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Towards a Net-Zero Chemical Industry – a Meta-Analysis of Recent Scenario Studies and Roadmaps

Results from the research project
“Green Feedstock for a Sustainable
Chemistry – Energiewende und
Ressourceneffizienz im Kontext der dritten
Feedstock-Transformation der chemischen
Industrie”

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1 Introduction

22 years are left until the German target for climate neutrality should be reached. For the industrial sector, this implies a fundamental change and an acceleration of emission reduction, as from 2000 to 2021 the sector has reduced its greenhouse gas (GHG) emissions by only 13% (ERK, 2022). For the large structures, plants and assets that are characteristic for the energy intensive industrial sectors, the timespan implies no room for delay. One sector facing particular challenges is the chemical industry. Here, fossil resources are used not only for energetic purposes but for feedstock as well, in the petrochemical industry in particular. The efforts made in the petrochemical sector thereby not only affects the sectors own emissions, but the chemicals value chain at large, including the management of end-of-life products. The dependency on energetic resources for material use also means that there is a particular connection from the chemical industry to the energy system at large, which also entails special consideration.

The chemical industry also has a particular relevance to the Antwerp-Rotterdam-Rhine-Ruhr-Area (ARRRA) which hosts several large petrochemical clusters in Germany as well as the Netherlands and Belgium, with complexly interlinked production chains. In reaching the climate targets, these regions especially face significant changes and may have the opportunity to position themselves as frontrunners for industrial transformation. That is, if a successful strategy can be found.

In the recent years, numerous scenario analyses and roadmaps have been released drawing out pathways for chemical industries to develop in line with national and international climate targets. This can entail mapping of technological options, important prerequisites, particular challenges as well as important opportunities and timeframes. This meta-analysis summarizes and compares the findings of some of the most recent previous works at the national, European and global level. As the goal is to investigate the various strategic options and development paths for Germany and the ARRRA, it has a particular focus on roadmaps for Germany, the Netherlands and Belgium. It takes a quantitative as well as qualitative approach, looking both at resource and production volumes, different emission reduction strategies relative importance, as well as policy recommendations and other important framework conditions. A particular focus is put on the use of non-fossil feedstocks to reduce emissions.

The following Chapter 2 describes the methodology of finding and selecting roadmaps for evaluation, the selected roadmaps and how the assessment was made. Chapter 3 gives a short description of the available overall strategies for reaching emission reductions in the chemical industry, focusing especially on feedstock related strategies. This is followed by an analysis and comparison of the selected roadmaps in Chapter 4. Here the overall emission reductions, energy use and demand changes are presented and analyzed, followed by a deeper look at the strategies and technologies in terms of feedstock and energy carriers, and after that a more qualitative summary of the challenges, opportunities and policy recommendations brought up in the roadmaps. The findings are then discussed in

Chapter 5, focusing on the similarities and differences, as well as an overall outlook and conclusions.

Embedded in the research project *Green Feedstock for a Sustainable Chemistry (GreenFeed)*, this work aims to shed light on the heterogeneous discussion about possible strategies and lines of development for the petrochemical industry in the context of the energy transition. The findings form a basis for subsequent work packages, which will focus on technology assessments, scenario developments and roadmapping.

2 Methods

The literature analysis carried out in this project was made in three steps: setup of selection criteria, search and selection of documents, and finally a mapping and analysis along a set of evaluation criteria. These steps are described in more detail below. The term “roadmap” is used to refer to a document drawing out ways for the chemical industry to reach reduced emissions. A roadmap can contain multiple different ways to do this, and these are herein referred to as different “scenarios”. These two terms are used here consistently for simplicity, although it can be noted that other terms may be used in the documents themselves, such as “pathways” rather than “scenarios” or “scenario-/pathway analysis” rather than roadmap.

2.1 Selection Criteria and Search for Publications

For the first step, the following criteria were set up for which documents would be included in the analysis:

- **Geographic:** With the focus being on the ARRA, roadmaps for Germany, the Netherlands, Belgium, or regions in those countries were prioritized. This was complemented by roadmaps for Europe or the world.
- **Recent:** Published earliest 2017.
- **Level of detail:** Should contain quantitative information for greenhouse gas emissions, energy demand and demand/production volumes for the chemical/petrochemical/plastics industry in the target year of the respective studies (either 2045 or 2050).
- **Level of ambition:** At least one scenario portrayed which is in line with a net-zero ambition for the target year. This was specified as the scenario reaching an emission reduction for the chemical/petrochemical/plastics industry of at least 90% compared to the reference year, and for the emission scope used in the document (see Table 2-1).

For the Netherlands and Belgium, however, only very few roadmaps came close to fully reaching these criteria. In order to include representation for all countries in the ARRA, roadmaps from the Netherlands and Belgium were included if they for the most part fulfilled the criteria.

The search for documents was then carried out by gathering the documents previously known to the authors, and supplementing by additional searches in online databases.

2.2 Selected Roadmaps and Scenarios

The selected documents can be seen in Table 2-1. Five documents were found for Germany, three for Netherlands (including Port of Rotterdam), and two for Belgium or parts of Belgium. Furthermore, four with a European scope and three with a global scope were chosen. In these, a total of 35 scenarios were found that reach at least a 90% reduction of greenhouse gas emissions for the chemical industry in their respective scopes. The scenarios *MIX* in *TransitVlaams*, and *CORE-95* in *ScenBel* reach a 88% reduction in greenhouse gas emissions, but were included anyway in order to get more representation for Belgium. The roadmaps are made by and for a

variety of actors, including government agencies, industry organizations and research institutions.

Table 2-1: Roadmaps and scenarios included in this analysis.

Codename	Title	Year	Publisher/Authors	Scope	Chosen scenarios
Wege	Wege in eine ressourcenschonende Treibhausgasneutralität	2019	Umweltbundesamt	Germany	GreenEe1 GreenEe2 GreenLate GreenMe GreenLife GreenSupreme
RoadChem	Roadmap Chemie 2050 – Auf dem Weg zu einer treibhausgas-neutralen chemischen Industrie in Deutschland	2019	Dechema, FutureCamp	Germany	GHG neutrality pathway
KlimaPfade	KLIMAPFADE 2.0 – Ein Wirtschaftsprogramm für Klima und Zukunft	2021	BCG	Germany	Proposed path
KlimaDe	Klimaneutrales Deutschland 2045	2021	Stiftung Klimaneutralität, Agora Energiewende, Agora Verkehrswende	Germany	KN2045
DenaLeit	dena-Leitstudie – Aufbruch Klimaneutralität	2021	Deutsche Energie-Agentur GmbH	Germany	KN100
DeepDecarb	Deep decarbonisation pathways for the industrial cluster of the Port of Rotterdam	2016	Wuppertal Institute	Port of Rotterdam	Biomass and CCS (BIO) Closed carbon cycle (CYC)
ChemforCli	Chemistry for Climate: Acting on the need for speed Roadmap for the Dutch Chemical Industry towards 2050	2018	Ecofys, Berenschot	Netherlands	Circular & biobased Electrification 2030 compliance at least cost Direct action & high-value applications
Manuel et. al.	High technical and temporal resolution integrated energy system modelling of industrial decarbonisation	2022	M. Sanchez Dieguez, F. Taminiau, K. West, J. Sijm, A. Faaij, (in: Advances in Applied Energy (7) 2020)	Netherlands	OPN BIO CCS ELE HYD
TransitVlaams	Transitiepotentieel van de Vlaamse industrie: Roadmapstudie en ontwerp van transitiekader	2020	Deloitte, VUB ies, Climact	Flanders in Belgium	MIX VAR1 VAR2
ScenBel	Scenarios for a Climate Neutral Belgium by 2050	2021	FPS Public Health: DG Environment: Climate Change Section	Belgium	CORE-95
LowCarb	Low carbon energy and feedstock for the European chemical industry	2017	Dechema	Europe	Maximum
IndInno	Industrial Innovation: Pathways to deep decarbonization of Industry	2019	ICF Consulting Services Limited, Fraunhofer ISI	EU	Mix95
IndTrans	Industrial Transformation 2050 - Pathways to Net-Zero Emissions from EU Heavy Industry	2019	Material Economics, VUB-IES, Wuppertal Institute	Europe	New Processes (NP) Circular Economy (CE) Carbon Capture (CC) (for plastics and ammonia respectively)
iC2050	iC2050 PROJECT REPORT - Shining a light on the EU27 chemical sector's journey toward	2021	Deloitte	EU27	High electrification Fostering circularity

	climate neutrality				Sustainable biomass CO ₂ capture
Meys et. al.	Achieving net-zero greenhouse gas emission plastics by a circular carbon economy	2021	R. Meys, A. Kästelhön, M. Bachmann, B. Winter, C. Zibunas, S. Suh, A. Bardow (in: Science 2021, 374, 6563)	Global	Circular carbon pathway (combo)
Saygin & Gielen	Zero-Emission Pathway for the Global Chemical and Petrochemical Sector	2021	D. Saygin, D. Gielen (in: Energies 2021, 14, 3772)	Global	1.5 °C case
PlanPos	Planet Positive Chemicals - Pathways for the chemical industry to enable a sustainable global economy	2022	Center for Global Commons, SYSTEMIQ	Global	LC-NFAX

2.3 Evaluation Criteria

The documents were assessed both quantitatively and qualitatively. Quantitatively in terms of emissions, energy, feedstock and production volumes, and qualitatively in terms of main challenges, opportunities and policy recommendations mentioned, as well as technologies used and the timeline of their deployment.

2.3.1 Quantitative assessments

The quantitative assessment was made by collecting the data presented in the roadmaps, and when necessary, complement with own calculations to achieve overall percent changes in emissions, energy use, and production volumes until the target year. Furthermore, if not already presented in the roadmap, the shares for different kinds of feedstocks and energy sources to be used in the target year were calculated. These calculations were aided by the online tool WebPlotDigitizer, if values had to be extracted from graphical illustrations. Since the feedstocks and energy sources were categorized differently in different roadmaps, some assumptions and recategorizations were made to enable comparison of the use of different strategies, but the original categories used in each roadmap were noted as well.

Some roadmaps showed how the emission reductions were achieved quantitatively by presenting the share each strategy contributed to the total reduction. This data was also collected and summarized, if necessary recategorizing the strategies for comparability into the nine categories Recycling, Biomass, CCU/H₂, Electrification, Electricity emission factor, Renewable energy (non-electricity), CCS, Efficiency improvements and Other. An illustrative example of this can be seen in Figure 2-1, which show the strategy “CCS” contributes to the total emission reduction in a fictional Example scenario.¹ Furthermore, production was often expected to increase in the roadmaps until the target year which would lead to increased emissions under ceteris paribus conditions. Emission reduction strategies must therefore be used even more to compensate for this increase. To capture this, the category “Growth effect” was introduced, which shows how much the emissions would increase (or decrease) under ceteris paribus conditions, and thereby the increased (or decreased) additional need for emission reduction strategies. This “Growth effect” is also

¹ In this example, the share of the emission reduction due to “CCS” would be calculated as the avoided emissions in 2050 due to CCS, divided by the total emissions in the reference year 2015, i.e., 25%.

illustratively visualized in Figure 2-1. It was calculated from the roadmaps using the difference between the emissions in a reference- or BAU scenario in the target year, and the emissions in the reference year.

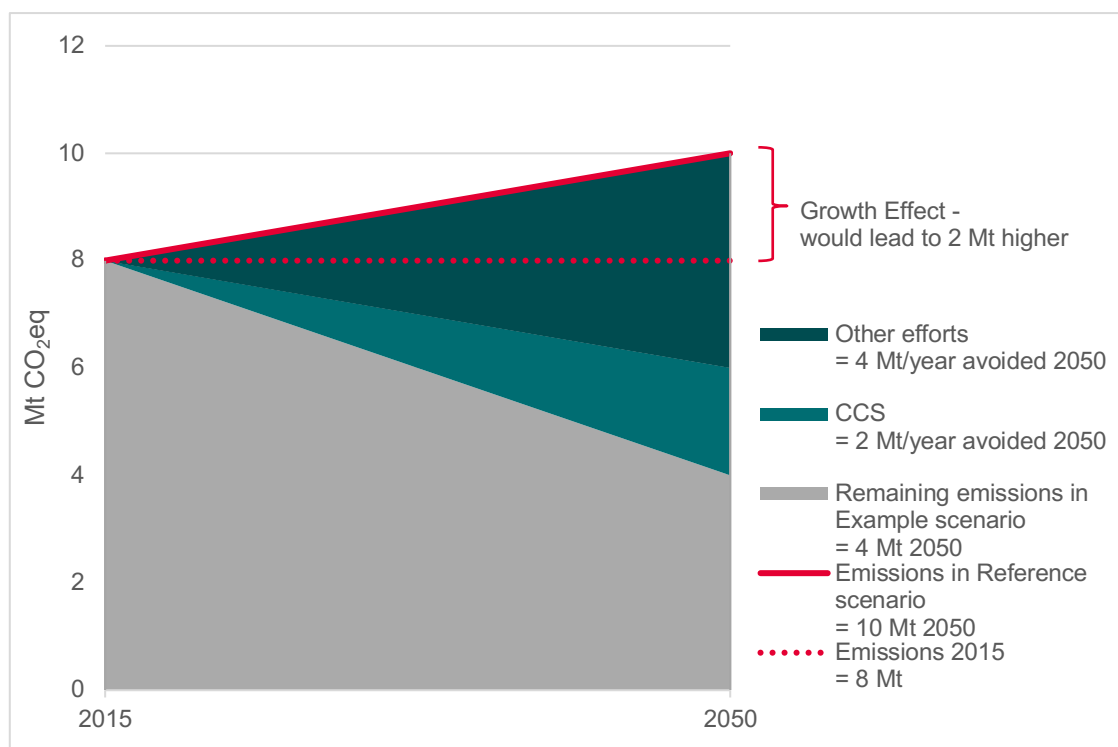


Figure 2-1: Illustrative example scenario.

Note: This fictitious scenario serves to illustrate how the emission reduction was calculated using the CCS strategy as an example and explains what is meant by "growth effect".

2.3.2 Qualitative assessments

The qualitative assessment focused on main challenges, opportunities and policy recommendations mentioned in the respective roadmaps, as well as the scope used in the roadmap, technologies, and timeline. These data were gathered from roadmap summaries, conclusions, figures and tables, and was complemented using word searches on relevant terms. Mentions related to each of these topics were noted for each of the roadmaps.

3 Strategies

The goal of defossilization of the chemical industry means that the material feedstock used in chemical products must be sourced from something other than the fossil naphtha, natural gas and other fossil feedstocks used today. The available options for sourcing carbon commonly discussed are recycled feedstock, biomass and captured CO₂. The energy content of the final products may also have to be provided, as these feedstocks, especially CO₂, are not always as energy dense as the fossil alternatives. This energy can be added in the form of sustainably produced hydrogen. In this section, these strategies are described briefly in terms of characteristics and available technologies. Furthermore, while the focus of this study is on the feedstock and its related emissions, the energetic emissions must also be mitigated in order to reach net-zero emissions. Efficiency improvements in terms of both energy and materials can also contribute both to emission reductions and reduce the need for emission generating processes overall. Additionally, there is the option to capture and store any remaining emissions, fossil or otherwise. These strategies are also briefly presented.

3.1 Change of Feedstock

3.1.1 Recycled feedstock

The need for sourcing virgin feedstock can be avoided or reduced by using recycled feedstock. This can be done either via the mechanical recycling of plastics used today, or chemical recycling for which technologies are being developed, e.g., solvolysis, pyrolysis or gasification. Recycling also avoids emissions from other end-of-life treatment of the waste material, which, according to an analysis by Material economics (2019), is approximately 60% of the life cycle emissions for plastic products when they are incinerated as waste. Challenges for this strategy include increasing the currently low collection rate as well as the rate of the collected material that can be returned to the cycle. Today, these rates are 35% each in the EU (Antonopoulos et al., 2021; Plastics Europe, 2022). The different potential recycling technologies are able to accept different types of waste, and more or less sorted waste. Mechanical recycling on the one hand is energy efficient, but requires a high degree of sorting, whereas gasification can essentially accept any mix but on the other hand is a much more energy intensive process.

3.1.2 Biomass

Virgin feedstock can be sourced from biomass. This strategy may be considered sustainable depending on which kind of biomass is used, and the term “sustainable biomass” is sometimes used to differentiate from biomass sourcing contributing to environmental harm and increased emissions. Many potential sources of biomass could be conceivable, including sugar or oil crops, but non-food sources such as agricultural or forestry residues, other woody biomass, starch, or food waste are often preferred from a sustainability perspective. The EU has set up sustainability criteria for the use of biomass for energy, which should for the most part be applied to biobased plastics as well (European Commission, n.d.-a, 2022b), but the sustainable biomass potential is debated (Agora Energiewende & Wuppertal Institut,

2019). Partly depending on the source material, processing of biomass into chemical products could be for example fermentation into ethanol, pyrolysis or gasification. There are also options to process the biomass in ways that retains more of the original molecular structure of the biomass, which could potentially be less energy intensive.

3.1.3 CCU

The third option for sourcing carbon is to capture it in the form of CO₂, either from point sources such as industrial processes, energy production, waste incineration and biogas/bioethanol plants or from ambient air via direct air capture (DAC). Capture and use of CO₂ from point sources can potentially lead to decreased emissions especially in cases where there are no options for avoiding or permanently geologically storing the CO₂. For example, the process-related CO₂ emissions from cement production are considered unavoidable without carbon capture. However, the overall emission reduction potential of the CCU strategy depends on various factors. These include the source of energy used for capture as well as how long the captured carbon is bound in the product or carbon loop, as it is released once again if the product is incinerated. A variety of capture technologies and methods are being developed, which may be applicable to different concentrations of CO₂. Typically, capture is more energy efficient for higher concentrations of CO₂ and larger point sources. CO₂ has a very low energy content, and to turn the captured carbon into hydrocarbons, energy in the form of hydrogen must be added. The CO₂ together with the hydrogen can then be turned into intermediate products such as methanol, ethanol or syngas, which can then be further processed into a variety of products.

3.1.4 Sustainable hydrogen

For the system to be fully carbon neutral, the hydrogen used in the chemical industry must also be produced accordingly. Hydrogen is needed for the aforementioned CCU strategy, but also in lesser amounts for production via other technologies, for example gasification of waste and biomass. Furthermore, hydrogen makes up an important part of the feedstock in certain chemical products such as ammonia. The main option for renewable (“green”) hydrogen is water electrolysis using renewable electricity, but renewable hydrogen could also be produced from biogas or biomass. Furthermore, hydrogen produced using nuclear electricity (“pink” hydrogen) or hydrogen from fossil-based production equipped with carbon capture (“blue” hydrogen) are also considered low-carbon production options.

3.1.5 New production processes

As described, the different raw feedstocks are often processed into the same base products, i.e., syngas, methanol, or oil-like liquids, which can then be further processed into final chemical products. Syngas can be turned into methanol or processed via Fischer-Tropsch into liquid hydrocarbons, methanol can be converted using methanol-to-olefins (MtO) or methanol-to-aromatics (MtA) routes, and the oil-like liquids can be treated as its fossil equivalents. The base products could also be imported and processed in a different location from where the processing of the raw material took place. This may be relevant for example if the access to feedstock or

renewable electricity is limited in the region where the final chemical products are produced.

3.2 Energy Related Emissions Mitigation, Efficiency Measures and CCS

3.2.1 Energy related emissions

The provision of heat and power must be defossilized for the chemical industry to reach net-zero emissions. Today, gas, electricity, heat and oil and petroleum products make up 94% of the final energy consumption in the EU chemical and pharmaceutical industry, where 36% is gas and 28% is electricity (Cefic, 2022). Apart from the renewable share of the electricity and heat, only 0.6% of the energy comes from renewables and biofuels. A major energy carrier in the chemical industry is steam, which is used for example in cracking, distillation, evaporation, hydrogen generation and as a carrier of heat (Directorate-General for Energy, 2016). One way to defossilize the energy use would therefore be to produce the steam from renewable energy sources, by having combined heat and power (CHP) plants and boilers run on low-carbon fuels such as biogas or sustainable hydrogen rather than natural gas or other fossil fuels. Some processes at various temperature levels could be electrified (power-to-heat), thus eliminating the need for fuels. Other processes require lower temperature heat, and then, geothermal or solar heat are possible options, as well as using waste heat from high temperature processes.

A parallel defossilization of the power sector contributes indirectly to reduced emissions from the chemical industry. Today, electricity is used in the production process of various chemicals, with chlorine being the main one. It is also used for example to power fans, compressors and pumps. It would be possible to electrify other processes as well, such as the aforementioned steam production using electric boilers, or other power-to-heat options such as heat pumps, mechanical vapor recompression and electrified furnaces. Furthermore, defossilized electricity is an important prerequisite for other feedstock-related strategies, as it is needed for the aforementioned production of renewable hydrogen via electrolysis.

3.2.2 Efficiency

Improved efficiency in various forms limits the need for energy and/or resources to produce a desired product or outcome. While energy efficiency has long been a priority for industry strategies and policy, measures aimed at material efficiency may also hold potential for emission reduction. Efficiency improvements can be made on all scales, and incrementally as well as fundamentally. Some examples include process optimizations, implementation of best available technologies, switches to new catalysts, improved heat integration, retrofits, but also more on an energy system level through for example industrial symbiosis, or circular economy concepts like designing or using products in a way that decreases the need for new material.

3.2.3 CCS

Remaining CO₂ emissions from the chemical industry and its value chains could potentially (mostly) be captured and stored using CCS technology. As was described for CCU, larger and more concentrated sources allow for a more efficient and

economic process. Storage requires particular infrastructure in terms of storage sites (such as depleted oil and gas fields or saline formations) and transport to storage sites. Of course, the CO₂ captured and stored may be of fossil origin as well as biogenic (BECCS) or atmospheric (DACCS), where the latter cases have the possibility to be net-negative in terms of emissions. It should be noted that none of the currently known CCS technologies can achieve complete CO₂ capture, resulting in residual emissions that should be taken into account.

4 Analysis of roadmaps

4.1 Overall Emissions, Energy and Demand Levels

The scenarios selected for this assessment all show routes towards net-zero emissions, although in their different respective regional, product and life-cycle scopes. This, as well as the changes in primary or final energy use and demand or production levels is presented in Table 4-1, each in relation to the target year compared to the reference year of the studies. The data presented in Table 4-1 shows the most specific data given in the respective roadmaps. As the level of detail varied in the different roadmaps, some roadmaps have more detailed descriptions in the table than others. Furthermore, different terms were used in the different roadmaps to describe emission scopes and energy use. For the sake of consistency, in the column "Scope", assumptions have in some cases been made regarding which emission scopes are included in terms of 1, 2, and 3, and whether the described energy use was primary or final.

Table 4-1: Overview of key information in the roadmaps and scenarios.

Codename	Scope	Scenario codename	CO ₂ /GHG reduction (%)	Primary or Final energy use (%)	Demand/production (%)	Ref year & Target year
Wege	Region: Germany Products: Chemical industry Emission scope: GHG Energy: Final Energy incl. Feedstock	GreenEe1 GreenEe2 GreenLate GreenMe GreenLife GreenSupreme	-98% -98% -99% -98% -98% -98%	-11% -11% +5% -11% -11% -11%	+/- 0% +/- 0% +/- 0% +/- 0% +/- 0% +/- 0%	2017 2050
RoadChem	Region: Germany Products: Ammonia, Benzene, Butadien, Chlorine, Ethylene, Methanol, Propylene, Toluol, Urea, Xylol Emission scope: GHG Scope 1, 2, 3 Energy: Primary Energy incl. Feedstock	GHG neutrality pathway	-98%	+87%	Basic chemicals +/-0% Special chemicals +81%	2020 2050
KlimaPfade	Region: Germany Products: Basic chemicals Emission scope: GHG Energy: Final Energy excl. Feedstock	Proposed path	-100%	-20%	HCV/Ethylene -38% Ammonia +3%	2019 2045
KlimaDe	Region: Germany Products: Basic chemicals (Demand for Ammonia & HVC) Emission scope: GHG Energy: Final Energy incl. Feedstock	KN2045	-175%	+1%	HVC/Ethylene -42% Ammonia -45% Polymers +3%	2016 2045
DenaLeit	Region: Germany Products: Ammonia, Aromatics, Chlorine, Methanol, Olefins Emission scope: GHG Energy: Final Energy excl. Feedstock	KN100	-114%	+6%	Chlorine +23% Methanol +0% Aromatics & Olefins -5% Ammonia -28%	2018 2045
DeepDecarb	Region: Port of Rotterdam Products: Chemical industry Emission scope: CO ₂ Energy: Final Energy excl. Feedstock	BIO CYC	-100%	-11% +31%	-	2015 2050

ChemforCli	Region: Netherlands Products: Petrochemicals Emission scope: GHG Scope 1, 2 part of 3 (end-of-life treatment) Energy: -	Circular & biobased Electrification 2030 compliance Direct action & high-value applications	-96% -95% -97% -96%	-	+56% +56% +56% +56%	2005 2050
Manuel et al.	Region: Netherlands Products: HVC Emission scope: GHG Scope 1, 2 Energy: Primary Energy incl. Feedstock	OPN BIO CCS ELE HYD	-100% -100% -100% -100% -100%	- - - - -	-54% -54% -54% -54% -54%	2020
TransitVlaams	Region: Flanders in Belgium Products: Ammonia, Chlorine, CO, Ethanol, HVC, H ₂ , Methanol Emission scope: GHG Energy: Final energy excl. Feedstock	MIX VAR1 VAR2	-88% -92% -93%	+2% -10% -5%	+12% +12% +12%	2015
ScenBel	Region: Belgium Products: Ammonia, Chlorine, Olefins, Other Emission scope: GHG Energy: -	CORE-95	-88%	-	-58%	2010
LowCarb	Region: Europe Products: Chlorine, Ethylene, Propylene, BTX, Bioethanol, Ammonia, Urea, MeOH Emission scope: GHG Scope 1, 2 Energy: Primary energy incl. Feedstock	Maximum	-247%	+162%	+225%	2015
IndInno	Region: EU Products: Ammonia, Ethylene (& other Olefins), Methanol Emission scope: GHG Energy: Final energy incl. feedstock	Mix95	-90%	+0,26%	+102%	2015
IndTrans	Region: Europe Products: Plastics Emission scope: CO ₂ Energy: Primary energy incl. Feedstock	Plastics NP Plastics CE Plastics CC Ammonia NP Ammonia CE Ammonia CC	-100% -100% -100% -100% -100% -95%	+0,12% -18% +0,61%	0% -14% 0% -12% -30% -12%	2015
iC2050	Region: EU27 Products: Ammonia, Benzene, Chlorine, Ethylene, Ethylene Oxide, Hydrogen, MEG, Methanol, PE, PET, PP, Propylene, PS, PTA, PVC, Styrene, Toluene, Xylene Emission scope: GHG Scope 1, 2, part of 3 (upstream) Energy: Primary Energy excl. Feedstock	High electrification Fostering circularity Sustainable biomass CO ₂ capture	-100% -100% -100% -100%	+36% +74% +78% +46%	+33% +33% +33% +33%	2019
Meys et al.	Region: Global Products: Plastics Emission scope: GHG Scope 1, 2, 3 Energy: Final energy incl. feedstock	Circular carbon pathway	-101%	-	+255%	2015
Saygin & Gielen	Region: Global Products: Chemical industry Emission scope: Scope 1, part of 3 (downstream) Energy: Final energy incl. Feedstock	1.5 °C case	-100%	+173%	+146%	2017

PlanPos	Region: Global Products: Ammonia, Ammonium Nitrate, Butadiene, Benzene, Ethylene, Methanol, Propylene, Toluene, Urea, Xylene Emission scope: GHG Scope 1, 2, most relevant 3 Energy: Primary energy incl. Feedstock	LC-NFAX	-107%	+30%	+143%	2020
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All roadmaps display close to net-zero emissions or even negative emissions for the target year. However, it is very important to note that the different roadmaps then refer to different emission scopes and use different accounting rules, and thus cannot be compared without taking this into account. The scope can be limited to certain parts of the life cycle (e.g., cradle-to-gate, only emissions from the given geographical region or different ways of accounting for biogenic and captured carbon), certain products (e.g., only plastics), or only including CO₂ emissions (i.e., not all GHG emissions). Indeed, no roadmap includes all greenhouse gas emissions from the full life cycle of all chemical industry products. The emissions from end-of-life treatment are especially significant from life cycle perspective in the current system, meaning that the inclusion or exclusion of these emissions can matter a great deal depending on how the used products are assumed to be treated. End-of-life emissions are included in the scope of about half of the roadmaps, although in some cases allocated to other sectors in an overall net-zero system. Different accounting approaches affects for example if and which carbon flows are counted as negative, especially when it comes to captured and biogenic carbon. For these reasons, while the overall emission reductions in these scenarios all indicate significant efforts on some level, the exact emission reductions cannot be fairly compared.

Figure 4-1 shows the development of greenhouse gas emissions in the various scenarios up to the year 2050. As illustrated here, the scenarios considered can be roughly classified into two categories in terms of their timing of emission reductions: About half envision a relatively linear decline (blue range of values), suggesting continuous mitigation efforts and an even scaling of decarbonization options. The other half of the scenarios (yellow range of values) on the other hand, show a more concave trajectory, with emissions declining more slowly at first, but then dropping more sharply from 2035 or 2040 onward. This suggests the use of breakthrough innovations, which will not be available on a large scale until later, but which are then assumed to rapidly reduce emissions.

Regarding the development of energy use, it is surprisingly difficult to draw conclusions from the comparison of the scenarios. The results can be drastically different in the different scenarios, where some show significant increases while others show decreases. The variations are partly due to different definitions of energy consumption, for example which processes are taken into account, whether it is primary or final energy demand, whether feedstock is included or not, and how energy related to hydrogen or synfuel is accounted for.

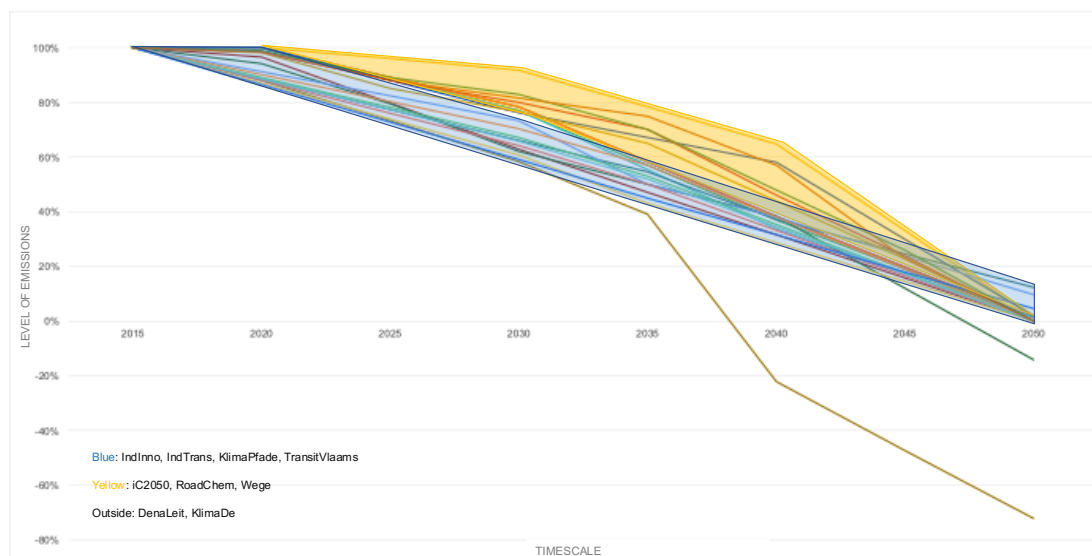


Figure 4-1: Timeline of greenhouse gas or CO₂ emission reductions in the considered scenarios.

Note: In this figure, only scenarios that provide at least one intermediate step in addition to a start and end point for the emission reduction timeline were taken into account. For some scenarios, additional intermediate steps were interpolated. For the *Wege* scenarios, a current emission level of 37 Mt CO₂eq was assumed in line with the other publications since no starting value was specified. In the *KlimaDe*, *DenaLeit* and *iC2050* scenarios, the reported carbon sinks which related to the chemical industry were taken into account, compensating for the industry's remaining emissions.

Looking at only final energy use, i.e., not including the energy for feedstock and the conversion losses in the provision of final energy sources, almost all scenarios predict a decrease in the range of 20% (in *KlimaPfade*) to 65% (in *DeepDecarb CYC* scenario, excluding electricity for hydrogen production; however, 31% increase if hydrogen production included). When the energy for feedstock is included, the image is more mixed. Then, when hydrogen and other e-fuels are accounted for in terms of energy content, most scenarios predict a decrease, while the rest predict an increase that is in the vast range of 0.2% (*IndInno*) to 173% (*Saygin & Gielen*). The large increases are there assumed for global scenarios, while the modest are for European/German scenarios. When the hydrogen and other e-fuels are accounted for in terms of the electricity needed to produce it, most scenarios predict an increase for the energy demand in the wide range of 1% (*KlimaDe*) to 173% (*Saygin & Gielen*). The decrease predicted by the other four scenarios is in the scale of 10% to 30%, but it should then be noted that of those, three are from the same scenario analysis *IndTrans*. From the discussion in the roadmaps, a number of factors are pointed out which have a large effect on the resulting energy need. On the one hand, energy efficiency measures and direct electrification allowing for more energy efficient processes in some cases help reduce the overall energy demand, while on the other hand, the production of green hydrogen and other e-fuels require large amounts of electricity.

As for production volumes or value growth, most scenarios expect increased production, but this is heavily dependent on the geographical scope. On a global level, the corresponding scenarios expect demand to at least double by the year 2050 (compared to the respective reference year), however on a European and national level the production assumptions are mixed. In other words, the global growth in

demand is assumed to mostly be met by production outside Europe, but the question remains whether the European industries will be able to grow as well and whether the current production can be retained. On a product level, it can be stated that the production of ammonia is more often assumed to decrease, at least regionally in Germany or Europe. The same may be true for HVC and ethylene as this production is also assumed to decrease in several scenarios, although this is more difficult to assess since it is often grouped together with the total industry. Four roadmaps present the demand specifically for plastics, where two of these are on a world basis and thereby show a dramatic increase, whereas the other two are for Europe and Germany and show overall stable production. Assumptions for production volumes are usually not varied within a given roadmap, i.e., the same assumption is made for all scenarios. The exception is *IndTrans*, where the circular economy scenario contains a decrease in production (including recycling) and is not stable as in the other two scenarios.

4.2 Comparison of Strategies

4.2.1 Contributions to emission reductions

Overall, the identified strategies in the roadmaps go along with the themes of feedstock switches, electricity, renewable heat and steam, end-of-pipe CCS and efficiency improvements of different kinds. Table 4-2 presents data for the roadmaps that show quantitatively with which strategies the emission reductions are achieved (for those roadmaps that presented such data).

There is no clear preference among the strategies, and the emission reduction is reached in the scenarios via a mix of feedstock- and energy switches as well as CCS and efficiency improvements. The strategy with the heaviest contributors to emission reduction vary among the scenarios, although recycling and renewable energy (non-electricity) stay at 11% or below, in the roadmaps where such indications are given. However, almost half of the scenarios do not provide specific data at this point; instead, the authors rely on qualitative statements about abatement potentials. *IndTrans*, for example, describes large potential for emission reduction through “Materials efficiency and circular business models” and especially “Materials recirculation and substitution”, arguing that such strategies are underexplored.

The use of biomass is a large contributor in several scenarios from different roadmaps, where often around 30% of the emissions are reduced through substitution to biomass. In two scenarios from different roadmaps, the CCU strategy stands out as the most important emission reduction strategy, but at the same time several other scenarios completely opt out from using CCU, or only reach marginal emission reductions through this strategy.

Table 4-2: Greenhouse gas emission reduction strategies by share.

Note: Numbers are presented as percentage of emissions during reference year, and the category “Growth effect” represents the need for more emission reduction due to the expected growth of the industry as described in Section 2.3.1. Emission reductions are given a cyan colour and increased emission are given a red colour. A darker colour corresponds to a larger absolute value. Yellow is used if the strategy is mentioned but not quantified (“nq”).

Notes and specifications of “Other” as named in the roadmaps: ¹Biomass used for feedstock and not for energy, if these were possible to separate ²Production of chemicals through CCU and H₂ routes, excluding ammonia where possible as this is presented in other categories ³Energetic use of renewable energy sources (e.g. biomass, solar thermal and geothermal), where possible excluding renewable electricity, which is represented in other categories ⁴Included in Renewable energy ⁵Reduction of N₂O emissions ⁶Included in Other ⁷“Non-IND levers” (e.g. behavioural changes), “material switch”, “tech development”, “energy carrier switch” ⁸Included in electrification. ⁹H₂ for ammonia/urea” ¹⁰Includes H₂ via electrolysis ¹¹All biogenic carbon removal, i.e., both for feedstock and energy ¹²Included in Biomass ¹³Other “direct emissions”, “upstream” and “imported building blocks” ¹⁴H₂ feedstocks including ammonia.

Roadmap	Scenario	Emission reduction	Recycling	Biomass ¹	CCU/H ₂ ²	Electrification	Electricity emission factor	Renewable energy (non-electricity) ³	CCS	Efficiency improvements	Other	Growth effect	Ref year
ChemForCli	Circular & biobased	96%	8%	59%	1%	0%	12%	11%	0%	3%	9% ⁵	-7%	2005
	Electrification	96%	7%	3%	58%	nq ⁴	11%	9%	0%	5%	9% ⁵	-7%	2005
	2030 compliance	96%	8%	37%	1%	nq ⁴	11%	11%	18%	7%	9% ⁵	-7%	2005
	Direct action	95%	7%	28%	11%	nq ⁴	11%	5%	23%	7%	9% ⁵	-7%	2005
ScenBel	CORE-95	88%	nq	nq ⁶	nq ⁶	nq ⁶	nq	nq ⁶	17%	32%	36% ⁷	-1%	2015
LowCarb	Maximum	206%	0%	25%	145%	25%	nq ⁸	nq	0%	2%	49% ⁹	-41%	2015
IndTrans	New processes (Pla)	100%	nq	nq	0%	nq	nq	nq	0%	nq	-	-11%	2015
	Circular economy (Pla)	100%	nq	nq	0%	nq	nq	nq	0%	nq	-	-11%	2015
	Carbon capture (Pla)	100%	nq	nq	0%	nq	nq	nq	34%	nq	-	-11%	2015
	New processes (Am)	100%	2%	0%	-	61% ¹⁰	nq	nq	0%	9%	-	27%	2015
	Circular economy (Am)	100%	5%	0%	-	50% ¹⁰	nq	nq	0%	18%	-	27%	2015
	Carbon capture (Am)	95%	2%	0%	-	18% ¹⁰	nq	nq	39%	9%	-	27%	2015
iC2050	High electrification	100%	nq	31% ¹¹	2%	nq	16%	nq ¹²	6%	nq	44% ¹³	-	2019
	Fostering circularity	100%	nq	19% ¹¹	3%	nq	13%	nq ¹²	17%	nq	47% ¹³	-	2019
	Sustainable biomass	100%	nq	27% ¹¹	2%	nq	13%	nq ¹²	17%	nq	41% ¹³	-	2019
	CO ₂ capture	100%	nq	31% ¹¹	0%	0%	12%	nq ¹²	45%	nq	12% ¹³	-	2019
Saygin & Gielen	1.5 °C case	100%	11%	6%	25% ¹⁴	nq	33%	7%	68%	70%	-	-115%	2017

For strategies targeting the emissions from energy, there is a combined contribution of 12 % up to 40% emission reduction via electrification of processes to avoid the use of fossil fuels, the parallel assumed development of the electricity system towards renewable or fossil-free electricity production, and substitution to energy sources like biomass or solar heat. CCS stands out as a technology potentially contributing a large share of the emission reduction, in several cases used to capture more than 30% and

in one global scenario even 68% of the current emission volume. The strategy is sometimes avoided completely in scenarios that have a different focus, and in the *LowCarb* scenario where captured carbon is prioritized for CCU. As for efficiency improvements, the emission reductions are usually modest, rarely more than 10%, and usually refer to energy efficiency (however in *ScenBel* it instead refers to material efficiency). The potential could however be much higher globally, as indicated by *Saygin & Gielen*.

Several roadmaps also showed emission reductions in categories that did not fit to the other strategies. *ScenBel* reduces 26% through “Non-IND levers” (e.g. behavioral changes), *LowCarb* indicates that 49% of the emission reduction is due to H₂ for ammonia/urea, and for *iC2050* large parts of the total emission reduction are due to reduction of other direct emissions as well as emissions in other parts of the value chain. Lastly, the expected growth of the chemical industry would in a “business-as-usual”-case contribute to an increase in emissions in all scenarios except the ones focusing solely on ammonia (“Growth Effect” in Table 4-2). This effect also varies between the scenarios, even when only considering scenarios with the same geographical scope.

Comparing the roadmaps for different geographical contexts (i.e., Germany, the Netherlands, Belgium, Europe and world), going beyond the data in Table 4-2, a few observations can be made. It should however be noted that the sample for each region is rather limited, especially for Belgium and the Netherlands. Starting with Germany, the roadmaps more often tend to avoid CCS for the chemical sector (although not necessarily for other hard-to-abate sectors like cement). While *Wege*, *RoadChem* and *KlimaPfade* all exclude CCS for the chemical industry, only *Wege* clearly motivates the exclusion, stating the technology’s association with political and environmental risks.

As for the roadmaps for the Netherlands, it could be said that efficiency improvements are less discussed as part of emission reduction – in two of the three roadmaps it is not mentioned for these scenarios, while its contribution to emission reduction in the third roadmap (*ChemForCli*) are at most 7%. The roadmaps for the Netherlands contain scenarios that each emphasize a particular strategy and in some cases with combined scenarios using a mix of the previously outlined strategies.

The Belgian examples found were not always aligned with a net-zero ambition for the chemical industry, for which the net reduction was around 90% rather than 100%. The results were also less detailed and based on direct assumptions of the use extent of various technologies, rather than this being modelled results based on other external assumptions.

For the international roadmaps, it was more common to divide the emission reduction effort on strategies as in Table 4-2. It can be seen that the emphasis on emission reduction technologies were all different, where the most heavily contributing strategy varies from CCU and hydrogen, to biomass, to CCS and efficiency improvements. The world scenario from *Saygin & Gielen* also clearly shows the potentially very strong effect from expected increases in global production volumes.

4.2.2 Raw materials used for feedstock

To supply the feedstock in a future net-zero chemical industry, the sourcing alternatives represented in the roadmaps are: fossil, recycled, biomass or captured carbon as well as additional hydrogen for ammonia and energy content in hydrocarbons. The various extents to which these sources are utilized in the different scenarios can be seen in Table 4-3. In some cases, the feedstock origin is not specified and the feedstock is instead classified in terms of intermediate products, i.e., methanol or synthetic naphtha, etc. These may also be imported, with the sourcing can then be left unstated in the respective roadmaps.

Table 4-3: Feedstock used in the target year, as shares of total feedstock base.

Note: The products 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. A deeper colour corresponds to a larger share. Yellow is used if the feedstock source is mentioned but not quantified ("nq"). The shares presented only reflects the feedstock volumes or shares that were specifically quantified in the roadmap. Thereby the recycled shares were sometimes not included, even though recycling may still be part of the described net-zero scenario.

Roadmap	Scenario	Fossil	Recycling		Biomass	CO ₂ /H ₂	Change in fossil feedstock use
			mech	chem			
Wege	(All scenarios)	0%	nq		22%	78%	-100%
RoadChem	GHG neutrality pathway	6%	11%		28%	55%	-92%
KlimaPfade	Proposed path	0%	18%	12%	0%	70%	-100%
DenaLeit	KN 100	19%	nq		9%	72%	-53%
Manuel et al.	OPN, CCS, ELE, HYD (HVC)	0%	0%		23%	77%	-100%
	BIO (HVC)	0%	21%		78%	0%	-100%
TransitVlaams	MIX (HVC)	59%	22%		8%	11%	-23%
	VAR1 (HVC)	78%	22%		0%	0%	1%
	VAR2 (HVC)	63%	22%		4%	10%	-18%
LowCarb	Maximum	4%	0%		4%	92%	-93%
IndInno	Mix95	0%	nq		0%	100%	-100%
IndTrans	New processes (Pla)	0%	15%	47%	38%	0%	-100%
	Circular economy (Pla)	0%	25%	38%	37%	0%	-100%
	Carbon capture (Pla)	38%	15%	14%	33%	0%	-60%
iC2050	High electrification	60%	8%		27%	5%	17%
	Fostering circularity	54%	19%		17%	10%	-19%
	Sustainable biomass	53%	7%		35%	5%	7%
	CO ₂ capture	88%	11%		1%	0%	28%
Meys et al.	Circular carbon pathway	1%	19%	25%	38%	17%	nq
Saygin & Gielen	1.5 °C case	36%	nq		25%	39%	nq
PlanPos	LC-NFAX (non-ammonia)	13%	22%	9%	31%	25%	nq

The different feedstocks are used to various extents in the scenarios, and while a mean estimate would put the different feedstocks as more or less equal in share, the spread suggests large uncertainties. The spread is particularly wide for the continued use of fossil feedstock and captured CO₂, while recycled feedstock and biomass is arguably more consistently estimated.

From recycled material, the contribution is commonly in the range of 20 to 35% of the total feedstock, although the aforementioned *IndTrans* suggests a significantly larger share of 62%, while *iC2050* and *RoadChem* rather assume the share to be around 10%. Furthermore, recycled feedstock is not always taken into account when presenting which feedstocks are used as it is not part of the chemical industry currently, although recycled feedstocks are nevertheless part of a future envisioned net-zero system. Feedstock is recycled in the roadmaps mechanically and chemically via pyrolysis or gasification. Plastic waste recycling through solvolysis or dissolution is also sometimes mentioned for certain plastic types. Apart from recycling technologies, some roadmaps also bring up material efficiency improvements in general, for example reducing demand, car-sharing and other circular business models, designing for longer life, less material or recyclability, improved separation, etc.

Biomass share of feedstock ranges relatively evenly from a few percent of feedstock up to almost 40%, with the *BIO* scenario from *Manuel et al.* as an outlier at 76%. The most commonly mentioned technology for biomass use is gasification, but several also mention ethanol-based processes or biomethane. A variation of less general production processes are also occasionally considered, for example, *TransitVlaams* mentions bio-refineries and processes focused on lignin. The feedstocks are in some cases specified towards e.g., organic waste and residues from agriculture or forestry, but others also include non-residue sources, or do not specify the source.

For captured carbon and hydrogen, the shares range from 0% to almost 100%, and no typical value can be given based on the investigated roadmaps. German roadmaps tend to rely more heavily on this strategy, as do the German-made roadmaps *LowCarb* and *IndInno*. The captured carbon can come from industrial point sources where the carbon may or may not be of fossil origin, or it can be captured from air. When specified, it is often assumed that the carbon is captured using direct air capture (DAC) or from industries with unavoidable or non-fossil emissions, e.g., cement and lime, waste incinerators or biomass sources. Some also assume CO₂ captured from industries and processes where the source is fossil and it is also not uncommon to leave the CO₂ source unspecified.

Several roadmaps also rely on imported intermediate products such as methanol and green naphtha, so that the carbon capture, production of hydrogen and first processing steps takes place in another country. In those cases, the production route or source of carbon is often not specified, although DAC may be presumed. It is not obvious or yet established how these potentially avoided emissions should be accounted for, for example which industry or country receives the carbon credit when it is not the same as the one where the carbon is used.

Fossil feedstock also shows widely ranging shares of use in the scenarios. Fossil feedstocks are still used in most scenarios, but when used, it ranges from a few

percent in *Meys et al.* and *LowCarb* to 88% in *iC2050*. However, several roadmaps also explicitly avoid fossil feedstocks and aim for complete defossilization as well as carbon neutrality, especially roadmaps made in a German context. It can be noted that reaching net-zero emissions from a life-cycle perspective may not be viable if too large shares of fossil feedstock remain. Indeed, neither of the two roadmaps that portray more than 50% shares of fossil feedstock, i.e., *TransitVlaams* and *iC2050*, include end-of-life emissions in their respective scopes. However, it may still be possible for fossil feedstock to make up a significant share even considering end-of-life emissions, as is the case in *IndTrans* and *Saygin & Gielen*, where fossil feedstock represents 36% and 38% respectively. In these cases, the use of fossil feedstock is compensated by a significant use of CCS. Additionally, even though fossils share of feedstock decreases significantly, the total fossil feedstock use may remain or even increase in some scenarios due to increased production. The total fossil feedstock use increases in three of the four scenarios in *iC2050*, between 7% and 28% and remains approximately constant in the VAR1 scenario of *TransitVlaams*.

Given the urgency to reduce emissions in order to reach the set targets, an important question is when the envisioned technologies could come into play and begin making up significant parts of the production. Indeed, the roadmaps commonly give indications of when technologies may come into use, and give varying estimations. Particularly important groups of technologies include biobased routes, CCUS applications, chemical recycling and new production processes (including electric steam cracking, MtO/MtA and ammonia from renewable hydrogen).

The use of biobased routes for the production of chemical feedstocks tends to be assumed only from around 2030 onwards in the considered scenarios, although two different roadmaps also see possible applications for gasification and bio-hydrocarbons before then.

Category	Technology	2020	2025	2030	2035	2040	2045	2050
Biobased routes	Gasification of biomass		◆					
	Biobased carbohydrates		◆		◆			
	Bio-Naphtha			◆				
	Bio-BTX				◆			
	Bio-Methanol				◆			
	Bio-HVC			◆	◆◆			

Figure 4-2: Availability of biobased routes in the scenarios considered.

Note: A black symbol on a green background marks the first use in a roadmap in each case.

CCUS technologies, and in particular capture and geological storage, are assumed to be in use within a few years in the scenarios considered, with four publications assuming deployment from 2025 and a further four assuming deployment from 2030, with the earlier information often applying to point sources with high CO₂ concentrations and the later to sources with lower concentrations. The time estimates regarding power-to-X based feedstocks, on the other hand, diverge widely. Synthetic methanol is seen significantly earlier than synthetic naphtha by various roadmaps.

Category	Technology	2020	2025	2030	2035	2040	2045	2050
CCUS	CCS		◆◆◆◆	◆◆◆◆	◆			
	PtX Methanol		◆	◆	◆			
	PtX Naphtha				◆	◆		

Figure 4-3: Availability of CCUS technologies in the scenarios considered.

Note: A black symbol on a green background marks the first use in a roadmap in each case.

The time estimates for entry into chemical recycling both in general and for some specific technologies are predominantly in the 2030s, with only two outliers in either direction.

Category	Technology	2020	2025	2030	2035	2040	2045	2050
Chem. recycling	Chemical recycling (not closer specified)		◆	◆◆◆	◆			
	Catalytic cracking of plastic waste			◆	◆			
	Solvolysis			◆	◆		◆	
	Pyrolysis			◆				

Figure 4-4: Availability of chemical recycling in the scenarios considered.

Note: A black symbol on a green background marks the first use in a roadmap in each case.

New production processes for olefins and aromatics, such as electrically powered steam crackers or methanol-based routes, also play an important role in most of the scenarios considered. Electrification of steam crackers is seen in 2030 at the earliest, but tends to be somewhat later. The production of olefins and aromatics based on synthetic methanol (MtO, and MtA, respectively) is estimated very differently with respect to timing, although the MtO route is generally mentioned more frequently and tends to be seen towards the 2030s.

Category	Technology	2020	2025	2030	2035	2040	2045	2050
New processes	Electric steam cracking			◆◆	◆◆◆◆			
	Methanol-to-Olefins	◆		◆◆	◆◆◆	◆		
	Methanol-to-Aromatics				◆			
	Methanol-to-X		◆					
	PtX Ammonia		◆			◆◆		

Figure 4-5: Availability of new production processes in the scenarios considered.

Note: A black symbol on a green background marks the first use in a roadmap in each case.

4.2.3 Energy carriers

Table 4-4 shows the energy sources used for heat and power purposes in the target year for different scenarios. These are at least in part shifted away from fossil sources to mainly electricity in the literature considered, which makes up 60% or more of the energy demand in most scenarios. The electricity is then for example used in electric boilers, electric steam crackers or heat pumps. As a supplement, and depending on temperature needs, other energy sources are used as well. This is usually a mix including for example biomass, biogas, hydrogen or other, which each typically contributes in the scale of 10-20% of the energy demand. "Other" here includes mainly district heating, ambient heat or synthetic methane. For energetic uses, however, synfuels are often not used or takes a smaller role around 10%. Much of the final energy demand is in the form of steam which is produced in boilers. Apart from

electric boilers, there are options for these to be fired by biomass, hydrogen or synfuels. *KlimaDe* and *TransitVlaams* also consider that these can be made to be able to operate flexibly, accepting both hydrogen or syngas, as the infrastructure develops.

Table 4-4: Energy sources as shares of total energy use, excluding energy for feedstock.

Note: A deeper colour corresponds to a larger share. Yellow is used if the energy source is mentioned but not quantified ("nq"), and "nm" indicates that the strategy is not mentioned. The energy of hydrogen and synfuel may be quantified either as the fuels energy content ("C") or the energy in form of electricity ("E") needed to produce the fuel, which varies between the roadmaps as indicated by Note. ¹H₂ refers to hydrogen which is produced outside the chemical sector and is counted as energy content, whereas electricity that is assumed for hydrogen production within the chemical sector is counted to electricity.

Roadmap	Scenario	Fossil	Waste material	Biomass	H ₂	Electricity	Other/Non-separable	Note
Wege	GreenEe1	0%	nq	0%	nq	74%	26%	C
	GreenLate	0%	nq	0%	nq	82%	18%	C
KlimaPfade	Proposed path	0%	2%	11%	2%	76%	8%	C
KlimaDe	KN2045	0%	0%	37%	5%	53%	5%	C
DenaLeit	KN100	5%	0%	17%	16%	50%	12%	C
DeepDecarb	Biomass and CCS	21%	7%	7%	nq	64%	nq	E
	Closed carbon cycle	5%	nq	0%	nq	80%	15%	E
TransitVlaams	VAR1	28%	0%	1%	0%	67%	4%	?
	VAR2	43%	0%	12%	0%	37%	7%	?
ScenBel	CORE-95	nq	nq	nq	nq	50%	-	-
IndInno	Mix95	2%	0%	3%	0%	73%	22%	C
iC2050	High electrification	12%	nm	0%	nq	88%	nm	Both ¹
	Fostering circularity	9%	nm	1%	36%	55%	nm	Both ¹
	Sustainable biomass	10%	nm	2%	34%	54%	nm	Both ¹
	CO ₂ capture	19%	nm	41%	9%	31%	nm	Both ¹
Saygin & Gielen	1.5 °C case	24%	nq	28%	19%	20%	9%	C

The energy input to the chemical industry is also in the form of feedstock, and some roadmaps thus instead presents the total energy needs including feedstock, as shown in Table 4-5. This shows a more mixed picture reflecting both the stronger role of electricity as well as the use of a variety of feedstocks as described above. Overall, either electricity, hydrogen or synfuels tend to be the main emphasis for energy, while biomass also plays an important contributing role representing 10 to 30% in most publications and even 87% in one scenario. *IndTrans* again stands out where end-of-life plastics plays a large role.

Table 4-5: Energy sources as shares of total energy use, including energy for feedstock.

Note: A deeper colour corresponds to a larger share. Yellow is used if the energy source is mentioned but not quantified ("nq"), and "nm" indicates that the strategy is not mentioned. The energy of hydrogen and synfuel may be quantified either as the fuels energy content ("C") or the energy in form of electricity ("E") needed to produce the fuel, which varies between the roadmaps as indicated by Note. ¹The energy for hydrogen is included in Electricity.

Roadmap	Scenario	Fossil	Waste material	Biomass	H ₂	Electricity	Other/Non-separable	Note
Wege	GreenEe1	0%	nq	15%	nq	22%	63%	C
	GreenLate	0%	nq	14%	nq	30%	56%	C
RoadChem	GHG neutrality pathway	2%	2%	11%	nq	81%	3%	E
KlimaDe	KN2045	0%	24%	14%	(15%) ¹	61%	1%	E
Manuel et al	OPN (HVC)	4%	0%	12%	0%	3%	81%	C
	BIO (HVC)	4%	0%	87%	0%	3%	6%	C
	CCS (HVC)	4%	0%	12%	0%	3%	81%	C
	ELE (HVC)	0%	0%	13%	0%	25%	62%	C
	HYD (HVC)	0%	0%	13%	24%	3%	60%	C
LowCarb	Maximum	3%	0%	7%	nq	90%	nq	E
IndInno	Mix95	2%	0%	2%	53%	34%	10%	C
IndTrans	Pla. New processes	0%	45%	29%	nq	29%	nm	E
	Pla. Circular economy	0%	46%	29%	nq	26%	nm	E
	Pla. Carbon capture	33%	20%	22%	nq	26%	nm	E
Meys et al	Circular carbon pathway	0%	nq	35%	nq	65%	nm	E
Saygin & Gielen	1.5 °C case	29%	nq	27%	29%	10%	5%	C
PlanPos	LC-NFAX	8%	16%		62%	11%	-	C

What is important to note is the large impact of hydrogen and synfuels on the energy situation in the scenarios. In the roadmaps, these are sometimes presented in terms of energy content of the fuel (noted with "C" in the table), and sometimes in terms of the electricity need to produce them (noted with "E"). When the energy is accounted for as the electricity needed for production, the energy demand may increase significantly, once again highlighting the large dependency on renewable electricity. However, as synfuels and sometimes hydrogen is often assumed to be imported, major parts of the electricity production might be needed abroad. The assumed imports also imply the need for an international market or bilateral agreements to be able to provide these forms of energy for the domestic chemical industries.

Fossils are still an important source of energy in several of the scenarios.

DeepDecarb, *TransitVlaams*, *iC2050*, *IndTrans* and *Saygin & Gielen* all contain scenarios where it constitutes more than 10% of the energy- or energy and feedstock use. At most, it represents a share of 43% of the final energy consumption in *TransitVlaams* VAR2 scenario.

electricity is a major challenge. Furthermore, CO₂ and hydrogen infrastructure needs to be in place, and capture technologies must be further developed and scaled up. Strategies partly unrelated to feedstock also face challenges, such as public acceptance for CCS, the accelerated expansion of renewable energies and technology development for electrification.

Some challenges apply to several of the strategies, and are particularly emphasized in the roadmaps. In particular, the requirement of large amounts of renewable electricity for several routes and processes is a major challenge. The electricity requirements of the chemical industry are expected to increase dramatically, often manifold (by up to almost 12 times in *RoadChem* and 42 times in *LowCarb*), and the electricity cannot be of fossil origin in the future. At the same time, the electricity price is crucial for the competitiveness of the CO₂-neutral processes and should be stable and low enough to compete with that of natural gas applications. This is currently not the case as the natural gas price for the first half of 2022 was about 80 €/MWh for the industry in the EU (Eurostat, 2022a), while electricity price was 160 €/MWh (Eurostat, 2022b). At the same time the fossil share, representing 36% of Europe's electricity production in 2021 (Eurostat, 2023), still needs to be mitigated significantly.

Other major challenges for several of the strategies is the need for related infrastructure. New or reconstructed infrastructures for electricity, hydrogen, CO₂, waste and biomass are needed - to varying degrees depending on the scenario. For the transformation as a whole, *KlimaPfade* writes that the German electricity production must close to double while simultaneously be decarbonized, after having been approximately constant since 1990. Furthermore, the future demand for hydrogen cannot be supplied exclusively from domestic sources according to the roadmaps, and a European hydrogen network is needed as well as a domestic one. The CO₂ infrastructure should preferably be coordinated with the biomass strategy and hydrogen infrastructure. Finally, several of the strategies require further development of technologies, especially with regards to the construction and testing of demonstration plants, gaining of operational experience, and scaling-up to reach market maturity. For the technologies that are yet to be proven at large scale, there is also the uncertainty whether or not they will even be able to work as envisioned in the future.

Challenges mentioned also relate to the framework conditions as a whole. In general, since many of the alternative process routes are currently considerably more expensive than the conventional, there is a lack of a business case and competitiveness. Furthermore, the large investments required to replace or retrofit current industrial processes are partly non-modular and require certainty and assurance of future viability, which is currently lacking. At the same time, if investments are delayed, there is a risk for fossil lock-ins and stranded assets for the investments the next coming years. For example, *IndTrans* and *PlanPos* suggest that these investments in new technologies and infrastructure require coordination, risk-sharing and other forms of public investments and support. Indeed, all challenges are brought to a head due to the urgency and speed needed in order for the defossilization to be successfully completed by 2050.

focusing on circular businesses and valorization of post-consumer materials, or on high value products. Not least, the transformation can create synergies for the energy system, with the chemical industry potentially acting as a flexibility provider. Some roadmaps also point out particular local advantages. Depending on location there may be close access to renewable electricity production, grid connections and gas infrastructure, biofeedstock, waste or other imported resources, trade connections, CO₂ storage as well as relevant actors and skilled professionals. While the limited access to renewable electricity production was noted above as a challenge for some European regions, the higher potentials in other world regions constitutes opportunities for those regions and for a global transition, as *PlanPos* points out. As e.g., methanol or pyrolysis oil provides a more easily transportable carbon source, and the Global South provides good conditions for renewable electricity for methanol and ammonia production, *PlanPos* point to the need for a (global) chemical intermediate infrastructure benefitting the Global South.

Lastly, apart from the aforementioned synergy with the chemical industry providing grid balancing for the energy system via its time flexible production of hydrogen, a few roadmaps also mention other synergies. For example, *IndTrans* brings up benefits that come with material efficiency, such as reduced resource needs, potentially saving costs and investment needs, as well as other benefits from reduced externalities. *Wege*, which additionally targets to limit biomass use, particularly emphasizes synergies with environmental aspects like biodiversity, and *DeepDecarb* mentions improved air quality associated with the transformation. Two roadmaps, *DeepDecarb* and *PlanPos*, also point out the opportunity the chemical industry has to go from a net-emitter to a climate protector, by providing net-negative emissions through the use of DACCS or BECCS.

4.3.3 Policy recommendations

In order to overcome the challenges and make use of the opportunities available, recommendations are given in the roadmaps considered directed at governments and policymakers. These often revolve around themes such as investments and economic support, robust and enabling regulatory framework as well as renewable energy and infrastructure development. The word cloud in Figure 4-8 also shows words touching on innovation, technology development and implementation.

Several roadmaps, especially those coming from industry actors, propose joint ventures for governments and industry. Particularly mentioned are programs for innovation and new technologies with an emphasis on making these reach market deployment. Other tools mentioned include public-private partnerships, ensuring funding and shouldering risks associated with major investments, infrastructure programs, setting up clear visions, and in general a closer dialogue between industry and policymakers. A goal according to the roadmaps is to give certainty for decarbonization long term.

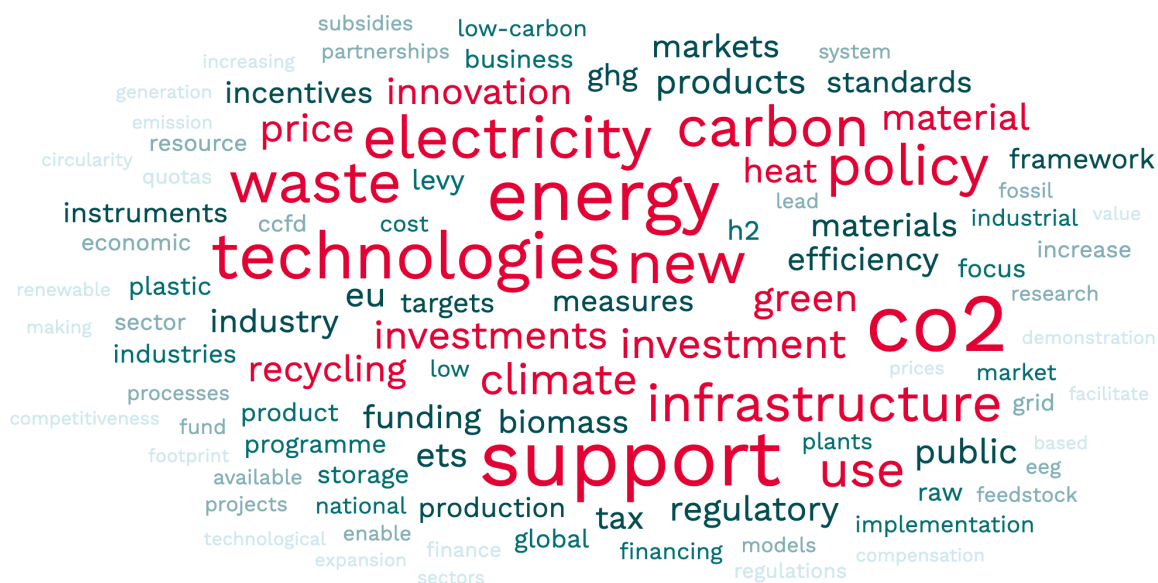


Figure 4-8: Keywords mentioned in the roadmaps related to recommendations to policymakers and governments.

Note: The size of the word reflects how often it is mentioned.

Since the price of electricity is identified as a major challenge, the task of ensuring cheap access to this is given to governments. Reduced taxes and fees are sometimes proposed, for example, exemptions and amendments of the German EEG levy for electrification technologies especially, and a cap on taxes. Furthermore, conducive conditions for green power purchase agreements (PPAs) are encouraged as well as acceleration and simplification of processes for the expansion of renewable energy supply and production. Adjustments to energy policy frameworks is also proposed to encourage the development of demand-side flexibility for electricity, which e.g., *DenaLeit* and *RoadChem* describe for their respective contexts.

Other tools are suggested in the roadmaps to enable more money for the industry to shift the market competition in favor of low-carbon production. Different forms of funding and investments in yet unprofitable technologies are suggested in the roadmaps, as well as more open rules for public economic support for low-carbon technologies, including modifying state aid rules to allow more strongly directed support. Green lead markets, e.g., in the form of material quotas and public procurement, are another tool mentioned in the roadmaps to create demand for low carbon products before they are fully able to compete with conventionally manufactured products. Carbon contracts for difference (CCfD) are also suggested, more commonly mentioned in the German roadmaps.

While low-carbon technologies are given more favorable conditions, other policy recommendations aim at making harmful activities less economic. Some suggest a tightening of EU ETS, and that industries currently outside the EU ETS can be brought into the system. Some roadmaps in particular point out the inclusion of emissions from waste incineration, at least when carbon capture technologies become commercially available for such facilities. Decommissioning of old or

particularly emission- or energy intensive plants are also suggested in several roadmaps. While working towards a global level playing field and international coordination, ways to ensure competitiveness in pioneer regions in its absence are proposed. In particular, the carbon border adjustment mechanisms (CBAM) are encouraged and *KlimaPfade* also recommends that the current free allocation of emission certificates for certain industries should remain to avoid carbon leakage (and furthermore that the free allocation remains after conversion).

There are also other legislative hurdles according to the roadmaps that can stand in the way. One such is the rules around trade of waste across borders, which *IndTrans* suggests could be modified to enable its use as feedstock. At the same time, *DenaLeit* and *PlanPos* point towards bans or reductions of waste exports to countries as to avoid that it ends up where it will not be properly managed. There is an emphasis of the recommendations in the roadmaps on the use of circular economy and the use of waste material for feedstock, with for example increased recycling targets. For this, as well as for other strategies roadmaps point to a need for definitions and framework legislation, e.g., definitions of plastic grades, how to account for carbon stored in products and if, when and how biomass should be used.

5 Discussion and Classification of Variations

The analysis of different available studies carried out in this meta-analysis shows a very varied picture of what transformation could take place in the chemical industry to reach net-zero. It also shows a very large number of uncertainties associated with such a change. Here, we will discuss more in detail how to understand and interpret this, and also draw conclusions on where to go from here, with regards to the development of transition strategies. Before that however, we will discuss the similarities between the roadmaps and draw out what consensus there is, despite the many differences. We will end the chapter by summarizing some recent developments on policy level, relating to the topics and recommendations brought up in the roadmaps.

5.1 Common Themes and Overall Reflections

The similarities that can be identified among the various roadmaps are for the most part general in nature. They concern the overall picture in terms of possible strategies, timeframe and overall challenges. Furthermore, the need for more renewable electricity is clear from most roadmaps and the German roadmaps could be said to share a few more similarities with one another. When many roadmaps point in the same direction for aspects such as these, they can be viewed as relatively robust elements in the transformation of the chemical industry. Knowledge about such elements can help governments and policy makers design and implement appropriate framework conditions more promptly. However, some important aspects are largely missing from these roadmaps, some of which are pointed out here.

5.1.1 Technologies and timelines

There is a large palette of available strategic options for the chemical industry, which most roadmaps identify. These are, as presented above, use of recycled plastics, biomass, and CO₂ based alternatives with regards to feedstock, and in terms of the chemical industry's energy needs, the main option is electrification. In some instances, fossil feedstocks still play a role in these future scenarios, even in the middle of the century, but new feedstocks (some combination of waste, biomass and CO₂) always receive a much greater importance compared to today. Furthermore, CCS and various types of efficiency improvements can play a complementing role. For these key strategies for successful transformation in the chemical industry, some key technologies are often repeated in the roadmaps, mainly gasification of waste and biomass, pyrolysis of plastic waste, direct air capture of CO₂, water electrolysis for hydrogen, electrified boilers and electrified steam crackers. Furthermore, important reoccurring technologies to process the feedstock are MtO/MtA and Fischer-Tropsch processes for methanol and synthetic naphtha respectively. While these strategies and technologies reflect a kind of consensus in terms of available options, there is still a lack of consensus around which of these options are to be preferred and to what extent they may be used. However, the roadmaps strongly indicate that some kind of combination of these options is most likely to be used, and thus these technologies could possibly be seen as “safe bets”. There is a large number of additional technologies that are only occasionally mentioned where their significance is difficult to determine, e.g., chemical recycling via dissolution or

solvolysis. The roadmaps tend to focus on the high-TRL technologies, and although low-TRL technologies are sometimes mentioned, they are usually excluded from the scenarios (e.g., direct electrocatalytic conversion for ammonia or ethylene, photocatalytic process for hydrogen and artificial photosynthesis mentioned in *LowCarb* and *IndInno*).

A very rough timeline for emission reductions and the introduction of various technologies can also be identified from the roadmaps considered. The timelines commonly suggest moderate emission reductions before 2030, mainly through reduced emissions from energy, before the technologies and structures are in place for a shift of feedstock. During this time, in other words, the new technologies to valorize alternative feedstock will have to be further developed and reach market maturity, and the right framework conditions must be put in place to enable their uptake. The roadmaps require that the then remaining 10-20 years until 2050 have a very rapid build out of new technologies and their corresponding infrastructure, markets, and value chains resulting in accelerated emission reductions.

At the same time the roadmaps at large give varying more precise indications on when the various technologies may come into use, which leaves a lot of room for uncertainty. Especially near-term, differences in timing for market introduction of different new technologies could change the shape of the transformation significantly. Therefore the decisions in the coming few years are especially critical. As for mid-term changes in feedstock, the US has seen a shift in the production of ethylene from naphtha to ethane, made viable through the country's extraction of shale gas (Kim & Oh, 2020; Michot Foss et al., 2021). Such an intermediate switch to other fossil feedstock has not been identified in the roadmaps. The roadmaps also rarely reflect on potential future changes in demand on a polymer level, but rather on a chemical sector level or in some cases specifying the demand for e.g., HVCs, or plastics as a whole. The demand at the polymer level may for example change and adapt to allow for higher recyclability of the produced polymers. Also, the production path for aromatics from alternative sources is different and more difficult than that for olefins. Thus, changes in the demand structure for olefins contra aromatics would give different implications for the necessary technology development and expansion of different solutions that can be more or less challenging.

5.1.2 Challenges

The picture is also generally coherent when it comes to identified challenges and necessary framework conditions. It is clear that in the current market environment, the changes needed to reach net-zero emissions are not economically viable. This has various reasons, but a major one is the high price of electricity compared to the fossil energy sources. This once again indicates the need for a rapid expansion of renewable electricity production, a conclusion in common with that of the overall discussion on energy system transition. This also indicates a new role for the chemical industry in the energy system. The electricity demand will increase due to electrification of processes and hydrogen production, while at the same the use of electricity from fossil sources will no longer be a viable option in the longer term. From industrial clusters such as Port of Rotterdam previously having been self-sufficient on electricity through fossil power generation on-site, the chemical

industry will now instead be much more dependent on the entire electricity system and resulting electricity prices there. At the same time, the use of hydrogen and hybrid heat supply systems in the industry can create a more flexible dependency, where the chemical industry may function as a balancing hub in the larger electricity-hydrogen system. In this way, by purchasing more electricity at times of relatively low electricity prices, the chemical industry can also save on such costs.

This also touches on the other major challenge, regarding the need for integration with other sectors and industries, as well as the necessary value chains and infrastructures this requires. As this relates to for example electricity, hydrogen and CO₂ infrastructure which are relevant for other industries as well, there is an opportunity for joint roadmapping and planning of such infrastructure together with those industries (which some roadmaps also point out). Need for other flows such as feedstock and platform chemicals may however be more specific to the chemical industry, and requires strategies and planning as well, possibly with the chemical industry taking an even more leading role. However, the roadmaps also point to the need for government agencies to be engaged in these types of system-wide integration projects. By contrast to the integration with new industries, the sector's current integrations are very rarely highlighted and discussed in the roadmaps, namely the close interaction with refineries (or the shale gas industry in the US) through the utilization of its by-products. Had it changed the shape of the scenarios and conclusions of the roadmaps if these interactions were more clearly considered?

Among the German roadmaps, the stronger reliance on imported methanol and green naphtha suggests that for countries with limited domestic potentials of renewable resources, a global renewable feedstock market will be very important for the chemical industry. There is an opportunity to create partnerships with countries in similar situations, and countries on the other side that may be able to provide these resources.

5.2 Understanding the major variations and uncertainties

This analysis has highlighted that there is an overwhelming spread of not only decarbonization options, but also ambition levels in terms of defossilization and emission reduction, ways to define the challenge in terms of the scope of the considered system, assumptions of future conditions, and strategic preferences. Unlike in the other energy intensive sectors like steel and cement, the path to net-zero still is yet very unclear in the chemical sector, which is characterized by high complexity and process diversity. Thus, the question of emission reduction strategies and future feedstocks to be used in the chemical sector is answered very differently in the different roadmaps and scenarios.

The relevant scenario literature on the chemical industry paints a very heterogeneous picture, for which there are various reasons. However, this poses major challenges for stakeholders and decision-makers when trying to analyze the situation, develop a coherent strategy and determine the next steps. This creates the risk of delayed action, which – ironically – is clearly and uniformly highlighted in roadmaps as something to be avoided at all costs. While the variations are at least in part unavoidable or important parts of the discussion, there is a need for future works to give more clarity. To sort between various kinds of variations, we here try to

categorize the variations into four groups: variations due to fundamental uncertainties, variations due to intentional exploration, variations due to different priorities and narratives, and variations due to different modelling approaches. These different categories are described and discussed below in terms of which variations adhere to which category and what role they play in the discussion. Using these groups, we can begin to create a clearer view of how to understand what the roadmaps as a whole tell us, and move forward towards clearer answers for the transition.

5.2.1 Variations due to fundamental uncertainties

We do not know what the future holds. This fact is reflected in the many variations within and between the roadmaps based on different assumptions. In other words, these are the variations that can be read as the authors implying: *“We don’t know what this specific factor will look like in the future, but here is our guess”* or *“We don’t know what the factor will look like, so we have varied it in what we think is a plausible range”*. As such, this can on the one hand refer to factual hypothesis, for example when new technologies will be available, what their performance and importance will look like (e.g. mainly MtO/MtA, chemical recycling and carbon capture, but also potential currently low-TRL game-changers like direct ethylene synthesis from CO₂ and hydrogen), future product portfolios and costs for different investments. These variations indicate a research gap to fill by mapping the potential for green feedstock technologies and their roles in the European overall system, which is a major ambition of the GreenFeed project. Even though some uncertainties may remain, a plausible range should be identified for important assumptions, which can be used in future assessments.

Some fundamental uncertainties are societal and structural rather than-, or as well as technical, and also have a significant impact on assumptions made in the roadmaps. For this kind of uncertainties, it may not make sense to limit the variation in results, but rather be clear about what surrounding factors may lead to the different results, and under what conditions the scenario is realistic. Examples include development for global markets for green synthetic feedstock, other resource availabilities and potentials (e.g., electricity production, sustainable biomass), infrastructure developments, future demand levels and the development of climate and trade policy in different world regions. These are all somewhere on the spectrum of societal and technical assumptions and are dependent both on political and practical uncertainties. These fundamental uncertainties in practical terms affect for example price assumptions but also what options are even possible to choose from.

5.2.2 Variations due to intentional exploration

Not seldom, the scenarios are for example made in a way with a purpose to explore the breadth of options available, without pointing out any initial preference. The roadmap may try to account for different exogenously given situations that cannot be influenced by the stakeholder groups involved. Thereby, the variation may indicate that there is a need for flexibility in the future to switch between the pathways. The strategies developed should then apply to both scenarios (e.g., an investment in MtO technology might be robust in a more waste based or a more CO₂ based future

chemical industry). In those cases, the individual scenarios are of less relevance in terms of what should be considered a realistic roadmap. In this analysis, we for example see that a very high use of biomass for feedstock is obtained solely in the one of the five scenarios from *Manuel et al.*, named *BIO*, and we have similar “outliers” in the thematic pathways from *ChemForCli*. *ChemForCli* also explicitly states this purpose of such thematic pathways:

“The shaping of each of the transition pathways has been done in a rather extreme way, to give insight into the opportunities and challenges that arise when implementing each of these pathways to its full potential. In doing so, the technical, economic and sustainable boundaries of the solution themes and pathways have been elaborated.” (Stork et al., 2018, p. 29)

In other words, the interest of this kind of scenario analysis are not the individual scenarios, but what remains robust despite the breadth of possibilities. This meta-analysis has however not taken this into account explicitly and treated all portrayed scenarios in the same way. This in part as a simplification since it can be difficult to make a clear distinction between what should be considered more or less likely. The wide variation however suggests that there is currently a need to find a clear and realistic path forward rather than to explore the boundaries. As in *Manuel et al.* and *ChemForCli*, more balanced combination scenarios (in addition to any extreme scenarios) should be provided and be the main focus of analysis, albeit with useful insights from previous explorations.

5.2.3 Variations due to different preferences and narratives

There is also a variation on views on what kind of future we want to achieve. In a roadmapping process it can be differentiated between scenarios that account for different exogenously given situations (as in the cases above) and scenario variations that are due to differing preferences of the stakeholders involved. Different people, actors and stakeholders have different priorities, and these variations are reflected in the roadmaps, sometimes, or more or less explicit, in the shape of different narratives. In other words, these are the variations that can be read as the authors trying to say *“We think x is missing from the discussion, and propose it should be considered in this way”*. Some examples of this from the roadmaps in this analysis could be the avoidance of biomass or CCS in *Wege*, the exceptionally high share of recycled feedstock in *IndTrans*, and the exceptionally large continued use of fossil feedstock in *iC2050*. In some cases, however, it can be difficult to tell to what extent certain assumptions are a result of the argumentation and narrative. For example, production volumes may be based on forecasts without a particular stance, but could also be shaped either by a narrative promoting sufficiency, or a narrative promoting strong industrial production on the other.

These variations thus play the role of contributing to a political and scientific discussion where many views and insights should be voiced. Ideally, then, insights from this discussion can be integrated into later roadmaps and decisions, and a common ground can be formed. That way, a decision can be formed based on which best aligns with the common priorities and best knowledge. Therefore, such variations contribute to an important discussion, as long as they are scientifically sound and bring something new to the debate. As a consensus is formed in the

discussion, these variations presumably decrease. It can however be difficult to distinguish between the scenarios that stand out due to exploration of external conditions, and those where the stakeholders involved present a preference and argument (often implicitly).

5.2.4 Variations due to different modelling approaches

The previous variations reflect differences in the described future reality, but results also vary due to the wide range of methods and framework assumptions used in the different roadmaps. The roadmaps in this analysis for example vary in terms of life cycle scope, how negative- and non-fossil emissions are counted as well as how to account for temporarily stored carbon. These are key assumptions that have a large impact on key indicators such as what is even counted as emission reductions, and when net-zero is considered to be reached. Two scenarios could show similar emission reductions in their respective scopes and models, but might reflect very different realities for these emissions, which would also show if the scopes and modelling approaches were switched. For example, *LowCarb* counts all CO₂ (fossil or biogenic) incorporated into products as negative emissions while on the other hand *Meys et al.* take a life-cycle approach and state that “*Net-negative greenhouse gas emissions over the life-cycle of plastics by CO₂ or biomass utilization can only be achieved by permanent carbon storage (25).*” (Meys et al., 2021, p. 9).

Some roadmaps do not describe the accounting of emissions explicitly, but may refer to the definitions in e.g., the German Klimaschutzplan. Then, for example emissions from end-of-life management may be allocated to the waste sector, and emissions from the external procurement of electricity and heat to the energy sector. A roadmap with a focus on the life cycle of a product from the chemical industry, on the other hand, would for example include end-of-life emissions in its assessment. A question then also arises around how to view recycled feedstock. In several cases, recycling or at least mechanical recycling is not considered part of the sector in scope given current definitions, but it may still an important part of a considered future circular carbon system. In roadmaps with such a system approach, this may be more clearly displayed. Another example of different modelling approaches is whether aspects such as use of different strategies, technologies or feedstocks are externally assumed, or a result of for example a modelled optimization. For some roadmaps (e.g., *Saygin & Gielen*, *ScenBel*) all usage levels are assumed whereas in others (e.g., *iC2050*, *RoadChem*) the choices of technologies are mainly based on economic optimizations of some kind. Also, as we have seen, the energy requirement can be quantified in many different ways, in particular including or excluding feedstock and counting e-fuels in terms of their energy content or the electricity demand for their production. These were some examples, but many various assumptions and modelling choices made are not always described and there are as many approaches as there are roadmaps.

As with the national sector accounting approach or the product life cycle approach, a reason for these differences is that different logics or standards are used. This can in part be traced back to different priorities as the use of a specific model reflects the research interest, which is driven by priorities. Thus, the different accounting methods serve some purpose. A further reason for these methodological differences

is the fact that investigating all aspects of systems like these is time and capacity consuming and may be associated with large uncertainties. For example, *LowCarb* writes that recycling of polymer waste streams was not integrated into the scenarios, and would require a thorough life cycle investigation of the recirculating loops. Instead, it focuses on the de novo processes. *iC2050* as presented here does not include end-of-life emissions and contains other simplifications that are to be included in an updated version (Gonsolin, 2022).

But while there are rationales for the different approaches, the loss of comparability makes the results very difficult to process correctly and meaningfully in a comparison. Some form of standardization would then help enable such a comparison. The topic of circular economy and the industry's downstream emissions are particularly interesting, as it is one of the more fundamental variations in approaches among the roadmaps. The distinction between waste management and material production may also become more blurred in the future, and the cooperation between the chemicals sector and waste sector may be intensified, as suggested by some of the roadmaps. On the other hand, a requirement to align to standards may also become a restriction in the making of scenarios and limit adaptability depending on research. Furthermore, when scenario developers want to explore new previously unconsidered options and possibilities there will still be a gap in conventions and thereby a limit to how much can be standardized. Which solutions may be feasible is still an open question, but in any case, transparency from the scenario makers and awareness of the various different methods, scopes and logics which have been applied previously makes it easier to align with the most appropriate approach. As roadmaps become more aligned and comparable, the road to a GHG-neutral chemical industry may become clearer.

5.3 Recent Policy Developments

There has recently been a lot of movement in the political discussion on the topics brought up in the roadmaps. On an EU level, efforts on hydrogen were renewed through the REPowerEU plan in May 2022, and two consultations on two delegated acts were launched which will propose criteria for what counts as renewable hydrogen, and how to calculate life-cycle emissions of renewable hydrogen respectively (European Commission, 2022a). These have however been delayed, even after an expected release in December (Kurmayer, 2022).

The EU has also been making dynamic developments in recent years regarding carbon management, including a communication from 2021 on sustainable carbon cycles listing actions for industrial CO₂ capture, use, storage and infrastructure, a proposal from November 2022 for certification of carbon removals, and the Commission is currently working on two studies to be published summer 2023, regarding an EU-wide CO₂ infrastructure, and regulatory oversights over CO₂ infrastructure, respectively (European Commission, n.d.-b).

Also in November 2022, the Commission proposed a revision of the Packaging and Packaging Waste Directive, as well as released a communication on a policy framework for biobased, biodegradable and compostable plastics (European Commission, 2022c, 2023a). The emphasis therein is on reducing the amounts of packaging waste, increasing recycling, and increase understanding and provide

clarity around biobased, biodegradable and compostable plastics. Key measures include targets for packaging waste reduction and targets for reuse, restrictions for overpackaging and unnecessary packaging, design criteria for recyclability, minimum recycled content rates for plastic packaging, mandatory deposit return systems for plastic bottles and aluminium cans, recycling labeling on all packaging and corresponding bins. For the biobased materials, the sustainable sourcing and sustainability criteria are emphasized, and criteria are set regarding claims for these plastics, e.g., claims about shares of biobased content, where mass balance accounting is not considered suitable.

One of the requested policy changes in the roadmaps, which has now been proposed by the European Commission (European Commission, 2023b), is to change the state aid rules to enable more direct government support to industries. The discussion around this was especially brought into light after the Inflation Reduction Act (IRA) was passed in USA (H.R.5376 - Inflation Reduction Act of 2022, 2022). The IRA consists of large volumes of government subsidies and tax credits for activities in e.g., renewable and CO₂-free electricity, manufacturing of clean vehicles, carbon removal, energy efficiency and energy infrastructure (Boehm, 2023). In reaction to this, the European Commission recently presented its Green Deal Industrial Plan which aims to massively promote climate-friendly technologies, loosen the rules for government subsidies and thus build a counterweight to the US-IRA (Simon, 2023).

Developments are also taking place on a national level. For example, the German government has released the outline for a national biomass strategy, and has announced the development of a dedicated carbon management strategy, after the German position on CCS was unclear for a long time (BMWK, 2022a, 2022b). It is also currently developing a pilot program on Carbon Contracts for Difference to offset the additional costs of climate-friendly production processes in energy-intensive sectors such as the steel and chemical industries (BMWK, n.d.).

5.4 Conclusion and Outlook

This analysis has given a broad mapping of the various roadmaps out there for climate neutral chemical industry. Important aspects from the roadmaps have been summarized and several similarities have been noted, including overall main strategies and technologies and the need for a combination of strategies to reach the targets, the need for large amounts of renewable electricity, a very rough timeline regarding when different technologies must be put into use and accelerated, what some major challenges are and some policy recommendations. But while similarities on these topics have been identified, the clearer issue to manage is the extreme variety among the roadmaps in terms of technical assumptions, priorities, approach, framework, and thus results that has been made apparent. The following recommendations have been formed for making the path forward more clear:

- Fill the research gaps on important assumptions regarding key technologies and structures, and their respective role in the future energy and industrial system. Such key questions relate to chemical recycling technologies and potentials, sustainable biomass potentials and conversion processes, CCU deployment and value chains. They also include questions on when and how infrastructures, policy frameworks and new value chains for hydrogen, CO₂, intermediates, waste and biomass can be applied.
- In future scenario analyses, the focus should be on finding and exploring plausible pathways, rather than emphasizing the boundaries in extreme cases. The goal should be to help shape a realistic way forward, although leaving enough flexibility in order to be able to react to exogenous shocks.
- There is need for discussions and information sharing between different stakeholders and decision makers especially regarding the duration of the continued use of fossil resources, the application of CCS and the use biomass in the chemical industry to shape a consensus, or at least clarify the different priorities and preferences for the decision makers. It may also help inform decisions if arguments and priorities made in roadmaps and similar works were explained and motivated more explicitly.
- A common practice ideally should be developed for how to manage and present key aspects. While some key indicators may depend on the applicable policy frameworks on a case-by-case basis, a more standardized approach for other key aspects would enable comparison between roadmaps generally. In particular, the whole life cycle of chemical products and particularly end-of-life should be considered in the development of industrial transition roadmaps, as it currently represents a large part of the chemical industry's products impact, and would be an increasingly integrated part in a future circular economy. Furthermore, the approach to counting captured emissions should be aligned with previous works or any available recommendations, for example how carbon captured from different sources including air, the chemical industry, other industries, biomass, and in other countries should be counted. Similarly, there is need for more clarity in how to account for carbon temporarily stored in products. If no such "common best practice" can reasonably be developed for these key aspects, future roadmaps should at least be clear about the choices made.

The current energy crisis due to Russia's invasion of Ukraine, and the new conditions for green investments in the US due to the recently passed IRA are two major recent developments that have only been briefly summarized in this analysis. These, alongside several other policy developments, are currently changing the conditions for the chemical industry and its defossilization in fundamental ways. Europe's dependency on Russian natural gas supply has proven to be not only unsustainable but also fundamentally unreliable and risky. The IRA has changed the global playing field for industrial production based on renewable energies in particular and indicated that also the US intends to take a leading role for the greening of industries. Developments like these show that there is no such thing as a business-as-usual for the energy intensive industries. The conventional industrial structure is in any case not viable in the future, meaning that the industry must undergo fundamental changes no matter what. However, the details of these changes and the extent to which it will be possible to implement them in a planned manner have not

yet been decided, particularly with regard to the chemical industry. Which path we approach and how we approach it is something that will depend on the choices made by industrial actors as well as government actors this year and the coming few years ahead.

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