmaps. Some also bring up the risk of lock-ins and stranded assets if investments are made that do not turn out as planned. The non-industry roadmap ECF19 describes the risk issue most clearly:

> "*The early investments will be undertaken in a situation of significant uncertainty about technical viability, future availability and cost of new inputs, and degree of policy support. Increased risk in turn increases the bar for raising capital, and the cost of both debt and equity.*" (Material Economics, 2019)

The aspect of risk thus influences investment decisions made by the chemical industry but is also something that is partly beyond the control of the chemical industry. This is a dependency that is further discussed in section 4.4.1.

Feedstock, energy and operational costs

The transition also means changed costs for energy and feedstock, and an overview of the estimations in the roadmaps can be found in Table B.2 in Appendix B. These costs constitute a significantly larger share of the total costs, being around 5 times higher but for some pathways as much as 20 times higher than the investment costs. Thus, variations of these costs have a larger impact on the total cost estimation. Here, we also see an increase typically around 20 to 80%, but sometimes more than doubled costs and sometimes lowered costs. Also here, CCS pathways and less ambitious pathways show lower costs, although in ECF19 it is shown that mechanical recycling is the cheapest production route out of all. Another notable exception is ACA21a which uses a global and life cycle perspective and find that the operational costs are in the same range in a circular carbon pathway as in a linear pathway with CCS. Biomass/biofuels or electricity are often the dominating factors for high costs, although fossil resources can also be among the most significant costs.

4.4 Dependency on other actors and stakeholders

The documents clearly point to the dependency of other actors to achieve the net-zero target. The industries operate within the given economic framework and as such transition will not happen unless it is economically justifiable. This baseline is communicated more or less directly in all roadmaps. Conversely, this implies that transition will naturally happen if it is the most economically viable option. This interpretation is likely oversimplistic as other factors and inertia could also be affecting decisions, but this is not discussed in the roadmaps. But what makes a transition economically viable is dependent on various framework conditions and can be changed. Figure 4.1 gives an overview of typically mentioned dependencies for chemical industry transitions, and several of these aspects are further elaborated on in this section. As can be seen, the role of governments and policy is the most detailed and emphasized in the roadmaps, but the energy sector and other businesses like the waste management sector and actors throughout the product value chain are also mentioned at times. The role of the public, consumers and civil society is less discussed. A general pattern can also be seen that collaboration with a variety of actors will be essential, as well as further technology development. The dependencies brought up in the roadmaps will here be described in overall and general terms, but more thorough notes on what is brought up in each of the roadmaps can be found in Appendix C, which forms the basis for this evaluation.

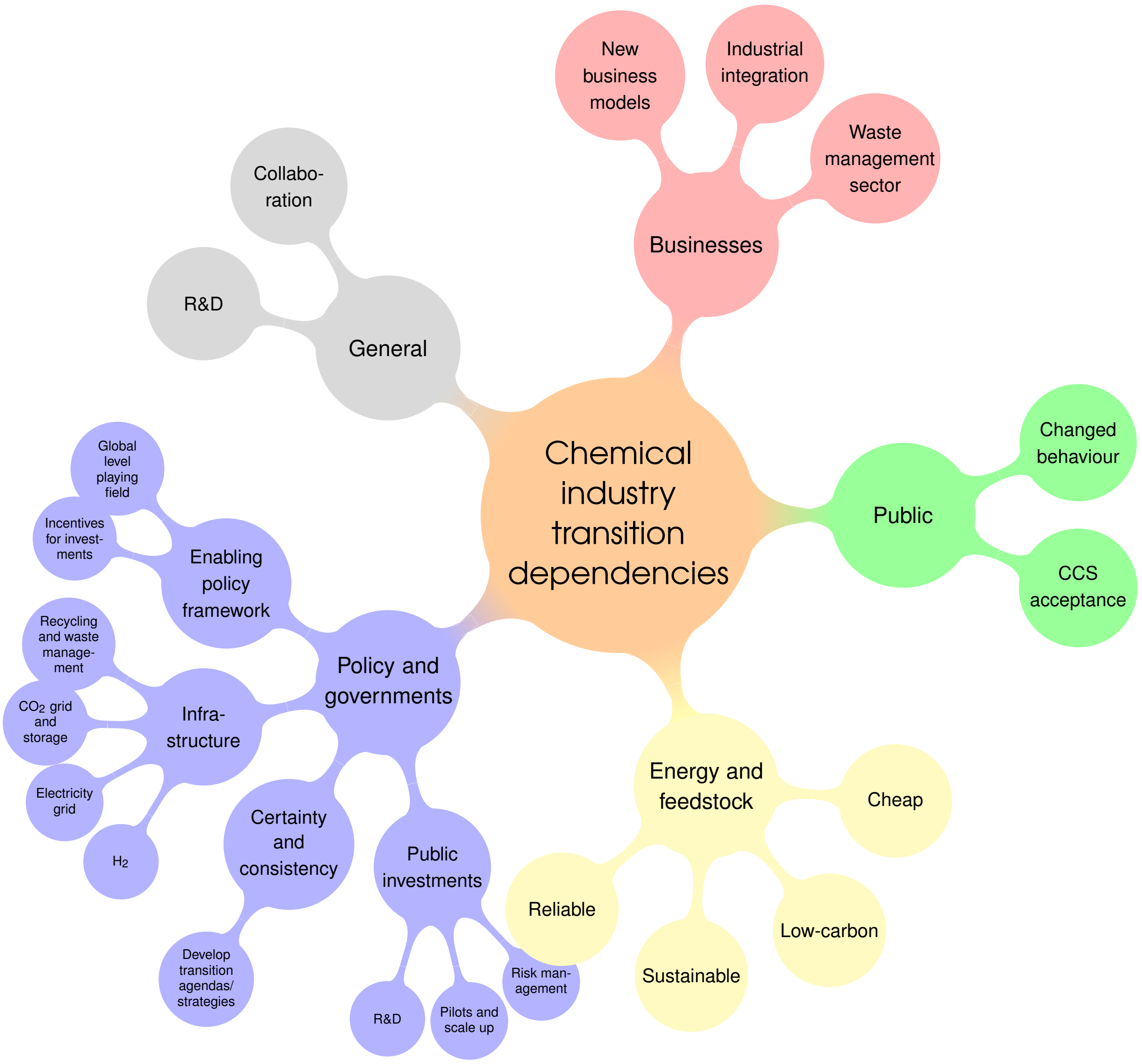

Figure 4.1 – Chemical industry transition dependency on surrounding framework.

4.4.1 Government and policy dependency

International, national and regional government bodies control many of the tools affecting the transition viability, both through finance and policy. One of the most commonly requested condition in the roadmaps is a global level playing field, but in the absence of such a framework, governments are asked for compensatory measures in order to remain competitive. Policy measures also relate to creating an enabling framework in general by providing clarity, removing legislative obstacles, investments in infrastructure and through R&D funding (including for demonstration and scale-up). The roadmaps also point to a need for these changes to be long-term, reliable and consistent over time.

Enabling policy framework

The central task of creating an enabling policy framework is a broad-spanning task with a wide range of specific actions, including showing direction, fair carbon pricing and other enabling economic conditions, as well as a variety of other actions. One way for the government to show direction is to develop strategies and visions for resources like biomass and H_2, but also for innovation and investment frameworks. Policy can also help enable the transition by recognizing new possibilities in legislation. For example, CEFIC19 asks for chemical recycling to be recognized in legislation as a valuable waste management option, and the framework can be made clearer through standards and definitions. CHEME18 points to redefining end-of-life plastics and CO_2:

> "*Laws and regulations may hamper Chemelot's ambition to become sustainable. This is currently the case in many areas. For instance, plastic is still seen as waste, rather than a raw material, which limits the ways in which it can be recycled. Obtaining used plastic from Germany and Belgium is extra difficult due to these restrictions. Legislation surrounding CO_2 can also hamper CO_2 storage solutions. Shipments of CO_2 to Rotterdam currently fall within the emission category. We're also asking for a new framework of CO_2 usage (CCU), for instance to develop the use of CO_2 in building materials.*" (Chemelot, 2018)

Fairness and carbon pricing

Fairness is a central topic in the roadmaps when it comes to incentivizing against harmful environmental practices. In the absence of equal legislation across the globe and a universal carbon price, enforcing EU legislation at the border and carbon border taxes are brought up as alternatives. The EU ETS is seen as an important tool which should be expanded and prices increased in some cases, yet it is not without fault. For one, as long as it is not global it gives a competitive disadvantage compared to other parts of the world, and the roadmaps seek compensation for this. At the same time, the EU ETS is also sometimes pointed out to not be sufficient incentive to spur transition. This is partly dependent on what carbon price is assumed in the roadmaps, and time has shown that many of these are underestimations. The CO_2 allowance price has increased rapidly the past two years (from around 25€ by the start of 2020 to around 90€ in May 2022 (Trading Economics, 2022)). However, their conclusions may not have changed dramatically even if the price was correctly estimated. Some roadmaps that try varying the price (e.g. EC17) find that it has a small effect on the end result. Other roadmaps, e.g. FCHEM20, find that higher prices would help enable solutions like carbon capture, and that will play a larger role if the electricity prices are high. That electricity prices have a more significant effect than EU ETS prices is also presented by GCHEM19, showing that electricity makes up >70% of the cost in 2050 in the most amitious scenario, whereas emission allowances make up $\sim$10% in the reference scenario.[6] Other ways to create more enabling economic conditions includes for example lowering taxes on renewable energy, creating lead markets and allowing state aid to be used for sector transformation measures.

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[6] Assuming an electricity price of 40 €/MWh and 100 €/t CO_2e respectively.

Financial support and infrastructure investments

The requests for financial support are mainly for R&D including pilots, demonstrations and commercialization (FCHEM20 especially point to a need for expanding R&D to RDD&D including deployment and demonstration). Another important financial issue is risk management. While this is a central point in several of the roadmaps, fewer discuss solutions to manage it. Still, some examples exist such as public-private partnerships for risk sharing. Some risk is also an effect of uncertainty about future regulatory conditions, which is naturally reduced by regulatory certainty. Highlighted among the investment needs is also the need for new, updated and optimized infrastructure, in terms of CO_2-grids, transport and storage, energy infrastructure like electric grid and energy storage, H_2 infrastructure as well as waste handling and recycling. The latter is especially important to enable higher mechanical recycling rates since this requires higher purity waste streams. The management includes efficient collection, sorting, cleaning and processing. This development of new material value chains opens up for new actors, as ECF19 mentions. The infrastructure requires investments and planning.

4.4.2 Knowledge and R&D

The roadmaps rely partly on non-commercialized technologies (some specifying e.g. TRL above 5, or technologies at a high development stage). This implies the need for further R&D in order to follow the described path. A large dependency thus lies in whether or not the R&D will be successful. Some also point to the need for education and attracting talents, and that this also requires funding and incentives. Education and talents are needed as a foundation for innovation and R&D, but education is also needed to enable the workforce to adapt, as FCHEM20 and NGOV18 point to. The consideration for the social agenda and effects on the labour market is especially emphasized in NGOV18, and solutions and suggestions for how to manage these effects are discussed thoroughly therein, for example:

> "*In addition to R&D, the chemical industry has to invest in training in particular. Employees need to be trained so that they gain knowledge of recycled and bio-based raw materials as a new "feedstock" for the plants. People must be versed in new innovative technologies for chemicals (use of catalysts) and biotechnology (use of enzymes and bacteria). Purchasers must receive different instructions and acquire more knowledge of the recycling market and the bio-based plastics industry.*" (*Transition agenda Plastics*, 2018)

4.4.3 Energy and feedstock dependencies

Despite the large number of dependencies, the question of electricity availability stands out as one of, if not the the most significant. FCHEM20 made a two variable sensitivity analysis with electricity and carbon price, and wrote thus:

> "*Trying to model the development of the world and all its driving forces during the next 30 years is being tried by many but will fail – too many wheels within wheels, too many surprises. What the indicative analysis with two variables points at is that the message in this study of the need for cost-competitive low-carbon electricity truly weighs heavy on the success of carbon neutrality.* (Pöyry, 2020)

The need for large amounts of reliable, cheap and low carbon electricity is emphasized in many of the roadmaps, and the need is at a level far from what is available today. GCHEM19, who assume an electricity price of 40 €/MWh, states that the industry cannot reach greenhouse gas neutrality by 2050 if the electricity price is 60 €/MWh. For comparison, the average price of electricity in the EU today is about 80-90 €/MWh (Eurostat, 2022), while at a fossil share of 37% of the electricity production (Jones, 2021).

The issue of sustainable biomass availability is frequently discussed in the roadmaps, and it is common to relate the biomass amounts in the pathways to estimated available amounts. Since the limited supply is an issue, and since several possible uses for this resource exists, some roadmaps also ask for the development of strategies and criteria for use, or generally call for biomass to be used strategically on a system level.

4.4.4 The public, civil society and costumers

Some of the roadmaps also lift up a dependency on the public. The most prevalent dependency is that of CCS public perception, where there is a need to overcome the low acceptance for CCS. Other mentions of the public are more general and fewer (mainly from CEFIC19), e.g. to share the same expectations, send clear signals and show participation and acceptance in decarbonization. Since costumer demand drives the industry, notions to changed costumer behaviour and demand are made but are implicit rather than emphasized. CEFIC19 touch on it when discussing other forms of measures:

> "*Europe also needs to encourage demand for more sustainable products via, for example, an economy-wide pricing mechanism that incentivises the use of chemicals which minimise environmental impacts over the whole life cycle, that streamlines a value-chain approach in all new policies, and that drives a behavioural shift toward optimal circularity and lower greenhouse gas emissions at a competitive cost.*" (Cefic, 2019)

As in this quote, some roadmaps mention the question of demand for more sustainable products, and this quote focuses on creating such demand through price-reducing measures. Other measures to create such demand are mentioned but mainly targeted at policy measures such as creating standards, although FCHEM20 also brings up marketing by the industry.

4.4.5 Collaboration

Several roadmaps identify a strong need for collaboration and coordination, for example with governments (e.g. for public-private partnerships, R&D and creating roadmaps), international collaboration to coordinate efforts, research, the energy sector, other industries in the cluster for industrial symbiosis, and coordination across the product value chains. It also includes a deeper integration with the waste management sector.

Not all roadmaps note the role of collaborations and different roadmaps note different collaborations. For example NCHEM18 emphasize integrations with the energy sector and FCHEM20 point to the deep sector integration for managing material flows. However as a sum it shows a transition coordinated at system scale. Cooperation is not new to the sector. The plastics industry was historically developed as a way of making use of the residual streams from fuel production (Bauer et al., 2018), and as is stated in CEFIC21: "*In improving its production apparatus, it has developed synergies, cross-industry cooperation and at times, co-dependencies with other industries and sectors.*". However, the level of collaboration, and the integration with new types of actors is more of a fundamental change. This can both be an accelerator if the different actors manage to help each other overcome hurdles in the transition, but may also risk falling short if the responsibility becomes too distributed and vague. ACA21b point out: "*A concerted global effort to transition the chemical and petrochemical sector seems unlikely. Front runners – consumers, governments and chemical and petrochemical clusters and companies alike – will need to force this change, and this will require attention for competitiveness issues and carbon leakage.*". This need for leadership is also pointed out by NCHEM18 who mentions the importance of leadership especially from top management in businesses but also from politicians.

4.4.6 The chemical industry's own role

Given the many dependencies, what is the view of the chemical industry's own role? Is their action anything more than a product of these surrounding factors? Can the industry itself have an effect on these surrounding dependencies? What share of the investments and R&D is meant to come from the chemical industry? These are questions that are rarely explicitly discussed in the roadmaps, which could be interpreted as a role of following market and legislative incentives, being open and cooperative, following the technology development and implementation in production. However, there are a few notable examples that point to a greater sense of agency, especially NCHEM18 (who also noted the role of leadership), but also PORT18, ACA21b (pointing to the role for frontrunners as mentioned) and FCHEM20. NCHEM18 point to the role of actively reaching out for cooperation and partnerships and taking a leading role:

> "*To achieve the potential of this pathway, we recommend the following actions:* [...] *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.*" (Stork et al., 2018)

Similarily, PORT18 provide recommendations to the port industries, including identifying networking opportunities and low-risk investments as well as to pressure policy makers to provide investment certainty. FCHEM20 gives solutions directed at the chemical industry at both short- and long-term, for such as own purchase and installations of low-carbon energy, own R&D and marketing. Joint ventures with energy and recycling sectors are also mentioned.

It can also at times be difficult to decipher whether a roadmap shows a real intention of escalated action or if vague language is used to obscure the actual intentions. For example when it is unclear who is expected to initiate or take a the leading role in joint efforts, or when wordings are used that do not give definitive signals of action:

> "*The European chemical industry aims to help prevent environmental damage, reduce waste, and develop technologies necessary to enable recycling, including chemical recycling, and cost-effectively sort materials from plastics to polymers in large volumes. We support collaboration with value chain and government partners to avoid letting recyclable end-of-life plastics end up in the environment and*

> *to develop solutions that help achieve a higher circularity in plastic value chains.*" (Cefic, 2019)

In this above example, wordings like "aims to help" and "we support" does not necessarily exclude fairly minimal efforts, but at the same time it sends a signal of action by the writer.

4.5 Timeline and concretion

The concretion and level of detail in the roadmaps give an indication of how mature and ready the industry is for transition. This was evaluated using eight aspects divided in three categories:

Timeline

- 1. Interval-based modelling
- 2. Timeplanning the next coming years (until 2030)
- 3. Statements about when technologies are assumed to be available

Strategies and technologies

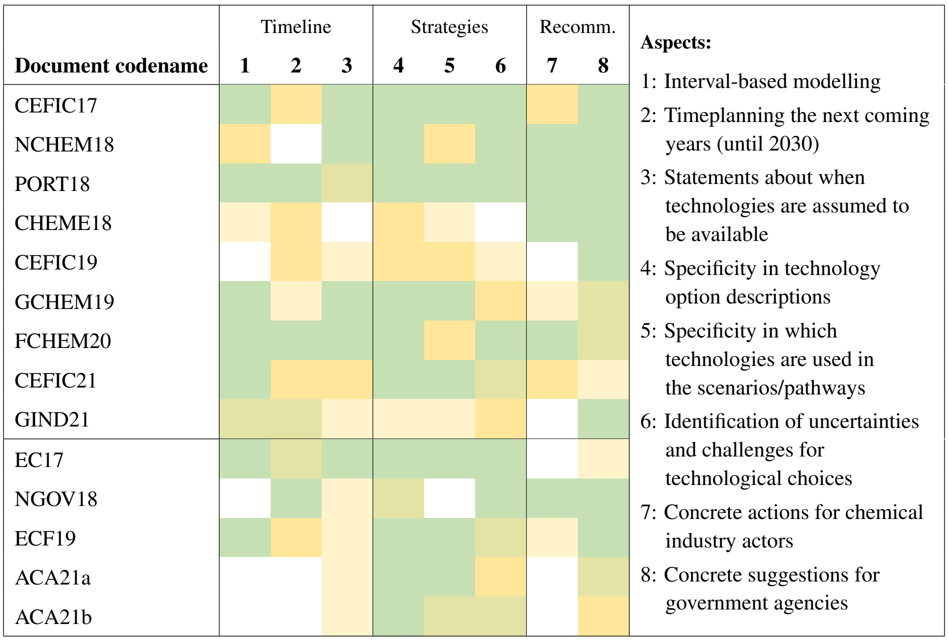
- 4. Specificity in technology option descriptions, e.g. specified process route, type of chemical recycling, type of biomass, etc.
- 5. Specificity in which technologies are used in the scenarios/pathways
- 6. Identification of uncertainties and challenges for technological choices

Recommendations

- 7. Concrete actions for chemical industry actors
- 8. Concrete suggestions for government agencies

Table 4.5 shows an overview of the maturity for each aspect and document, comments for each roadmap and category can be found in Appendix D.

Table 4.5 – Evaluation of concretion and maturity in the roadmaps. Aspect 1-8 are colour graded based on to which extent they are present in the roadmaps according to: white - Not at all; light yellow - Very minor indications; yellow - To a small degree, with low specificity; lime green - To a larger degree, but with some vagueness; green - To a higher degree.



	Timeline			Strategies			Recomm.	
Document codename	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
CEFIC17	🟩	🟨	🟩	🟩	🟩	🟩	🟨	🟩
NCHEM18	🟨	⬜	🟩	🟩	🟨	🟩	🟩	🟩
PORT18	🟩	🟩	🟢	🟩	🟩	🟩	🟩	🟩
CHEME18	🟡	🟨	⬜	🟨	🟡	⬜	🟩	🟩
CEFIC19	⬜	🟨	🟡	🟨	🟨	🟡	⬜	🟩
GCHEM19	🟩	🟡	🟩	🟩	🟩	🟨	🟡	🟢
FCHEM20	🟩	🟩	🟩	🟩	🟨	🟩	🟩	🟢
CEFIC21	🟩	🟨	🟨	🟩	🟩	🟢	🟨	🟡
GIND21	🟢	🟢	🟡	🟡	🟡	🟨	⬜	🟩
EC17	🟩	🟢	🟩	🟩	🟩	🟩	⬜	🟡
NGOV18	⬜	🟩	🟡	🟢	⬜	🟩	🟩	🟩
ECF19	🟩	🟨	🟡	🟩	🟩	🟢	🟡	🟩
ACA21a	⬜	⬜	🟡	🟩	🟩	🟨	⬜	🟢
ACA21b	⬜	⬜	🟡	🟩	🟢	🟢	⬜	🟨

Aspects:

1: Interval-based modelling
2: Timeplanning the next coming years (until 2030)
3: Statements about when technologies are assumed to be available
4: Specificity in technology option descriptions
5: Specificity in which technologies are used in the scenarios/pathways
6: Identification of uncertainties and challenges for technological choices
7: Concrete actions for chemical industry actors
8: Concrete suggestions for government agencies

4.5.1 Timeline

When it comes to defining the timeline for reaching the stated targets, most of the roadmaps contain some kind of interval-based modelling from around today's date to 2050, most often using 5-year intervals. The results of these are then shown in graphs for e.g. emission reduction, production, investments, etc., in more or less detail. It should be pointed out however that these do not typically show the exact path which the industry is proposed to follow, but rather the result of a model given certain assumptions and conditions. It can inform actions by the industry but is not meant to dictate it. Specifying a precise path to 2050 may still be considered too early and too riddled with uncertainty to be a useful practice.

It is therefore also interesting to see what timeline is drawn out for the more recent years. Since the surrounding conditions are more set, and the decisions are closer in time, the earlier timeplanning to a greater extent shows what the industry will or should do, according to the roadmap. Setting out a more detailed path for the closest coming years is less common in the roadmaps, where only a few notable exceptions exist that do it to a larger degree. These are all on a national or smaller scale. Of these, FCHEM20 shows the most applied approach to for beginning the transition, with sketches of year-by-year action plans both at company level and a more general level.

The least specific in terms of timeline are the academic, global scope roadmaps, which mainly present an end-state in 2050 but not how this point is reached or any intermediate states. Less specific are also the documents with deviating formats, i.e. the Chemelot brochure CHEME18, Cefics mid-century vision CEFIC19 and the Netherlands government transition plan NGOV18. These documents serve a partly different purpose making it difficult to fairly compare them to the more in-depth versions and it is for example likely that a more detailed plan exists for Chemelot than is presented in a brochure.

If something general can be said about the contents of the timelines drawn out in the roadmaps it is that earlier emission reductions are obtained mainly by switching energy sources, whereas the fundamental shifts in feedstock and processing are put later in time. For newer technologies, research, piloting and demonstrations will be needed before full-scale deployment and as discussed in section 4.3, the largest investments are typically expected after 2030. Some state this timeline explicitly. CEFIC19 refers to the EU long-term vision *A clean planet for all* (COM/2018/773 final) which shows steep emission declines only after 2030 as time is first needed to pilot technologies before scaling up, and CEFIC21 writes:

> "*To achieve climate neutrality within the chosen emission scope, efforts should first and foremost focus on reducing heat and steam-related emissions, then on producing low-carbon feedstocks which can be using with existing processes before investing in more capital intensive investment to change the production processes further allowing the use of low-and circular carbon feedstocks.*" (Deloitte, 2021)

4.5.2 Concretion

The roadmaps are more or less specific, both when it comes to technologies or strategies used, and with regards to recommendations and actions for the industry and policymakers. The specificity is at a sufficiently high level when describing technology options, but less specific when it comes to concrete actions for the chemical industry. This is elaborated on below.

Concretion in strategies and technologies

The roadmaps are generally specific and detailed when it comes to identifying and describing technological options (which is understood from section 4.2), at least to the level of detail considered high in this thesis. It shows that the available technologies have been mapped and these are explained for the reader at a level high enough to give context for the roadmapping. It is for example common to present the different kinds of process routes such as gasification, pyrolysis, Fischer-Tropsch and methano-to-olefins, as well as to mention different kinds of available biomass feedstock options. Electrification measures can also be specified by describing measures like electric furnaces, electric boilers or heat pumps. The level of detail may be lower for other technologies like carbon capture, but in this case, pointers are sometimes given for where carbon capture could be applied, e.g. on crackers or waste incinerators. However, when it comes to which technologies are actually assumed to be installed in the pathways, the roadmaps are not always as clear and detailed. When the pathways are described, the technologies and strategies assumed are often more generalized making it more difficult to assess which of the described technologies are included. Clarity about which technologies are used in the pathway is important if the roadmap is to be followed and used as a guide.

Uncertainties and challenges regarding the strategies is often brought up to some extent, but may be more or less thorough, and be described for all or some of the strategies. It is mainly discussed in a larger sense, for example by discussing biomass and electricity availability or technology development, which is discussed more in Section 4.4. Some assess uncertainties and challenges on a slightly more detailed level, by technology. They may describe the specific policy, cost or development issues for each technology. Exploring different pathways with different technology focuses is a way to manage the uncertainties of the future, and is an approach which several of the roadmaps take.

Identification of issues and difficulties that may arise is a crucial part of making a plan that can be followed in practice. The challenges must be identified in order to be managed or worked around. At the same time, it is worth pointing out that they can also be brought up partly as reasons or excuses for not pursuing the goal of decarbonization. It can be tricky to distinguish for which reason the issue is discussed in the roadmap, but it is worth keeping in mind these intentions both when reading and creating roadmaps.

Concretion in actions and recommendations

All roadmaps include recommendations or suggestions for future measures or considerations, or at least some notion of it. This is important for enabling continued action. The recommendations in the roadmaps are to a much larger extent directed at government agencies and policy makers than to the chemical industries, but examples of both exist. In some cases the recommendations are more broad in nature, e.g. "*New technologies must be recognized as progress in regulations and must not be hampered by additional obstacles.*" (GCHEM19), "*Co-operation and coordination across chemical product value chains and production pathways should be considered.*" (CEFIC19) or "*Incentives to companies for switching to low-carbon energy*" (FCHEM20). These are however in some cases more elaborated on in the text. Other recommendations are more precise with examples like "*Based on the port's Decarbonization Roadmap, the Port Authority should:* [...] *Develop exclusion criteria for new* CO_2*-intensive* *investments in the area (in cases where it has the authority to grant or deny investments).*" (PORT18), and the more detailed descriptions in GIND21 for instruments such as Carbon Contracts for Difference and development of efficiency standards for combinations of technologies.

If recommendations are well thought out and actionable, they can give a starting point for action. On the other hand, recommendations that are more general function more as noting observations or as conclusions from roadmap modelling than as results of a project aimed at finding ways forward. The precision of the recommendations are likely influenced by what methods were used in making the roadmap and how deeply the different possibilities were investigated. Roadmaps that have used methods like stakeholder workshops or more thorough technological assessments have a higher precision, as these methods likely work to find precision and core challenges to manage. This in turn enables transition and reaches a higher level of maturity for the parties involved.

The fact that the recommendations and appeals are largely directed at government agencies however begs the question of whether or not these are acting on it. This depends on to what extent they are communicated and if they are reaching the responsible parties. It also depends on those parties ability to act accordingly, given that other frameworks, agreements and interests may or may not stand in conflict. If the recommendations are not communicated well enough or do not consider surrounding obstacles, the recommendations in the roadmap may end up being toothless and spur passivity when the recommendations are not followed. This thesis is not aimed at investigating to what extent this may be the case, but notes the need for deep investigation and discussions in order to provide useful recommendations.

4.6 Individual companies and roadmaps

The roadmaps discussed thus far have not been from individual companies but from industry organizations and other types of actors. For this thesis, a search was made for roadmaps from individual companies, and the very limited findings are analyzed here. Only those showing quantitatively how emissions will be reduced are evaluated. It is likely that companies present efforts, plans and desires in other ways for example in sustainability reports, but investigating these in detail would go beyond the scope and time limitations of this thesis.

Table 4.6 – Company commitments to net-zero.

Company	Has announced net-zero target, scope, target year	Quantified planned emission reductions	Reference
BASF	Yes, scope 1 & 2, 2050	Until 2030	(BASF, 2021)
Dow	Yes, scope 1, 2 & 3 plus carbon benefits, 2050	None found	(Dow, n.d.)
Sabic	Yes, undefined scope, near mid-century	None found	(Sabic, 2021)
Ineos	Yes, undefined scope, 2050	None found	(INEOS, 2021)
ExxonMobil Chemical	For ExxonMobil, scope 1 & 2, 2050, (but not specifically ExxonMobil Chemical)	No, roadmaps to be completed end 2022-2023	(ExxonMobil, 2022)
LyondellBasell Industries	Yes, scope 1 & 2, 2050	Until 2030	(LyondellBasell, 2021)
Mitsubishi Chemical	Yes, throughout product life cycle, 2050	Until 2030	(CDP, 2021d; Gilson, 2021)
DuPont	Yes, scope 1 & 2, 2050	None found	(CDP, 2021b)
Evonik Industries	No	-	(CDP, 2021c)
Covestro	Only as alignment with other initiatives/organizations	-	(CDP, 2021a)

While most of the ten largest chemical companies active in Europe have a net-zero target set for 2050, roadmaps for reaching this target seem to be lacking (see Table 4.6). Only three of the companies (i.e. BASF, Mitsubishi Chemicals and LyondellBasell Industries) have available and quantified plans for how to reach targeted emission reductions, but even those only quantify until 2030. A short summary of the company roadmaps that were found are given below.

BASF (2021): Our journey to net zero 2050

This roadmap sets the emission reduction targets for BASF as net-zero by 2050 (scope 1 and 2) and 25% reduction by 2030 compared to 2018 (BASF, 2021). The 2030 goal is to be reached through technologies referred to broadly as: “Green-to-grey” (∼34% of reduction), “Power-to-steam” (∼22%), “New technologies” (∼21%), “Bio-based feedstocks” (∼1%), “Opex” (∼13%) and “Temporary measures” (∼9%). Green-to-grey refers to the use of renewable power and Power-to-steam includes heat pumps and steam compressors to utilize waste heat and replacing steam turbines with “eDrive”. New technologies for example includes electric steam crackers, water electrolysis, methane pyrolysis and CCS. Bio-based feedstocks refers both to drop-in feedstock and product specific feedstock, Opex refers to measures like optimizations of processes and models, and Temporary measures is emissions offsetting. The roadmap gives no details about how to reach the emission reductions after 2030 to 2050, but projected capex after 2030 is given as >10 billion €. The Q&A for the presentation clarifies that plans beyond 2030 are foggy, since it will be largely dependent on the framework. It is also stated there that decarbonization will not happen if the framework conditions are not right.

Mitsubishi Chemical Holdings (2021): Forging the future

This is a presentation about the company’s new management policy, and briefly shows the “roadmap” for reaching 29% emission reduction by 2030 compared to 2019 and net-zero by 2050 (Gilson, 2021). The emissions included in the presentation seem to include scope 1 and 2 although it is not clearly stated. The emission reduction until 2030 is a result of improved emission factor for purchased power (∼54% of the reduction), fuel conversion (∼36%) and process optimization (∼10%). After 2030, the emissions are to be reduced by 30% through a emission factor of zero in the purchased power. The remaining emissions are not given any quantified solutions, however key initiatives given are fuel conversion from liquid natural gas to ammonia and H_2, biomass feedstock, rationalized manufacturing processes, new technologies (e.g. artificial photosynthesis, CCU and CCS) and offsets through investments in renewable resources. The presentation also talks about an exit from petrochemicals and coal starting fiscal year 2023, and contains mentions of CO_2 recycling, chemical recycling, bio-chemicals and increased efficiency.

LyondellBasell Industries (2021): 2021 Sustainability Report

In their sustainability report (LyondellBasell, 2021), LyondellBasell Industries show their goal and pathway to reach 30% reduction of scope 1 and 2 emissions until 2030. The reduction consists of planned greenhouse gas reduction projects (∼53%), renewable electricity (∼20%) and other greenhouse gas reduction options (∼27%). The planned emission reduction projects include for example minimizing flaring, switching to less carbon intensive fuels and optimizations of energy use. The “other greenhouse gas reduction options” are not specified but are being studied and are said to be dependent on energy availability and regulatory frameworks. Renewable electricity is secured through purchase agreements of wind and solar power. Alternatives like electrified crackers, H_2, CCS and CCU are also being assessed.

4.7 Summary of analysis

Throughout the analysis, a number of overall patterns, similarities and differences have been found in the roadmaps. The overview of roadmaps found that many are built as technical reports modelling one or a variety of pathways given a number of assumptions. Other roadmaps are more visionary in nature, describing a possible desired future mainly qualitatively. The roadmaps furthermore differ in what emission targets are set, geographic, product and emission scopes, as well as in several assumptions. These differences should be kept in mind when comparing roadmaps one to one. Overall, non-industry roadmaps to a greater extent includes the full life cycle emissions, and show a larger variance in structure as they are made by different types of actors. The industry roadmaps often has a greater focus on building a number of pathways and evaluating their implications.

In terms of the technologies and strategies used to reach lower emissions, the roadmaps together do not show a coherent vision of which technologies will be most important. Instead it can be said that a variety of strategies will likely be used in combination. Recycling, biomass feedstock, CCU and low-carbon H_2, CCS and electrification are all relevant strategies used in several roadmaps. Furthermore, efficiency improvements will continue and play a role, the development of the energy sector will be an important contributing factor, and the use of other renewable energy sources may also be used in some cases. As for industrial symbiosis and other system measures, these are often also part of the story, but are not quantified separately. A dramatic increase in the use of electricity is almost always expected, mainly for the production of H_2 via water electrolysis.

Investments and production costs are expected to increase dramatically as a result of the transition. The largest investments and costs are often associated with the use of biomass and H_2. Less ambitious efforts in terms of emission reduction are also naturally expected to require less investments, and CCS-type strategies are also typically estimated as less costly.

The large costs and need for cheap electricity with an emission factor close to zero are two reasons why the industry sees its transition as very dependent on other actors. Governments and policy makers are perhaps the most important enabling actors. They are asked to provide public investments, create an enabling and consistent policy framework and facilitate necessary infrastructure. A need for coordination and collaboration with public authorities and other businesses (e.g. the waste management sector and other businesses in the cluster) is also emphasized, as is the need for and support for research and development including pilots, demonstrations and scale-up projects. The dependency on the public and consumers is less emphasized, but the need for CCS acceptance is sometimes mentioned. The industry's own role is also rarely brought up. If the framework makes the needed investments economic it is implied that the industry will also act accordingly, however the transition is fully dependent on economic feasibility for the company and will otherwise not happen. The industry could have a role to play in taking initiative and lead, promoting, communicating and lobbying for the necessary enabling frameworks, but this is rarely discussed in the roadmaps.

In terms of maturity, timeline and concretion in the roadmaps have generally in greater detail evaluated the technology options and provided recommendations for government agencies. To further speed up action, more detailed short term timelines and timeplanning, as well as recommendations for chemical industry actors would be needed, and is something which fewer roadmaps contain. Here, there is a difference between more local roadmaps and roadmaps with larger geographical scopes. The roadmaps which show greatest detail in this regard are those for the Finnish and Dutch chemical industries. Roadmaps with a global scope and roadmaps with a different structure (e.g. brochures and vision statements) show less concretion of this kind.

Finally, the less detailed evaluation of individual companies and net-zero roadmaps found that while most of the largest chemical companies have set net-zero targets, only a few give quantitative indications of how the emissions are meant to decrease, and the emissions considered are usually only scope 1 and 2. The emission reductions are also never quantified beyond 2030, likely to avoid the large uncertainty of future conditions. In the three examples of companies that show how emissions will be decreased until 2030, the focus is on decreasing emissions from energy rather than fundamental changes to feedstock. Two also show that emission offsetting through carbon credits will play a part.

5 Discussion

The roadmaps evaluated in this thesis have shown a multitude of different ways the chemical industry could fit into a net-zero greenhouse gas emissions society. They have also brought up opportunities and challenges for reaching that goal. This thesis has attempted to gather, evaluate and summarize these, and has in doing so noted several interesting aspects. In this section, a few of these will be discussed in greater detail, namely the large variations of different forms and how to relate to the large dependencies. The discussion will also put focus on some identified gaps and what could be done to fill these in. The interesting question of fairness in transition will also be explored, and as a finish, this section will put emphasis once again on the context of climate change and global well-being which is the reason for industry transition and these roadmaps existing in the first place. Having this context in mind is vital to maintain motivation and succeed in reaching the climate targets.

5.1 Large variations

The strategies and resources used in the different scenarios show large variation both between and within the roadmaps. The wide range of possible strategies and solutions which is perhaps unique to the chemical industry may be a double-edged sword for the roadmapping process. On the one hand it creates many different opportunities for how to decarbonize. It opens up for a multitude of local solutions that can be used under different conditions, whether it is about feedstock and energy availability, knowledge and experience or infrastructural connections. Using a variety of solutions may also create a structure that is less vulnerable, since different industrial clusters do not need to rely on the same resources and value chains. On the other hand the variety of options also creates uncertainty in which technologies to pursue, as well as which framework conditions to create. If there were only one option, the focus would be clearer and it might have been easier to align and cooperate both within and outside the sector.

The wide range of pathways and emission reduction goals suggest that the European chemical industry as a whole is still not ready to embark on a fundamental transition. Most notably, Cefic, which represents the whole European chemical industry, has only publicly released one roadmap-like document in the last 5 years (since Deloitte (2021) is only available upon request), which assumes 50% reduction of emissions until 2050 and thus does not align with the EU net-zero target.

However, higher levels of maturity can be seen in more regional projects. In this thesis, roadmaps for the Finnish chemical industry, German and Dutch chemical regions were found, but there could be more which were not found, especially since regional roadmaps might be written in languages other than English. The higher level of maturity can be seen in these regional roadmaps through higher precision of technologies, more concrete suggestions for e.g. policy and interactions with other industries. There are also more of this type of documents available, and here two German and four Dutch were identified. Although no concrete timelines are given, some rough planning can be seen through information on when technologies are available and how and when decisions can be made.

Because the chemical market is highly globalized with many companies being active globally within and outside the EU, shaping the boundaries for a net-zero roadmap is not obvious. Having regional roadmaps means that companies have different targets for different sites, whereas having company roadmaps means that different actors on a site can have different targets. Neither may be natural, which could complicate formulations of roadmaps. This is different from for example the steel industry, where companies like Swedish LKAB is only active in Sweden. Yet, it seems that a regional scope for a roadmap may be more powerful than a company scope. In this comparison, it appears that regional roadmaps are more developed than general or company roadmaps (which often exclude scope 3 altogether). This could relate to conditions being less general at a local level. One factor is that the legislation is more harmonized, and especially the EU frameworks do not apply globally. Other known local conditions make it easier to assess which possibilities exist and are most appropriate in the specific case (for example in terms of industrial symbiosis, feedstock and energy availability and trade connections). Furthermore, deciding on more ambitious strategies and pathways may be easier when there are fewer parties involved that need to find common ground. All this suggests that regions and clusters have a better opportunity to be front-runners in the transition, given favorable conditions and clear leadership. However, while local clusters can provide enabling conditions for investments, it is mainly companies who hold the investment decisions for the businesses. Companies and clusters thus play partly different and complementary roles and transition is dependent on both.

5.2 Large dependencies

This thesis has shown that the chemical industry sees their transition as greatly dependent on other factors. Much of the emission reductions are obtained through the (assumed) transition of the energy sector, passively by the chemical industry through the energy sectors continued development and actively through electrification of processes. As is often pointed out this puts high requirements on the energy sector to deliver large amounts of low-carbon electricity at a low price. While it is fundamental to switch energy sources away from fossil fuels, this dynamic also may shift the responsibility and heavy lifting to other sectors. This over-reliance in the worst case risks a stand-still for the emissions if the energy sector fails to deliver on these demands. It also risks missing emission reductions through alternative and more fundamentally transformative strategies like demand reduction and full scale circular economy development, which may be more sustainable from a system perspective (since for example large expansions of the energy system can cause political controversies and resource overuse could be limited if materials and products were used more mindfully in society).

The dependencies are no doubt of high importance, but when the key to transition is viewed to be held by other actor, and the industry's own role and agency is unspecified in the roadmaps, the risk of over-reliance and passivity is concerning. An industry willing to decarbonize should prepare as much as possible, gather knowledge, coordinate and cooperate with related actors and use its influence to help enable its own transition.

The findings of this thesis hint to that what is currently being done in practice by chemical industry actors, governments, policymakers and other actors to enable the transition is not sufficient. However, this is not to imply that there are no actions being taken. On the contrary, a multitude of projects are ongoing or on the way, BASF for example write in their roadmap document that they are directly investing in new renewable energy assets, and several companies are increasing the share of wind and solar in their purchased power. It would surely be interesting to see a compilation and evaluation of all actions currently underway and assess how far the sum of these actions will bring us on the way to net-zero emissions, but this is beyond the scope of this thesis.

5.3 Gaps in roadmaps

A number of gaps can be identified in the roadmaps, both related to their method and scope, and related to their message and conclusions. In terms of scope, it should be standard to including scope 3 emissions, and this should be done in a consistent way in all roadmaps. Undoubtedly, these are more difficult to assess than scope 1 and 2, but are of great importance. Since the end goal is preventing climate change by reducing emissions, all emissions that arise from these industries value chains must be assessed and addressed when making these roadmaps. While the downstream end-of-life emissions are more often considered in some way, it is not always done in a uniform way and other scope 3 emissions are more rarely included at all. In a more circular system negative emissions and avoided emissions in other industries or parts of the value chain become more central. Direct and indirect emissions from production of biofeedstock should also be assessed in the roadmaps, something which is rarely done. It is important that opportunities on system level are not missed even when they are not under direct influence of today's chemical industry. It is encouraging that several of the roadmaps note the need for coordination between sectors, as this will also be vital in finding these options and making plans to realize them.

This thesis has shown that there is a range of emission targets envisioned in these roadmaps, and not all are aimed at net-zero or close to net-zero. While it is almost never stated in the roadmaps, it is important to remember that a roadmap not aiming for net-zero implies either that it does not intend for the EU target to be reached, or that other sectors are expected to somehow reach negative emissions compensating for those left in the chemical industry. The company roadmaps are more transparent in this regard and explicitly show that compensatory practices in the form of offsetting projects are part of the strategy for reducing emissions until 2030. All roadmaps that do not reach net-zero should be honest about this implication and it should be discussed. Furthermore, several roadmaps also allow continued use of large amounts of fossil resources while others conclude that even measures like CCU are not compatible with a net-zero scenario. The recognition of what strategies are viable in a net-zero context is needed in all roadmaps, and pathways relying on fossil resources should be more critically evaluated. For example, those aiming to reduce emissions by switching to natural gas need to evaluate if this can be compatible with the long term goal or if it creates lock-ins that prevent net-zero solutions. Furthermore, switching to biogenic carbon sources or carbon captured from air opens up to going beyond net-zero to net-negative production, something which can never be achieved with fossil carbon. The war by Russia in Ukraine has also put into question the security and ethics of relying on fossil imports and natural gas especially.

Maturity in terms of timeplanning the next coming years and recommendations for early actions are also missing from many of the roadmaps. There is a lacking signal of agency from the industry as has been discussed above. When commissioning roadmaps, this should be one of the questions the projects should investigate. This would ideally be done by involving all different types of actors that have a role in the transition, in order to find the core issues. Some roadmaps do however do this to a greater extent than others, meaning that there is an oppurtunity to learn from each other. Furthermore, several of the dependencies are likely shared by other industries, so joining forces could help enable faster change.

I have here discussed the gaps that have been identified in the roadmaps that do exist, but it should be pointed out that more chemical industry actors, clusters and countries exist for which there are no roadmaps at all. Preparing for significantly reducing emissions, exploring alternatives, oppurtunities, challenges and creating roadmaps will be necessary for all industries in the next coming years. This work should begin as soon as possible and thankfully there is plenty of knowledge and information to be gathered in previous works such as the roadmaps evaluated in this thesis.

5.4 What is fairness in climate change policy?

Fairness is called for in the roadmaps and the concept is also a central component in the discussions on climate change. The roadmaps from the European chemical industry point out a need for a global level playing field in order to avoid unfair competition due to different requirements and costs in different parts of the world. At the same time in the climate discussion, the developed and rich parts of the world is said to carry the largest responsibility for the global transition, both due to their larger historical emissions and since they have more resources to do so. This larger responsibility is part of the principle of Common But Differentiated Responsibilities (CBDR) from the United Nations Framework Convention on Climate Change (UNFCCC) from 1992 (United Nations, 1992). In this context of fair burden sharing globally, adding new costs and requirements to industries in developing worlds (to match those in Europe) could be seen as unfair since it shifts the burden from the richer countries to poorer.

While the ideal conditions for industry transition might be a global uniform carbon price and equal legislative conditions, this is clearly not the situation that we are in today, such shifts in policy are not unproblematic and most importantly fundamental emission reductions will need to happen before such equal global conditions may be agreed upon. It is thus worth discussing what this principle of fairness in climate work means in this context of chemical industry decarbonization. The larger responsibility of developed regions like Europe should mean that their industry also bears the largest responsibility for developing and deploying decarbonization solutions. Not doing so, or lowering the ambitions should not be an option, since no one else can be more expected to do this work. What is less clear however is which actor should provide the resources for this transition: the European industry, governments, consumers, or someone else. It could be argued that the governments hold the responsibility of ensuring the safety of its inhabitants, and by extension are more responsible for preventing climate change. The companies responsibility is then mainly to be profitable. However, it can also be argued that climate change necessitates responsibility from all actors, since a warmer planet threatens the structure of all of society. Then, all who have an ability to act should do so and who exactly holds the most responsibility is less interesting. The main conclusion is then that there is no reason for any actor, especially in this part of the world, to lower their ambitions. If the European industry becomes less competitive as a result of the transition, and other poorer regions can enjoy higher profitability, this may in a sense work to reduce global inequality and even out the historical unfairness.

5.5 What is climate change to the chemical industry?

Sustainable development involves three aspects: environmental, social and economic sustainability. All of which interact and are necessary to reach a future where today's needs are met without threatening those of future generations. However, this dynamic is sometimes brought up as a reminder when discussing solutions to environmental issues that might have a negative impact on (primarily) the economic aspect. This implies that there is a sort of balance between these three factors today, when it is arguably the case that the environmental aspect is severely more threatened than the other two and that economic and social sustainability hinges on a balanced climate and functioning ecosystems. The interdependence of economic and environmental sustainability also comes up in the roadmaps, where environmental sustainability and reducing emissions is seen as dependent on economic profitability more so than the other way around. This is worth paying attention to.

For the industry, the expected investment and production costs are large, unheard of even. They are also associated with large uncertainty and risk. Given only that context, any hesitation to act is understandable. But the context of this transition goes far beyond any normal state as well. It is about avoiding climate change, fundamental disruptions to the natural world. We have thus far lived in a relatively stable climate, a stability which has enabled farming, human settlement and which has been foundational for the development of societies. Furthermore, it is becoming increasingly clear that the costs and consequences of failing to limit climate change far outweigh the costs of preventing it and that earlier action is the most preferable. Given this context, hesitation to act becomes less understandable. Even less understandable considering that there has been historical investments on the same scale before (see section 4.3).

The decision makers in the chemical industry have some level of knowledge about full context of climate change, but are presumably not making decisions based on it, at least not directly. But since the conclusions are so fundamentally different - whether to wait for the right conditions before acting or acting as soon as possible - the level of knowledge about the climate crisis among the decision makers could play a role. Even if the legislation and energy system today is not where it needs to be, the general direction is clear and the goals are set. By around the 2040's, when the investments in these roadmaps reach their peak and the transition would be in full bloom if followed, the conditions will likely be much more directed in favor of transition. Furthermore, beginning the transition of the chemical industry could itself spur enabling conditions from other actors given that the EU would not want the industry to be punished for following climate ambitions that are in line with the stated goal. Courage to act and increased knowledge about the consequences and costs of climate change may thus be of essence for industry transition.

6 Conclusions

The 28 years left until 2050 could be a fundamentally transformative period for many industries, not least for the European chemical industry. In order to maintain a stable climate and live up to climate targets, the path must be set at net-zero emissions by 2050. However, this evaluation of chemical industry roadmaps shows that the road is still behind a veil of uncertainty. It is also not clear whether the industry intends to reach net-zero emissions by 2050 at all. These are two main overall conclusions from this thesis which purpose is to investigate how the European chemical industry envisions its role in reaching the EU greenhouse gas emission target. Comparisons of roadmaps were however made difficult due to differences in geographic, product and emission scopes as well as assumptions. An especially important factor is how scope 3 emissions are accounted for, as these can make up a majority of the emissions from the products life cycle. The variety could partly be a result of the very complex nature of the industry itself, but also that it is in the beginning of the process of mapping it's transition. More roadmaps will have to be constructed, especially on regional and cluster levels and in future assessments, scope 3 emissions should be more deeply evaluated and be as integrated as scope 1 and 2 emissions.

In terms of the types strategies and technologies envisioned for reducing emissions, a broad range of possibilities has been identified and no clear preference can be seen. The considered strategies concern both feedstock, energy, efficiency improvements and carbon capture and storage. Feedstock strategies often include switches from fossil feedstocks to biomass, captured carbon and end-of-life products. Electrification with low-carbon electricity and utilization of other renewable energy sources like biomass and biofuels are considered for reducing energy-related emissions. The supply of cheap low-carbon electricity and sustainable biomass is often brought up as a prerequisite and a challenge. Many of the strategies entail increased use of electricity, mainly to supply green hydrogen for processing new feedstocks, but also for other new processes and electrification. An emission reduction through decreased production is not part of the industry roadmaps since the market is assumed to grow, albeit not equally in all sectors. However, the question is sometimes discussed and roadmaps from actors outside the industry sometimes include such strategies.

The investments needed are calculated to be at a scale well above what the industry is used to, typically peaking in 2030's and 2040's when the large scale implementations are made. The more in-depth discussions of investments mention the risks associated with the transition. The timing is of importance, as the plants and facilities have long operational life, and there is a risk of lock-in effects and stranded assets if the wrong calls are made. At the same time, uncertainty about future policy framework, energy and feedstock prices and technology development also makes investment decisions more difficult.

When it comes to maturity, the chemical industry as a whole has gathered much of the knowledge needed for a transition. If not always broadly, then at least locally. Thorough roadmaps exist, and knowledge ought to be actively shared within the industry. At the same time, the local conditions matter and roadmaps will need to be more or less specific to each case. However, given the many challenges in terms of framework conditions, multitude of choices and complexity of the industry itself, the industry shows varying signals of whether they will perform the transition until 2050. This thesis can not identify their intention going forward. While the large scale implementations of new technology and fundamental feedstock transitions would happen after 2030, actions such as preparatory work, technology demonstrations, as well as investment decisions about older equipment will still need to be made before then.

A clear signal from the roadmaps is that the transition of the chemical industry is dependent on other actors. Most often policy makers and governments are asked to help create good conditions. They are asked to give clear and long term signals, provide a global level playing field (or in lack thereof other compensating measures), and create economic incentives for development from research to full scale demonstrations. Depending on the type of roadmap document, the requests are more or less precise. Another dependency is that of energy and infrastructure which relates to both governments and the energy sector. The industry thus sees its role as performing the transition given the right framework conditions. It cannot be seen from this study if the industry also see their role as actively pushing for these framework conditions to materialize, or if it will be mostly passive until then.

As it stands today, the threats of climate change are clear, and so is the goal set up in the Paris Agreement and by the EU. At the same time, the road is not paved for reaching said goals. The road is foggy, contains obstacles and even pitfalls, but remaining still or moving too slowly is not an option. It is encouraging that the work of mapping out pathways and roadmaps has begun for the chemical industry, but it is now important to not get discouraged by the challenges that are identified. We unfortunately do not have the luxury of unlimited time which means that the industry as well as other actors have a responsibility to do all in their power today to enable and begin a transition to net-zero emissions. Planning, experimenting, collaborating within the sector and with other sectors, industries and actors, being front-runners and pushing other actors and stakeholders to help pave the way are all parts of that responsibility. While the path to a sustainable society is unclear, the direction is not. An industry that is reliant on fossil resources will have a weaker business case going forward, and will certainly fit poorly into a sustainable society where other sectors have moved on.

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A Appendix 1: Classification of quantified emission reductions, feedstock and energy

The roadmaps used a variety of names for the different strategies, feedstocks and energy sources quantified. For the purposes of this thesis, they had to be classified into other categories as presented in Tables 4.2, 4.3 and 4.4. The original names used in the roadmaps and how they were classified can be seen in Tables A.1, A.2 and A.3.

Table A.1 – The terminology of emission reduction strategies as they are named in the roadmaps and their corresponding classification in this thesis.

Document codename	**Categories classified as**
	Recycling:
NCHEM18	Closure of the materials chain
FCHEM20	Process changes (combined with Biomass)
ECF19	Materials recirculation and substitution (for ammonia)
ACA21b	Recycling
	Biomass:
CEFIC17	MeOH, bio-based
	Olefins, bio-based
NCHEM18	Replacement of fossil feedstock
FCHEM20	Process changes (combined with Recycling)
CEFIC21	Biogenic carbon removal
	CCU/H_2:
CEFIC17	MeOH via H_2, chem.
	BTX, via H_2 to MeOH
	Olefins via H_2 to MeOH
FCHEM20	Power-to-X
	Carbon capture (combined with CCS)
ACA21b	H_2-based chemicals
	CCS:
NCHEM18	CCS
FCHEM20	Carbon capture (combined with CCS)
CEFIC21	CCS
ECF19	Carbon capture and storage
ACA21b	Energy recovery + CCS
	CCS for combustion and processes
	Electrification:
CEFIC17	Steam recompression
	Electricity based steam
FCHEM20	Electrification
ECF19	New processes (for ammonia)
	Electricity emission factor:
NCHEM18	Renewable energy
FCHEM20	Development of energy sector
CEFIC21	Electricity
ACA21b	Renewable power
	Renewable energy (non-electricity):
FCHEM20	Fuel switches
ACA21b	Solar process heat
	Biomass process heat
	Efficiency improvements:
CEFIC17	Efficiency measures
NCHEM18	Energy efficiency
FCHEM20	Energy efficiency
ECF19	Materials efficiency and circular business models (for ammonia)
ACA21b	Energy efficiency
	Demand reduction
	Industry relocation
	Other:
CEFIC17	Urea via H_2 to NH_3
	NH_3 via H_2
NCHEM18	N_2O
CEFIC21	Other direct emissions
	Upstream
	Imported building blocks

Table A.2 – The feedstock sources as they are named in the roadmaps and their corresponding classification in this thesis.

Document codename	**Feedstocks classified as**
	Fossil:
CEFIC17	Naphta
	Heavy oil
	Natural gas
GCHEM19	Fossile Rohstoffe
FCHEM20	Fossil
CEFIC21	Naphtha
	Crude oil
	LNG
	Fuel oil
NGOV18	Virgin (fossil raw material)
ECF19	Electric steam cracking
	Electric steam cracking with CCS
	Steam cracking with CCS
ACA21a	Fossil resources
ACA21b	Oil
	Gas
	Coal
	Recycling:
GCHEM19	Kunststoffabfälle
FCHEM20	Recycled
CEFIC21	Mechanical+chemical
GIND21	Mechanisches Recycling
	Chemisches Recycling
NGOV18	Mechanically recycled
	Chemically recycled
ECF19	Mechanical recycling
	Chemical recycling (incl steam cracking)
ACA21a	Mechanical recycling
	Chemical recycling
ACA21b	(Recycled)*

Document codename	**Feedstocks classified as**
	Biomass:
CEFIC17	Biomass
GCHEM19	Biomasse
FCHEM20	Renewable
CEFIC21	Lignocellulosic biomass (for bioethanol)
	Agricultural residues (for biomethane)
	Sugar crops (for bioethanol)
	Woody biomass (for bionaphta)
GIND21	Syn. Naphtha im elektr. Steamcracker
	Methanol-to-X
NGOV18	Bio-based
ECF19	Bio based production
ACA21a	Biomass Utilization
ACA21b	Biomass
	H_2 and/or CCU:
CEFIC17	CO_2 feed
GCHEM19	CO_2
FCHEM20	Carbon from CCU, power-to-H_2
CEFIC21	CCU
ACA21a	Carbon Capture and Utilization
ACA21b	Green hydrogen feedstocks

*Recycled share of feedstock is not quantified with the other, but is elsewhere shown to be 42% of plastics and thus 12% of key chemicals.

Table A.3 – The energy sources as they are named in the roadmaps and their corresponding classification in this thesis.

Document codename	**Energy sources quantified as**
	Fossil:
CEFIC17	Naphta
	Heavy oil
	Natural gas
PORT18	Naphta
	Pet coke
	NG
	Refinery gas
	Steam (generation from fossil sources)
GCHEM19	Rohstoffe fossil
	Brennstoffe (fossil)
CEFIC21	Fuel oil
	NG
ECF19	Fossil fuels
ACA21b	Fossil fuel
	Waste material:
PORT18	Steam (generation from waste)
GCHEM19	Rohstoffe Abfallkunststoffe
GIND21	Müllverbrennung
ECF19	End-of-life plastics
	Biomass:
CEFIC17	Biomass
PORT18	Steam (generation from biomass)
GCHEM19	Rohstoffe Biomasse
	Brennstoffe (erneubar)
CEFIC21	Woody biomass
	Agr. Residues
GIND21	Biomasse
ECF19	Biomass
ACA21a	Biomass
ACA21b	Bioenergy

Document codename	**Energy sources classified as**
	H_2:
CEFIC21	H_2 from market
GIND21	Grüne Gase
ACA21b	Green hydrogen
	Electricity:
CEFIC17	Electricity
PORT18	Electricity
GCHEM19	Strom
CEFIC21	Electricity
	Electricity for H_2 from market production
GIND21	Strom
ECF19	Electricity
ACA21a	Renewable electricity
ACA21b	Electricity (excluding green hydrogen production)
	Other/Non-separable:
PORT18	Steam (Energy source not specified)
GCHEM19	Fernwärme, extern
GIND21	Fernwärme
ACA21b	Solar thermal
	District heating

B Appendix 2: Investments and production costs

The investment needs and percentage increase compared to a reference state that are estimated in the roadmaps are presented in Table B.1, along with the time period when they are assumed to peak and the factors stated to make up the largest portions of the investment needs. Table B.2 similarly shows estimated costs for energy, feedstock and other operational costs. The BAU/reference scenarios are shown for comparison in gray in these tables. The roadmaps are constructed and present their data in different ways, which is why the basis for comparison and cost categories in these tables are shown to differ as well.

Table B.1 – Investment costs in the different pathways for the different roadmaps.

Document codename	**Scenario**	**Total investments over period (bill €)**	**Average per year (bill €/year)**	**% increase**	**Compared to**	**Peak around**	**2 most significant costs**
CEFIC17	BAU	72.3	2.1	**0**	BAU	-	Ethylene Propylene
	Intermediate	594	17	**710**	BAU	-	Methanol Ethylene
	Ambitious	672	19.2	**810**	BAU	-	Methanol Ethylene
	Maximum	934	26.7	**1170**	BAU	-	Methanol Ethylene
NCHEM18	Circular & biobased	24.5[1]	0.8[1]	**-**	-	After 2030	Alternative feedstock Renewable energy (geothermal+biomass boilers)
	Electrification	91.3[1]	2.8[1]	**-**	-	After 2030	Alternative feedstock Energy efficiency
	CCS	12.4[1]	0.4[1]	**-**	-	After 2030	CCS Closure of material chains
	2030 compliance at least cost	16.2[1]	0.5[1]	**-**	-	After 2030	Energy efficiency Closure of materials chain
	Direct action & high-value applications	24.5[1]	0.7[1]	**-**	-	After 2030	Alternative feedstock Energy efficiency
PORT18	BAU	-	-	**-**	-	-	-
	Technical progress	-	-	**-**	-	-	-
	Biomass and CCS	-	-	**-**	-	-	-
	Closed carbon cycle	-	-	**-**	-	-	-
CHEME18	Propsed plan	-	-	**-**	-	-	-
CEFIC19	Plausible estimate	-	-	**-**	-	-	-

GCHEM19	Reference pathway	210	7	**0**	Ref	-	-
	Technology pathway	233.5	7.8	**11**	Ref	2050 or later	Additional investments for HVCs: Electrolysis and Fischer-Tropsch for naphta Biomass gasification and Fischer-Tropsch for naphta
	Greenhouse gas neutrality pathway	278	9.3	**32**	Ref	2040s	Additional investments for HVCs: Electrolysis and Fischer-Tropsch for naphta Electric crackers for HVC production from naphta
FCHEM20	BAU scope 1&2	34	1.0	**0**	BAU	Continuous increase	BAU fixed BAU R&D
	Fast development scope 1&2	50	1.4	**48**	BAU	2030-2035	BAU fixed BAU R&D (of additional: New technology (mainly bio-based feedstock production, chemical recycling and electrification of heat) Asset conversion)
	Carbon neutral chemistry scope 1&2	58	1.7	**72**	BAU	2030-2035	BAU fixed BAU R&D (of additional: New technology Asset conversion)
	BAU feedstock	1	<0.1	**0**	BAU	-	-
	Fast development feedstock	28[2]	0.8[2]	**2700**	BAU	2040	
	Carbon neutral chemistry feedstock	42[2]	1.2[2]	**4100**	BAU	2040-2045	
CEFIC21	High electrification	280[1]	8.8[1]	**45**	Current annual investment 20 bill €	2045[3]	Biomass feedstock technologies (mainly gasification) H_2 related processes (mainly alkaline electrolysis and methane pyrolysis)
	Fostering circularity	288[1]	9.0[1]	**46**	Current annual investment 20 bill €	2050 or later[3]	Biomass feedstock technologies (almost only gasification) H_2 related processes (mainly alkaline electrolysis and methane pyrolysis)
	Sustainable biomass	350[1]	10.9[1]	**56**	Current annual investment 20 bill €	2050 or later[3]	Biomass feedstock technologies (mainly gasification) H_2 related processes (mainly alkaline electrolysis and methane pyrolysis)
	CO_2 capture	160[1]	5.0[1]	**26**	Current annual investment 20 bill €	2035 and 2045[3]	CO_2 capture, transport and storage technologies Conventional technologies
GIND21	Proposed path	-	-	**-**	-	-	-
EC17	Prospective scenario	-	-	**-**	-	-	-
NGOV18	Transition agenda	<<0.1[4]		**-**	-	-	"Prevention, more with less and avoidance of leakage" "Increased renewable supply and demand"
ECF19	Pla. Baseline	-	2	**0**	Baseline	Constant	-
	Pla. New processes	-	6.0	**200**	Baseline	2040	-
	Pla. Circular economy	-	5.2	**160**	Baseline	2035	-
	Pla. Carbon capture	-	4.4	**120**	Baseline	2030	-
	Amm. Baseline	-	0.6	**0**	Baseline	Constant	-

	Amm. New processes	-	0.7	**17**	Baseline	2030	-
	Amm. Circular economy	-	0.6	**6**	Baseline	2030	-
	Amm. Carbon capture	-	0.8	**26**	Baseline	2030	-
ACA21a	Linear carbon pathway	-	-	**-**	-	-	-
	Circular carbon pathway	-	-	**-**	-	-	-
ACA21b	Planned Energy Scenario	1950[4]		**0**	Planned Energy Scenario	-	Fossil fuel based production Energy recovery
	1.5 °C case	4500[5]	140[5]	**131**	Planned Energy Scenario	-	Renewables based hydrogen feedstock Energy efficiency

[1] Additional costs
[2] Partly overlap with scope 1 and 2 investments
[3] Peak for capacity deployment (not necessarily same as investment peak)
[4] Only cost of proposed government actions, until 2030
[5] USD

Table B.2 – Costs for energy, feedstock and operation in the different pathways.

Document codename	**Scenario**	**Average per year (bill €/year)**	**% increase**	**Compared to**	**Note**	**2 most significant costs**
CEFIC17	BAU	103	**0**	BAU	Production costs	-
	Intermediate	107	**4**	BAU	Production costs	-
	Ambitious	108	**5**	BAU	Production costs	-
	Maximum	110	**7**	BAU	Production costs	-
NCHEM18	Circular & biobased	12.6	**110**	2015	Energy, feedstock	Biodiesel Wood
	Electrification	10.8	**80**	2015	Energy, feedstock	Electricity Wood
	CCS	5.5	**-8.3**	2015	Energy, feedstock	Fossil oil Natural gas
	2030 compliance at least cost	10.0	**65**	2015	Energy, feedstock	Biodiesel Wood
	direct action and high-value applications	9.0	**50**	2015	Energy, feedstock	Biodiesel Electricity
PORT18	BAU	-	**-**	-	-	-
	Technical progress	-	**-**	-	-	-
	Biomass and CCS	-	**-**	-	-	-
	Closed carbon cycle	-	**-**	-	-	-
CHEME18	Propsed plan	-	**-**	-	-	-
CEFIC19	Plausible estimate	-	**-**	-	-	-
GCHEM19	Reference pathway	23.2	**0.87**	2020 (incl. specialty chemicals)	Energy, feedstock, emission certificates	Fossil raw material Fuel costs

	Technology pathway	26.5	**18**	2020 (excl. specialty chemicals)	Energy, feedstock, emission certificates	Electricity Fossil raw material
	Greenhouse gas neutrality pathway	36	**61**	2020 (excl. specialty chemicals)	Energy, feedstock, emission certificates	Electricity Biomass/Plastic waste/CO_2 material costs
FCHEM20	BAU scope 1&2	0.4	**11**	2015	Electricity	-
	Fast development scope 1&2	0.9	**170**	2015	Electricity	-
	Carbon neutral chemistry scope 1&2	1.6	**360**	2015	Electricity	-
	BAU feedstock	13.2	**30**	2015	Main raw material costs	Fossil
	Fast development feedstock	14.2	**40**	2015	Main raw material costs	Fossil Renewable
	Carbon neutral chemistry feedstock	13.8	**35**	2015	Main raw material costs	Renewable Recycled
CEFIC21	High electrification	100.6	**110***	2019	Energy, feedstock, opex *Only energy+feedstock	-
	Fostering circularity	91.0	**92***	2019	Energy, feedstock, opex *Only energy+feedstock	-
	Sustainable biomass	98.4	**120***	2019	Energy, feedstock, opex *Only energy+feedstock	-
	CO_2 capture	95.0	**83***	2019	Energy, feedstock, opex *Only energy+feedstock	-
GIND21	Proposed path	-	**-**	-	-	-
EC17	Prospective scenario	-	**-**	-	-	-
NGOV18	Transition agenda	-	**-**	-	-	-
ECF19	Pla. Baseline	1.2*	**0**	Current process	Production costs incl. CAPEX and downstream *€/tonne	-
	Pla. New processes	1.5-1.8*	**20-46**	Current process	Production costs depending on technology, incl. CAPEX and downstream *€/tonne	-
	Pla. Circular economy	1.5-1.8*	**20-46**	Current process	Production costs depending on technology, incl. CAPEX and downstream *€/tonne	-
	Pla. Carbon capture	1.5-1.8*	**20-46**	Current process	Production costs depending on technology, incl. CAPEX and downstream *€/tonne	-
	Amm. Baseline	354*	**0**	Current process	Production costs incl. CAPEX and downstream *€/tonne	-
	Amm. New processes	418-553*	**18-56**	Current process	Production costs depending on technology, incl. CAPEX and downstream, at 40 €/MWh electricity *€/tonne	-
	Amm. Circular economy	418-553*	**18-56**	Current process	Production costs depending on technology, incl. CAPEX and downstream, at 40 €/MWh electricity *€/tonne	-
	Amm. Carbon capture	418-553*	**18-56**	Current process	Production costs depending on technology, incl. CAPEX and downstream, at 40 €/MWh electricity *€/tonne	-

ACA21a	Linear carbon pathway	822-1366*	**same range**	Baseline with only CCS	Operational costs incl. EoL *USD	Oil Energy recovery
	Circular carbon pathway	839-1110*	**same range**	Baseline with only CCS	Operational costs incl. EoL *USD	Biomass or chemical recycling (depending on electricity price)
ACA21b	Planned Energy Scenario	860*	**0**	-	Energy, feedstock *USD	-
	1.5 °C case	1170*	**36**	Total energy & feedstock cost for sector in 2050	*"Total mitigation cost" (310 bill USD) + PES energy+feedstock, USD	CCS for combustion and processes H_2-based chemicals/Energy efficiency

C Appendix 3: Notes on dependencies and additional pointers

The notes in this Appendix are those compiled while reading through each roadmap. They show what the roadmaps said regarding dependencies on surrounding factors and other pointers made, as well as short reflections on what is said or implied about the industry's own role and the role of other actors. These notes functioned as an overview for the evaluation, but were not the only basis used. For the evaluation, the roadmaps were revisited for verification and to find more detail and illustrating quotes.

CEFIC17

Other pointers from roadmap
Ambitious Research and Innovation program
Public-private partnership efforts
Cross-sectorial collaboration for industrial symbiosis
Sustainable material recycling
Intense dialogue between public and private stakeholders
European database of CO_2 sources and infrastructures for industrial symbiosis

Reflections on how the industry's own responsibility is addressed
Follow the incentives, take part in discussions with e.g. stakeholders

Reflections on dependency and how other actors responsibility is addressed
Very dependent. Policy, public stakeholders, investments, risk abatement, research etc.

NCHEM18

Other pointers from roadmap
Government to take active role, level global playing field or help financially (abatement costs lower than for other sectors, but not profitable for company)
Infrastructure: electricity, H_2, biomass, CO_2, heat, waste handling and recycling, CCS on incinerators
Joint task force with government and energy sector to coordinate energy system and infrastructure, as well as innovation programs
Energy sector has significant role with close links and connected infrastructure
Leadership from top management one of the most important success factors
Energy transition collaboration (can act as balancing hub)

Sustainable industry collaboration (innovation, technology progress, closing material loops, industrial symbioses, best uses of biobased materials etc.)
Public acceptance, e.g. for CCS, geothermal
Risk of lock-ins/opportunity to lead if short term focus
Multiple reasons why “direct action” is preferred despite higher costs
Concerted action of stakeholders
Global level playing field
Focused innovation
Infrastructure investments
Leadership by politicians and business leaders
Points out chemical sectors role for other industries (e.g fertilizers, light weight and components for automotive, efficient tyre materials, coatings, P2X, batteries, large scale batteries, CFCs for cooling, material for renewable energy, new ruminant feed, meat replacements, food packaging, aiding in efficient use of fertilizer, insulation materials, working (innovative) fluids/components/thermochemical heat storage for low temperature heat in heat pumps and ORC, efficient pipes, cooperation for common infrastructure, innovative material for HEX, enabler for biofuels and CCU, co-development for efficient materials, grid flexibility)
Adequate pricing and financing for right incentives (discuss with government/energy sector)
Accelerate innovation and implementation with targeted programs (joint industry+government, regional long-term partnerships), With stakeholders in value chain, energy, built environment, transport, waste management. E.g recycling/circularity, biobased, efficiency and electrification, heat, CCS. Regional programs to speed implementation
Criteria for sustainable biomass

Reflections on how the industry’s own responsibility is addressed

Initiating and reaching out for cooperation and partnerships, taking leading role in cooperation programs together with government, having active role
(Developing/providing emission reducing solutions to other sectors (e.g materials, components, innovations))

Reflections on dependency and how other actors responsibility is addressed

Government, energy sector, collaboration with other sectors/parts of value chain
Government to stimulate when not economically feasible (towards global playing field, or if not, financial support)
Expressed need for close collaboration with energy sector, closely intertwined
Partnerships to facilitate impact

PORT18

Other pointers from roadmap

Technical/economic/social issues for CCS assumed to be solved
coal+CCS not sufficient emission reduction for >90% reduction
Favourable location for bio, but bio restricted
Need for high investments in synthetic fuels and water electrolysis (but not necessarily in port area)
Import of Fischer-Tropsch-wax in some scenarios
(Potential offshore wind, demand-side energy management/storage at port)

Well pre-positioned due to existing infrastructure and location, considerations for future business models
Scenarios highly reliant on successful research, development, demonstrations
*Recommendations for Port Authority:
Make Decarbonization Roadmap with industry, society stakeholders and scientific advisers (prioritize, observe and attract new relevant actors)
Support ROAD CCS demo project before deciding on CCS
Win EU/national support (financial, regulatory, other) for becoming flagship (e.g NER400 innovation fund)
Consider changing business model
Continue to anticipate and prepare for future
*Recommendations to port industries:
Identify strategic networking on the future role of the cluster
Identify low-risk investments in line with decarbonization and closely observe other
Pressure policy makers for investment certainty
*Recommendations for EU/national policy makers:
Provide clear vision with high certainty for decarbonization
Increase emission costs (and ensure global competitiveness)
Schedules for phase-out of CO_2-intensive industries
Subsidise RD&D, investments in low-carbon technologies and infrastructure (keeping in mind whether they will be invested in anyway or not)

Reflections on how the industry's own responsibility is addressed
Strategic networking, identify low-risk technologies, pressure policy makers

Reflections on dependency and how other actors responsibility is addressed
Yes, assumptions in scenario are based on EU policy enactment (tightened EU ETS, carbon tax, favourable energy efficiency economics/policy).
Builds on the assumption of action around the world, in line with 1.5 °C
Dependent on large supply of renewable energy/sustainable biomass
availability/price, near 100% renewable electricity in BIO/CYC
Requires support in the form of ambitious, clear, credible, stable and pretictable policies on European/national level
CO_2 grids/storage implementation is supported through secure regulatory framework for investments
Reliant on successful RD&D
Port authority to take more active role in research and innovation. Close collaboration with industry for roadmap process. Help win financial/regulatory support from national/EU.
Public participation and acceptance, support within affected communities (e.g for CCS)
Dependency on whole energy system, e.g transport electrification, energy

CHEME18

Other pointers from roadmap
Opportunities from cross-border collaboration
Policy/government:
Needed for technologies that are impossible, do not exist, not allowed

Financial arrangements
Financial incentives
Level playing field - global CO_2 tax
Infrastructure - energy from sea, CO_2 storage. development, planning, financing, pipelines.
Expanding infrastructure fund
Regulations - plastic seen as waste limits plastic recycling, e.g importing used plastic, CO_2 shipments count as emissions, CCU framework
The right incentives - for innovating, using CO_2 from other sectors
Using the location - promote and support cross-border collaboration, e.g waste heat
Magnet for talent - stimulate knowledge collaboration
Intelligent and robust financial instruments

Reflections on how the industry's own responsibility is addressed
Not further addressed

Reflections on dependency and how other actors responsibility is addressed
Government and policymakers

CEFIC19

Other pointers from roadmap
Universal carbon tax
Need clear signals from customers, governments, regulators, society
Need for infrastructure and processes for recycling
Investments in R&D and production of new recyclable materials
Policy framework to help stay competitive, long term and stable industrial strategy
European standards in international agreements
Enable EU state aid for refurbishments, deploying alternative feedstocks and innovative electricity storage
New and reinforced forms of sustainable financing such as external investment plan
EU policy framework for externalities based on LCA developed by policymakers, industry and civil society
Encourage demand for sustainable products through pricing mechanism, drives lower impact chemicals, streamline value chain, drives behavioural shift
EU ban landfilling and recognize chemical recycling
EU implement bio-economy strategy
Facilitate waste transport
Framework combining competitiveness with climate objectives (e.g measuring, creating demand through standards, monetary value on sustainability), Juncker plan, securing feedstock and energy supply, H_2 infrastructure, "new approach to state aid and deprecation, including national tax credit schemes"
EU needs to create supportive framework for innovation
Stronger enforcement of EU rules at border
Dialogue with all stakeholders, governments, other industries, academia and civil society
Integration with waste sector
Attract workers, skill, talents
Electric grid infrastructure

Focus on Africa
Renewable energy expansion
Recyclable by design
New business models e.g. chemical leasing

Reflections on how the industry's own responsibility is addressed
Refurbish, install best-in-class tech
Lead the way in preserving value through life cycles
Develop new technologies and solutions (e.g for chemical recycling, sorting) and with partners (e.g design for recyclability)
Support collaborations with business partners, authorities and society
Connect with civil society
Be involved in creating solutions (eg for entire life cycle)
Continue to improve and invest, under right prerequisites
Develop business models and policy framework (with EU)

Reflections on dependency and how other actors responsibility is addressed
EU/policy, civil society. Points most often to EU, but also stakeholders and society in general. Also points to consumers to recycle, and for signals on what they are willing to pay for. Dependency on global trends central focus.

GCHEM19

Other pointers from roadmap
Enabling economic conditions
State funding and support
Energy-policy framework
Relief scheme regulations (also in reference pathway)
Regulations to protect European production sites
Enough cheap energy and raw materials (if electricity is 60 euro/MWh it is too high for plants to be economically viable)
Cannot pass on costs to customers (global market prices)
Must remain competitive in each phase
Otherwise "not worthwhile for companies to introduce new technologies to cut CO_2"
Promotion of new processes at every phase, R&D to demonstrations to large-scale, sped up by state subsidies for investments
Competitive prices for e.g. H_2 with no taxes
Not hindering new technologies with policy obstacles
International agreement for comparable competitive conditions or improved carbon leakage measures
Remove policy obstacles for use and generation of renewable energy

Reflections on how the industry's own responsibility is addressed
Research and develop, make investments to implement in new plants

Reflections on dependency and how other actors responsibility is addressed
Enabling policy
Renewable energy production at 40 euro/MWh, the sooner the faster transition

Sensitivity analysis varies parameters +-50%, and shows that electricity costs and fossil costs affect the most

FCHEM20

Other pointers from roadmap
Must be competitive, viable
Investments need for stable, long-term policies and operating environment
Barriers: long investment cycles - rare opportunities to change, risks perceived for R&D, "cyclical nature of business", lock-in from incremental investments, stranded assets, lack of costumer demand, valley of death and becoming stuck in pilot
R&D should be expanded to Research, Development, Demonstration and Deployment (RDD&D) to speed up commercialization
Need for innovation, technology development and scale up
Policy to fund RDD&D and scale up
Need stable, cheap, low-carbon electricity, low price essential
Reliability of feedstock needed for investments
Case dependency, local conditions and availability
Public investments for large enough recycling infrastructure
CCS needs infrastructure, revision of international agreements, technology development
CCU seen as more promising, closing cycle. Clustering of sites helps
CCS public acceptance can be a barrier
CCU/S benefit from carbon prices, cheap hydrogen and energy, "cost of energy and fossil fuels", regulations on infrastructure and transport, investments in pilots, demos, scale-up
Sector integration for recycling
Investments and innovation for recycling: in collection, sorting, storage of waste plastic, hydrogen capacity, "possible feedstock and product tanking and piping changes", pyrolysis/gasification, hydrotreatment of pyrolysis oil, filtration with mineral filters, destillation
Consider biodiversity, water/land use needed for bio-based
Investments and innovation for biofeedstock: "possible feedstock and product tanking and piping changes", extraction of oil, removal of algae cell walls, filtration with mineral filters, HVO process, distillation
For H_2 economy: solving commercial/technical challenges, cost-competitiveness, end-use applications
Interlinkage of recycled, bio and H_2 economies: Need for new value chains, transfer of knowledge, money and products. Pilot, demonstrations and scale-up. Enabling trade across borders, valuing waste through new waste hierarchy implementation, regulating conventional products, promotion through government procurement. Focus needed to find strengths and bottlenecks for each category from nation viewpoint.
Carbon neutral: import is important, transformation of key dynamics of material flow and value chain, need recycling infrastructure, deep sector integration, strategic and synergistic locations, supporting legislation, large-scale investments, technology advancement, changed consumer behaviour
Solutions are plant/process/company specific
Calling for interindustry cooperations: energy-industry integration, circular economy infrastructure, new financial instruments for innovation, research consortia covering whole value chain

Resources into education and expertice, R&D funding
Promoting exports, paths for commercialization and global markets, and international frameworks.
Seeing technology and piloting environment as export products
Incentives for education of workforce, attract talents
Competitiveness: EU ETS, carbon border tax
Incentives to invest in RDD&D
Energy policy incentives for switching energy
Discussions of digitalisation opportunities and issues

Reflections on how the industry's own responsibility is addressed
(Whose responsibility is the RDD&D?)
Discussion on impact outside industry, e.g. providing electricity demand flexibility, hydrogen for other industries, technology spillover, industrial symbiosis
Mentions joint ventures with energy sector and contributing to recycling system
Own purchase of e.g. solar panels
Marketing
Own R&D

Reflections on dependency and how other actors responsibility is addressed
*Policy:
long-term, stable
funding RDD&D, scale-up
Recycling infrastructure investments
*Costumers for demand
*Availability, stability and price of electricity & feedstock

CEFIC21

Other pointers from roadmap
Chemical sector can't do it alone

Reflections on how the industry's own responsibility is addressed
Employ most cost-efficient technologies given the circumstances
"joint effort with other industries" (fig. 49)

Reflections on dependency and how other actors responsibility is addressed
Meant to "spark debate with policymakers and all other interested stakeholders" and "inform of implications" for 2050 neutrality
Scenarios based on what happens around the sector

GIND21

Other pointers from roadmap
(Measures by other parts of industry already part of path)

Long-term, internationally comparable goals
Stronger global/pan-European governance
Critical changes in climate policy direction to reach set emission goals
Regulatory framework will also need to build support for the investments required among citizens and businesses
Endorse European/international climate policy (e.g. “climate club”, integration and coordination, extended and ambitious EU ETS)
More open setup of EU state aid law to enable for supporting climate transformation
Faster, better and more effective political governance, accelerating planning and approval
Supply of renewable energy carriers
Need for sufficient economic support and incentives for industry to invest
All requires determined political decisions in coming legislative period
Fair burden sharing and societal compensation for households particularly burdened (e.g. removing EEG levy)
Overarching:
Rapid infrastructure development - build up and integration (power, DH, rail, e-mobility, H_2, CO_2)
Make fossil more expensive (EU ETS, non ETS carbon pricing - New ETS, energy taxes differentiating on sustainability) and lower costs of renewable technologies
Incentivize switch to electric (reduce electricity levies for renewable heat applications)
Accelerated electric grid expansion
Faster hydrogen strategy than anticipated, H_2, NG and CO_2 network infrastructure and decentralized H_2
National biomass strategy (large scale DH plants for BECCU/S, phase out subsidies for decentralized biomass use)
*Need for strongly sector-specific political governance, e.g.:
Carbon contracts for difference (reduces risks about carbon price/offsets cost difference between renewable vs fossil technology that has carbon leakage protection)
Investment incentives for renewable heat
Efficiency standards and subsidies
Green lead markets (e.g. quotas)
Definition of green raw materials
Higher recycling rates, more recyclable material
*Research and innovation (e.g. accelerated scaling of high temperature P2H, CCUS, focus innovation agenda on promising green tech)
*Compensation and financing:
Carbon leakage protection (e.g. allocation, carbon border adjustments)
Funding (savings, levies, taxes, debt) needed for government
R&D funding
*Political process:
Climate governance (bundling, central coordination of responsibility, indicator monitoring, faster procedures, “capacities for states/municipalities”, etc.)
Societal consensus (on infrastructure expansion, burden sharing etc., long-term)

Reflections on how the industry’s own responsibility is addressed
Not further addressed

Reflections on dependency and how other actors responsibility is addressed
Path depends on global investment programs in technology (e.g. hydrogen), social preferences,

or a desirable stronger international coordination than today
Clearly addresses regulatory gap, investment gap, emission reduction gap
Political decisions, incentives and investments needed to fill gaps
Import of synthetic naphtha

EC17

Other pointers from roadmap
Need for additional research priorities such as CCS
Need for effective push and creating the right conditions for technologies to be implemented
Competitiveness important and needed for investments to happen

Reflections on how the industry's own responsibility is addressed
Not further addressed

Reflections on dependency and how other actors responsibility is addressed
Not further addressed

NGOV18

Other pointers from roadmap
Collection: more points, more bins for hard plastic, better sorting installations
Better post-separation of residual waste
Closed-loop return system for furniture, clothing, facade construction and automotive
Decreased export of unsorted plastics
(Constant import of high quality waste)
*Prevention/Avoid leakage:
From product to service (new business models, agreements, big data knowledge)
Linear to circular design (sector plans, agreement with stakeholders, education program, business models)
Usage value (develop calculation method to determine usage value)
Multi-use instead of singe use (inventory of products, incentive assessment)
Avoid harmful additives (ban cosmetic microplastics, R&D for avoiding microplastics, framework for handling SVHC, R&D investments in new materials, learn from biomimicry, dandelions for rubber)
Long to short chain (finding ways, financiers are invited)
*Increase supply and demand for renewable plastics
Price (fossil input tax, research on energy use tax)
From ownership to right of use (explore, circular design, return system, new economic model)
Circular purchasing (Circular procurement by companies, governments and EU, green labels, pilot scale-up, promotion in EU)
Producer responsibility (expand and intensify to incentivise circular design, repair and extended life span, include littering)
Sectors with large uses of plastic find ways to substitute
Discourage export and incineration of recyclable (waste taxation, certificate for non-recyclable, export tax, adjust incineration industries)

Recycled/renewable content (overview of applications and regulation, EU guidelines)
Mechanical recycling action plan
Chemical recycling action plan (R&D, public-private support program)
Bio-based action plan (joint public-private, overview, certification, phase out oxo-degradable)
Explore CCU
*Better quality and environmental efficiency
Quality action plan: confidence in quality, standard "grades", guide for track and trace system
More and better sorting (jointly made action plan, sorting and separation technology, standards/definitions, incentives)
Standards for recycled material/circular design
*Strategic cooperation:
Chain management industry+NGO+government cooperation, voucher scheme
Focus on early signs and trends in innovation
New financial arrangements for chain innovation
Regional innovation cooperation, with finance
International: Europe/rest of world must follow, Dutch government+NGO+companies cooperate to influence international frameworks, EU lobbying strategy, incorporation in trade agreements, finance, international collaboration
Focus on entire product life cycle, actions throughout value chain at the same time
Calls for technical, social and system innovations
Interests of entrepreneurs and businesses - need added value in long term and level playing field
Must be anchored in the economic system
*Social agenda: dealing with the social effects and respecting social boundaries:
Labour market: Study how related sectors (chemical, plastic/rubber, implementing, recycling) are affected (role, investments, R&D, new training, employment, education level, internal dialogue)
Training and skills: Investing in curricula at different levels, sites with practice/education links, better use of training funds, support to municipalities/provinces
Organisation: develop strategy for: internal coordination, sustainability management higher on agenda and from top, stringent criteria, asking employees for contribution, regional networks and local connections
*Knowledge and innovation agenda:
Linking different knowledge and innovation agendas/roadmaps (chemical, bio-economy, energy and industry, product-as-service)
Keeping innovation agenda close to intended users, gives more direction
Private investments are dependent on market conditions

Reflections on dependency, how the industry's own responsibility and other actors responsibility is addressed

Responsibilities for proposed tasks are explicitly stated, often combination of various actors and organisations, e.g industry organisations from chemical/plastic/rubber/waste/recycling, government and ministries, municipalities, provinces, standardisation organizations, banks, knowledge institutions, research institutes, educational establishments, NGOs

ECF19

Other pointers from roadmap

General:
Shared expectation and concerted efforts by government, industrial companies, companies in major value chains, cities, civil society, and individuals
Need to be more tightly linked with other sectors (for CO_2, getting feedstock, H_2, waste)
Cannot choose only based on cost, e.g local conditions matter
Need for circular economy
Affordable electricity (prices have large impact on total costs)
Deep integration across value chain
More reliance on local EoL-resources
Investments also in energy, CO_2 and waste management infrastructure
Circular economy/productivity improvements can reduce needs and some costs and eases many challanges (but maybe hidden costs)
Need step-change both in policy and company strategic choices
Improved EoL-management (enabling, control, collection, sorting, reduced contamination)
Ensure that changing to new processes is economically viable even when it costs more
Public acceptance for CCS
Different types of cost: innovation, risk, conversion, transition (redundancy), higher capex
Innovation both for demand and supply (business, design, as well as processes)
Recognition of biomass for chemicals in policy and discussion, biomass used strategically
Need focus on avoiding double investments, policy help (maintaining old and then also investing in new)
Different investment model for transition in EU
Significant change to waste handling sector
Policy:
Ensure a future business case most important, need to understand why investments are needed in different stages (different kinds of costs)
*Accelerate innovation and scaling (innovation agenda, new mechanisms and approaches, also later stage, mission-driven, earlier innovation loops)
*Enable early investment and reduce lock-in risks (public finance, risk-sharing, tax and depreciation of new assets, change state-aid guidance, low regulatory zones, handle stranded assets)
*Create lead markets and safeguard competitiveness (supporting and creating certainty for the costlier low CO_2 options, remove regulatory hurdles, subsidies, quotas and standards, public procurement, border adjustment, (but also risk with picking winners)),
*Create systems for high quality recirculation (cleaner flows targets, charges for landfill and incineration, enable cross-border trade, dismantling regulation, definitions and standards for sorting, infrastructure, better incentives, business case for use),
*Ensure access to and coordinate new inputs and infrastructure (CO_2, H_2, clean electricity, waste as resource, right incentives for biomass, heat), (generation, transmission, distribution, storage) and encourage clusters, industrial symbiosis, vertical integration, more public action and less expectation on private
*Integrate materials eff. especially demand-side efficiency in policy and new business models in key value chains (like with energy efficiency, e.g. standards, quotas labelling, use targets, like eco-design directive, fix market failures so those that have most potential to avoid over-use have the incentives, e.g. design)
need for strong supporting policy, especially near term - Additional costs cannot be borne by

companies (“bet-the-company”)
EU ETS not enough on its own, needs complements (market failures, innovation support, international competition...)
Balance the cost between business and consumers
Ammonia:
CO_2 easier to capture (concentrated and few sources)
Logistics and supply unpredictability challenging
210 g/kWh electricity emission intensity needed for water electrolysis lower than SMR
Water electrolysis needs efficient H_2 storage, infrastructure, cheap electricity (new actors)
CCS needs infrastructure (new actors)
Coordination across value chain

Reflections on how the industry’s own responsibility is addressed
New processes:
Current industry need to make early decisions and adjust production
Circular economy:
(Cooperate and adapt)
CCS:
Cooperate and adapt

Reflections on dependency and how other actors responsibility is addressed
Decarbonized electricity
New processes:
Electricity
Policy to enable the investments and provide business case
Circular economy:
Actors throughout value chain and new actors
Innovation upstream and for new business models
Control of EoL flows
CCS:
Sector coupling (e.g. steel and chemicals)
Concerted efforts for demonstration
Policy for economic confidence and coordination, infrastructure
Social acceptance
Ammonia:
Complex food value chain with many actors

ACA21a

Other pointers from roadmap
Improved waste management, increasing profitability of material recycling, investments in infrastructure and coordination
Economic incentives for waste management and CCU/biomass technologies
Including whole life cycle, e.g. waste incineration in emission pricing scheme by e.g. extended producer responsibility
Incentivize value addition at start of waste chain (consumer), e.g. through deposit systems
Global policy instruments to increase plastic availability as a resource and increased invest-

ments in biomass and CCU
Balance against other environmental impacts

Reflections on how the industry's own responsibility is addressed
Not further addressed

Reflections on dependency and how other actors responsibility is addressed
Best strategy combination depends on availability of resources and carbon intensity of electricity. Provides pointers to policy makers

ACA21b

Other pointers from roadmap
Access to large amounts of (renewable) affordable and reliable energy and feedstock
Infrastructure: power, H_2, CO_2, heat, waste and recycling
Need for life cycle policies including energy and materials
Risks for wrong investments and stranded assets
Need for regional/local tailoring
Maybe decentralized plants close to biomass production, adjustable biorefineries, remote desert H_2 production with ammonia/methanol production close
CCS acceptance
Biomass availability
CCU and green H_2 are a bit too slow for big impact 2050
Ways to compensate for higher product price (e.g. premium for green products, carbon pricing)
Transition has large impact on global energy system
Making certification for green supply chains, creating market niches, mandatory green share

Reflections on how the industry's own responsibility is addressed
(Doing what must be done = fundamental changes)
Front runners forcing change

Reflections on dependency and how other actors responsibility is addressed
Dependent on product policy, waste management policy, innovation and R&D in materials, logistics in EoL
Renewable, cheap electricity
Biomass availability
That rest of industry will join a zero-emission pathway
Dependent on front runners (consumers, governments, chemical and petrochemical industries and clusters) - rather than the unlikely global concerted efforts
Governments to create enabling environments for experiment, learning, growth

D Appendix 4: Evaluation comments for timeline and concretion

Table D.1 shows the comments regarding timeline and concretion for each roadmap, and functions as complementary to Table 4.5.

Table D.1 – Clarifying comments for the evaluation of concretion of timeline, strategies and recommendations, complementary to Table 4.5. T, S and R stand for comments regarding technologies, strategies and recommendations respectively. Supplementary material was considered as well for ACA21a and ACA21b.

Document codename		**Comments**
CEFIC17	T	5-year interval modelling for production and production costs. Clear assessment of the TRL. Time planning until 2030 only implicit from modelling.
	S	The document is an in depth technology study focusing on existing options, opportunities and challenges. Pathways show which technologies are used.
	R	A list of recommendations is given, mainly directed at policy.
NCHEM18	T	Intermediate results for 2030 are shown, but no more detail is given. TRLs are given and a graph shows clearly when technologies may be available.
	S	Clear descriptions of available technologies, although not as clear which technologies are used in the scenarios. Challenges are explored, e.g. through scenario exploration.
	R	Clear recommendations both for industry and other stakeholders given and discussed.
PORT18	T	Employment and decommissions at unit level with approximate dates makes up the scenarios. When technologies are available is implied by when they are used and some broad estimations are shown.
	S	Some specifications of technologies are given and are described in scenarios, and a range of technologies have been considered and discussed. Contains sections focusing on challenges for the different scenarios.
	R	A list of recommendations for port industries, port authorities and policy makers are given and elaborated on.
CHEME18	T	The available English document does not contain much detail (due to the brochure format), but it is likely that this exists elsewhere. A list of envisaged projects is given, but without time frames. A graph of the emission curve until 2030 is shown without elaboration.
	S	Types of technologies at times implied from the projects. Low level of detail likely due to the format.
	R	The list of projects shows concrete actions for the cluster industry. A list with elaborated requests for governments is presented.
CEFIC19	T	One figure depicting a timeline for some technology development projects. Unclear if it is planned projects or estimations, likely not exhaustive.

	S	Information on a basic level. Challenges and uncertainties are at most implied.
	R	More directed at stakeholders that are not industry. Appeals are made and discussed in some cases giving specific policy recommendations.
GCHEM19	T	5-year interval modelling for emissions, costs and energy/feedstock input, no further short-term detail. TRL given and assumed to increase by 1 every 7 years.
	S	Detailed descriptions of technologies given, and which are used (in German version). Sensitivity analysis shows dependence on some factors, but discussions of challenges and uncertainties seemingly missing (although difficult to assess in for document in German).
	R	Stated that the goal is not to make recommendations for concrete political instruments, but options for action are still discussed. It is done in general terms but mainly leaning towards policy more than the industry sector.
FCHEM20	T	Year-by-year action plan, both general and company example are given for 2020-2030. 5-year interval modelling for emissions, investments, electricity, etc. TRL and some estimations of commercialization until 2050.
	S	Overall descriptions of technology options, their uncertainties, challenges and impacts for each strategy. Less detail in which are used.
	R	Action plan suggested for industry actors. Policy instrument suggestions discussed in general terms.
CEFIC21	T	5-year modelling for emissions and capacity but no further time planning. Technology availability mostly implied through this.
	S	The list of technologies assessed clearly stated, as well as what is used in the scenarios, although not described in detail. Clearer descriptions than other regarding biomass types. General notes regarding uncertainty and challenges.
	R	No concrete actions for the industry, but no regret options are pointed out and some less specific recommendations are given. Policy is central to the modelling but no recommendations are given other than minor infrastructure comments.
GIND21	T	(German version) 5-year interval modelling shown for capacity only. Early measures with years given for coming into effect. Assumed technology development not further specified.
	S	Suggested technologies and uncertainties mentioned mainly on a very basic level.
	R	Clear and concrete recommendations for policy makers, but none directed at industry was found.
JRC17	T	Year-by-year economic model at facility level (implying early planning). Technologies are assumed to be available from start, 2020, 2030 or 2040 based on TRL.
	S	Considered technologies are described in detail, and for the most part their deployment in the model is explained. Challenges and uncertainties are discussed, but mainly from a technical perspective. Technologies are avoided if information is lacking.
	R	Only recommendations found are need for "decisive push" and "additional research priorities", and "creating right conditions".
NGOV18	T	The plan stretches only to 2030, and projects until then are suggested with time frames. Only few very minor hints regarding pilot plant installations.
	S	Technologies are described at a basic level, but deeper descriptions are given for a larger variety of measures. Which technologies will be used is not specified since the actions suggested will determine this. A broad variety of issues to be solved and focused on are pointed out.
	R	Consists of descriptions of transition, a list of government assigned projects, their involved actors, budgets and time frames.
ECF19	T	Timeline is mainly communicated through graphs over time: of emission reduction, production and investments. No more detailed description for early years, nothing more precise than that technologies are available or emerging.

	S	Descriptions of technologies on a clear level with some technological depth. Challenges mainly elaborated on regarding CCS, otherwise general.
	R	Clear recommendations targeted at policy and providing the right framework. Some signals to industry but very little concrete.
ACA21a	T	Model is only for the year 2050. Technologies are divided into low and high TRL (below or above 7), where high TRL technologies are said to already be commercialized.
	S	Precise descriptions of which technologies are used in the model. Dependencies brought up on a basic level.
	R	Policies are discussed and more or less general suggestions are given.
ACA21b	T	Model only for 2050. Availability is not specified, although said that the proposed production pathways are available in principle but that more efforts are needed for industrial scale deployment.
	S	Technologies are described with references to current plants, pilots and projects, but not as clear precisely which are assumed in the scenario. Uncertainties and challenges discussed for some aspects but mostly general.
	R	Some advice and considerations are given for policy makers but no concrete suggestions.