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Full-length article

Reaching net-zero in the chemical industry—A study of roadmaps for industrial decarbonisation

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A B S T R A C T

Striving to mitigate climate change, the European Union has adopted net-zero greenhouse gas emissions as a target for 2050. In this paper, European chemical industry roadmaps from the past six years are assessed and compared to uncover how the industry envisions its role in the transition to net-zero emissions. The roadmaps are assessed in terms of ambition level, technology and feedstock strategies, investment needs and costs, agency and dependency on other actors, as well as timeline and concretion. Although net-zero pathways are often drawn out in the roadmaps, some also choose to emphasize and argue for less ambitious pathways with emission reductions of only 40–60 %. The roadmaps vary widely in terms of the importance they assign to mechanical and chemical recycling, switching to biogenic carbon and carbon dioxide as feedstock, electrification and hydrogen, and carbon capture and storage. A commonality though, is that low-tech or near-term mitigation pathways such as demand reduction, reuse or material efficiency are seldom included. High investment needs are generally highlighted, as well as the need for policy to create enabling conditions, whereas the agency and responsibility of the chemical industry itself is downplayed. Our analysis highlights that the chemical industry does not yet have a strong and shared vision for pathways to net-zero emissions. We conclude that such a future vision would benefit from taking a whole value chain approach including demand-side options and consideration of scope 3 emissions.

Abbreviations, units, and nomenclature

BAU	Business as usual
CO_2	Carbon dioxide
CO_2-eq	Carbon dioxide equivalents
CCS	Carbon capture and storage
CCU	Carbon capture and utilisation
DAC	Direct air capture
EU	European Union
EU ETS	European Union Emission Trading System
H_2	Hydrogen
IEA	International Energy Agency
Mt	Megatonne
MWh	Megawatt hour
N_2O	Nitrous oxide
R&D	Research and development

Introduction

The need for sector-specific roadmaps made in cooperation with each industrial sector was expressed by the European Commission in 2011 [1]. Since then, the EU has updated its climate target and is now aiming at net-zero greenhouse gas emissions by 2050 [2], which has further increased the need for holistic and long-term strategic plans to enable transitions. Roadmaps and the process of roadmapping can be used to form and establish visions, goals, and targets, assess technology alternatives, identify gaps and barriers, as well as strategies to overcome these and formulate guidelines for policymakers [3]. The process, often involving scenario analysis and workshops, also serves the purpose of improving communication and coordination between stakeholders, and the resulting roadmap is used as a tool for communication internally and externally [3]. Thus, they are useful for understanding how different organisations perceive and want to communicate their role now and in the future, in the context of different goals and interests of various stakeholders. The call for roadmaps has been answered for several

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high-emitting sectors, especially energy and transport [4–6], but more recently also by energy-intensive industrial sectors, such as chemicals, steel, and cement [7,8].

The chemical industry's climate impact originates both from direct and indirect emissions. If only direct greenhouse gas emissions from the industry itself are considered (i.e., scope 1 emissions), the chemical industry accounted for 135 Mt CO_2-eq in absolute terms which is 3.1 % of the EU total in 2017 [9]. This level of emissions has been roughly constant since the mid-2010s, after the elimination of most nitrous oxide and methane emissions since 1990 [10]. The production of petrochemicals is the most significant contributor to greenhouse gas emissions, but ammonia and methanol production via hydrogen gas/syngas production, together with processes to produce heat generates large emissions as well [11,12]. Taken together, the process of steam cracking, ammonia, chlorine, methanol, and aromatics production together made up around 70 % of greenhouse gas emissions from the EU chemical industry in 2013 [12]. However, the chemical industry also has considerable indirect emissions. According to IEA [13], petrochemicals account for 14 % and 8 % of total global primary demand for oil and gas respectively, where almost 60 % of the energy input is used as feedstock. This implies that the scope 3 emissions may potentially account for about 60 % of the emissions during the products' life cycle, with end-of-life treatment being the most significant part [14]. For example, the EU plastics and ammonia industry alone account for an annual life cycle emissions of 217 Mt CO_2-eq, i.e., much larger than the direct emissions from the whole EU chemical industry [14].

Industry roadmaps have been developed by a variety of actors with different expertise and priorities, and as a result, the visions for 2050 and the paths proposed can vary widely. In this paper, the term roadmap is understood as documents that adhere to what Johnson et al. [8] describe as industry transition roadmaps, i.e., "*long-range strategic plans setting out actionable measures on innovation, policy, public–private partnership, and finance required to transform industries*". This means that roadmaps are a way of envisioning the future by exploring and answering questions like: How can this industry decarbonise? What changes with regard to technologies, innovations, institutions, etc. are necessary to introduce or phase out to achieve that? As such, roadmaps can express technological expectations in the form of "*real-time representations of future technological situations and capabilities*" [15]. Expectations expressed in such exercises can both reflect and shape the governance and innovation trajectories for the industry in question [15]. Industry actors hold a particular agency since they have specific knowledge and power to influence the transition processes. By focusing on roadmap documents made by or for industry it is possible to explore these actor's ambitions, prioritised alternatives, and presumed agency in reaching net-zero emissions.

A number of meta-analyses and comparative studies of industry roadmaps and scenario analysis have been made, but they are mainly focused on energy transitions [4,16–19] or the industry as a whole [7,8,20]. Besides a summary of nine chemical industry decarbonisation scenario analyses [21], the unique challenges facing the chemical industry and its wide range of produced transition pathways remains underexplored through meta-analyses. This motivates specific attention to the considerable challenges that make the chemical sector hard-to-abate, e.g. the high temperature needs for unit processes, long-lived capital assets, global and highly complex value chains, and the fact that fossil fuels are used both as energy and material inputs [21].

This paper presents a comparative analysis of greenhouse gas reduction roadmaps for the chemical sector that are made by or commissioned by industry actors. By focusing on such roadmaps, we aim to identify and compare how the European chemical industry envisions and communicates its role in reaching the EU net-zero emissions target for 2050. By comparing a multitude of visions and paths towards a decarbonised future as presented by the industry, the dominating options, commonalities, and gaps are highlighted. To represent the range of topics which the roadmaps typically address, and which are relevant for the actualisation of low-carbon transitions in different ways, we evaluate and compare roadmaps in terms of the following aspects

- ambition level,
- technology and feedstock strategies,
- investment needs and costs,
- agency and dependency on other actors, and
- timeline and concretion.

The first two are chosen to capture the visions for the target year drawn out in the roadmaps focusing on proportions and volumes of different options. The last three complement by focusing on the efforts and actions required to initiate the transition and reach the target vision on time.

The paper proceeds as follows. The next section presents the roadmap selection and evaluation process and is followed by a condensed summary of mitigation strategies for the chemical industry in subsequent section. After that, the net-zero roadmaps are presented and analysed according to the evaluation aspects stated above. The paper ends with a discussion on identified gaps in the roadmaps and a conclusion.

Method

First, a search and selection of roadmaps to include was undertaken. Thereafter the selected roadmaps were evaluated along the five aspects above.

Roadmap search and selection

The search and selection for appropriate roadmaps was done based on our aim to uncover how the European chemical industry envisions and communicates its role in the transition to net-zero emissions. The search was done between December 2021 and May 2022 and was aided by expert advice and databases such as the Industry Transition Tracker webpage [22]. To best capture the current industry perspective, we selected roadmaps from 2017 and onwards. From a wider sample of roadmaps that were openly available online or available upon request, two key priorities were made in the selection of roadmaps. First, given the focus on industry views, documents directly from or for industry actors such as industry organisations and industrial clusters were prioritised. While such roadmaps best illustrate the perspective and narratives of the industry actors and even at times function as lobbying instruments, other kinds of perspectives and solutions are likely less reflected. Such missing perspectives may be on a societal system-scale and solutions outside the sphere of the current chemical industry. Thus, second, some roadmaps from other actors were chosen as well to complement the purely industry driven roadmaps. In total, nine roadmaps from the industry and five roadmaps from other actors were selected (see Table 1).

Several individual company roadmaps were screened but were found to lack the level of detail required for our analysis and they were therefore not included. Furthermore, the selection of non-industry roadmaps was made by only including roadmaps that include quantifications, timeframes and at least a country-wide geographical scope. Thus, several roadmaps not fullfilling these aspects made by non-industry actors were excluded. Roadmaps written in languages other than English were also excluded unless there was an English summary. In those cases, the English summary was used as the main base for evaluation, but graphs, values and translated sections of the original text were used as complement.

What is and is not called a roadmap was found to vary considerably, and indeed the term roadmap lacks a generally agreed upon definition where all sorts of forward-looking documents have historically been referred to as roadmaps [23]. Thus, the above-mentioned definition by Johnson et al. [8] could not be strictly applied in the search for

Table 1
Overview of the roadmaps evaluated in this paper.

Roadmap codename	Name of document	Made by	Made for	Reference
Industry roadmaps				
CEFIC17	Low carbon energy and feedstock for the European chemical industry	Dechema	Cefic	[24]
NCHEM18	Chemistry for Climate: Acting on the need for speed Roadmap for the Dutch Chemical Industry towards 2050	Ecofys and Berenschot	VNCI	[25]
PORT18	Deep decarbonisation pathways for the industrial cluster of the Port of Rotterdam	Wuppertal Institute	Port of Rotterdam	[26]
CHEME18	We have more than just a plan!	Chemelot	Chemelot	[27]
CEFIC19	Molecular managers; A journey into the Future of Europe with the European Chemical Industry	Cefic	Cefic	[28]
GCHEM19	Working towards a greenhouse gas neutral chemical industry in Germany	Dechema and FutureCamp	VCI	[29]
FCHEM20	Roadmap to Reach Carbon Neutral Industry by 2045	Pöyry	Kemianteollisuus	[30]
CEFIC21	iC2050 PROJECT REPORT Shining a light on the EU27 chemical sector's journey toward climate neutrality	Deloitte	Cefic	[31]
GIND21	CLIMATE PATHS 2.0 A Program for Climate and Germany's Future Development	BCG	BDI	[32]
Non-industry roadmaps				
EC17	Energy efficiency and GHG emissions: Prospective scenarios for the Chemical and Petrochemical Industry	JRC	European Comission	[12]
NGOV18	Transition agenda Plastics	(a Transition Team)	Government of the Netherlands	[33]
ECF19	Industrial Transformation 2050 Pathways to Net-Zero Emissions from EU Heavy Industry	Material economics in collaboration with VUB-IES and Wuppertal Institute	European Climate Foundation	[14]
ACA21a	Achieving net-zero greenhouse gas emission plastics by a circular carbon economy	Meys et al.	(Published in Science)	[34]
ACA21b	Zero-Emission Pathway for the Global Chemical and Petrochemical Sector	Saygin and Gielen (IRENA)	(Published in Energies)	[35]

documents. For the sake of simplicity, all documents reviewed in this paper are referred to as roadmaps. This despite some of the documents explicitly avoiding the term and instead referring to themselves as for example scenario or pathways analysis. Furthermore, most roadmaps present different future decarbonisation trajectories, these are consistently referred to as pathways in the paper. In summary, this paper is based on an analysis of 14 roadmaps and their 28 mitigation pathways.

Roadmap evaluation and comparison

The extent to which different technologies and strategies contribute to emission reductions in each pathway was compiled and compared. To enable such comparison, the reduction strategies, feedstocks and energy sources in all roadmaps and their pathways were reclassified into broader categories (Tables A.1, A.2 and A.3). The quantitative contribution of each strategy was then compared in relation to the emission levels of a reference year as presented by the roadmap. We abstained from analysing and taking into account that the calculations in the different roadmaps are partly based on different assumptions, scopes, and methods, mainly because discrepancies in data in the different roadmaps made such an analysis unfeasible. Such exact detail is not needed for the purpose of showing how this sector envisions and communicates its role but it should be noted that the values extracted from the roadmaps are not necessarily comparable. We thus provide an overview of technologies, strategies, emission reductions, and costs estimated in the selected roadmaps.

Qualitative assessments of agency and dependencies, timelines, as well as overall specificity and concretion expressed in the roadmaps were also made. Mentions related to these aspects in the texts and figures were noted and collected to enable a systematic assessment. This text analysis was done through an iterative process of careful reading of the roadmaps, initial collection of notes, identification of key themes and keywords, and complementary reading and note-taking by keyword searches in the roadmaps [36]. The notes, in combination with the overall experiences gathered during the process, guided the choice of specific aspects relevant for the analysis. The iterative process ensured that the notes were complete and sufficiently captured all mentions of the overall themes and the chosen specific aspects.

Strategies for decarbonisation and policy positions

The different greenhouse gas emissions from the chemical industry, their scale and origin shape which mitigation options are available. Emissions can be reduced through demand-side measures, for example material efficiency, reducing demand or demand growth, as well as supply-side measures such as switching feedstock and energy supply or applying carbon capture and storage (CCS) [37]. This section provides a short background on the mitigation options presented in the roadmaps. It should be noted that these options each have limitations and in part target emissions of different origins, meaning none of these strategies alone are enough to fully reach net-zero emissions. The toolbox for climate action available to industry actors also includes its engagement in climate policy, and thus this section also gives a short background on how the chemical industry has related to recent public policy proposals.

Switching feedstock

A substantial amount of the carbon in the fossil fuel input to the chemical industry ends up in products and thereby contributes to carbon dioxide emission throughout its value chain. There are three key alternatives for sourcing this carbon: recycled feedstock, biomass feedstock, and synthetic feedstock.

First, the carbon input to plastics can be sourced as recycled feedstock. Currently, the most common method used is mechanical recycling of plastics [38,39]. However, this route has limited potential due to the low quality and low collection rate for post-consumer material and the material degradation that occurs within the process, resulting in even lower-quality materials with limited market potential [40]. As a complement, chemical recycling is gaining increasing interest [39]. Using for example chemolysis, pyrolysis or gasification, the plastic waste is broken down into its chemical constituents that allow for the production of new products also from heterogenous and contaminated plastic waste [41]. Besides the challenges of access to plastic waste, where only about 35 % is presently collected [38], a key drawback is the high energy intensity of the processes [42].

Second, carbon can be sourced from biomass of different sorts. The most common route is to use 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 [43]. Depending on source it can be processed through e.g., gasification, pyrolysis, and fermentation [37,44]. Challenges include resource scarcity and ensuring that the feedstock is sourced in a carbon-neutral and sustainable way [45].

The third and least developed alternative for decarbonised feedstock in the chemical industry is carbon capture and utilisation (CCU). Synthetic feedstock through CCU includes direct air capture (DAC) and carbon dioxide from point sources, e.g., biomass combustion, anaerobic digestion, or fermentation [46]. Using carbon dioxide of fossil origin is also sometimes considered part of this mitigation pathway [47]. The carbon dioxide is then combined with hydrogen to produce intermediate products, e.g., methanol, ethanol, or syngas [48], that are then converted into e.g., aromatics, olefins or oxygenates. This hydrogen then requires a low-carbon production route, such as electrolysis of water using renewable or low-carbon electricity, using biomass or biogas as source material or by equipping conventional fossil-based routes with carbon capture [49]. Smaller amounts of hydrogen are also needed for chemical recycling and biomass-based routes as well as in the production of ammonia. Most synthetic feedstock routes are however currently highly energy intensive, currently not economically feasible and not commercially available [48].

Carbon capture and storage

Carbon capture and storage (CCS) is an alternative to using carbon dioxide as feedstock and enables continued use of fossil energy and feedstock. The carbon dioxide can be injected and permanently stored in geological formations, e.g., saline aquifers or depleted oil and gas fields. CCS is a comparatively technically mature technology, however, full-scale development requires integrated infrastructure and storage sites, which is unlikely to be developed by private actors alone [50]. CCS is also facing limited political and social acceptance [51].

Heat and electricity

Fossil-free energy alternatives include biofuels, synthetic fuels, solar thermal, geothermal, electrification and hydrogen. Biofuels, including biogas to replace natural gas, can be readily used but the potentials are limited by resource scarcity [52]. Solar thermal and geothermal can produce high and medium temperature process heat, respectively, but have geographic limitations [53].

Renewable electricity, used directly or indirectly as hydrogen or synthetic fuels, appears to offer the greatest potential for decarbonisation [37]. Electrification options includes power-to-heat technologies such as low and high temperature heat pumps, mechanical vapour recompression, electric steam generation and electric furnaces for steam cracking [54]. Other options include switching to direct electro-catalytic processes, membrane separation and chemical production via water electrolysis for syngas, ammonia, and methanol [54]. Electrification requires large investments in renewable or other near-zero emissions electricity production and infrastructure [37].

Demand-side and system efficiency measures

Reduced demand or demand growth is a relatively unexplored climate mitigation option for plastics and other products [37], but is an option that is getting increased attention [55,56]. If a historic global annual growth rate of about 4 % continues unbridled, the total plastic production will increase from 370 Mt (2019) to 1240 Mt in 2050 [40]. With growth limited to 2 % the corresponding production is 680 Mt. Demand side measures may involve design for longer use, reuse, materials efficiency, substitution, changes in practices, and avoiding certain uses altogether [13,57]. This would require demand-side regulation and other policies, so that plastics become more valuable throughout the value chain [13,40,58,59]. The increased attention to demand and production volumes is reflected in global policy discussions. For example, in the ongoing (2022–2024) UN negotiations for a plastic treaty [60], a global production cap on primary plastic polymers is discussed [61].

It is also important to pursue energy and resource efficiency measures on the supply-side. However, in a mature industry like the chemical industry conversion losses are already very small in the major production processes [13]. The chemical industry is already organised in clusters to a large extent and thus engaged in sector integration and industrial symbiosis. Nevertheless, continued such efforts can be further enabled by mapping and sharing of various flows, and building trust and shared visions between partnering companies, facilitated by cluster organisations and public incentives [62].

Recent policy positions

Climate policy affects the opportunities and challenges for emission reductions in industry as well as in other sectors. The policy discussions between the European chemical industry and climate policy actors mainly takes place through the trade association the European Chemical Industry Council (Cefic) [63]. Cefic is also among the most prominent trade associations in terms of lobbying in the EU [63,64]. Historically, the chemical industry and Cefic have opposed several climate and energy regulation policies such as increasing the EU emission reduction target and the EU taking global leadership [63], support for renewable energy [63,65] and previously the EU ETS [66]. Since 2015, there seems to have been a shift towards a more positive engagement with climate-related regulations and Cefic supports the EU's ambition to become climate neutral by 2050. The approach is however mixed and still mostly obstructive, for example opposing the increased ambition of the EU ETS [67]. Emphasizing the need for competitiveness and the risks of carbon leakage, they argue against legislation that is not matched by efforts in other parts of the world [63,65,67]. Furthermore, support for renewable energy is seen as an inefficient policy which distorts the market, and instead, EU ETS should be the only instrument used [63,65,67].

Analysis of chemical industry roadmaps

The following sections summarise and compare the contents of the roadmaps. The first three subsections focus on the quantitative aspects in terms of ambitions for emission reduction, the contribution through different strategies, and estimated costs. The final two subsections concentrate on qualitative aspects regarding dependencies and agency (i.e., "*the ability to take action or to choose what action to take*" [68]), as well as readiness and early actions described in the roadmaps.

Roadmap overview and ambition level

Table 2 presents the decarbonisation pathways in each roadmap, the pathways emission reduction compared to a reference year, and the scope of the emissions. Most roadmaps include a path aimed at close to net-zero, but this is not the case for all pathways. It is important however

Table 2
The evaluated roadmap's pathways, emission targets and scopes.

Roadmap codename	Pathway	Remaining emissions	Compared to	Scope (geographical, products, life cycle, greenhouse gases)
CEFIC17	Intermediate	58 %	2015	Europe
	Ambitious	23 %	2015	Nine largest products
	Maximum	−106 %	2015	Cradle-to-gate
NCHEM18	Circular & biobased	4 %	2005	Netherlands Petrochemical and fertilizer routes
	Electrification	4 %	2005	
	CCS	40 %	2005	Scope 1, 2 and end-of-life for sold products
	2030 compliance at least cost	4 %	2005	
	Direct action & high-value applications	5 %	2005	
PORT18	Technical progress	26 %	2015	Port of Rotterdam area Direct emissions from electricity generation, waste incineration and the petrochemical cluster
	Biomass and CCS	2 %	2015	
	Closed carbon cycle	2 %	2015	
CHEME18	Proposed plan	0 %	–	The chemical cluster Chemelot
CEFIC19	Plausible estimate	50 %	2015	Europe Scope 1 and 2
GCHEM19	Technology pathway	39 %	2020	Germany Six major basic chemical products Scope 1, 2 and end-of-life
	Greenhouse gas neutrality pathway	3 %	2020	
FCHEM20	Fast development (Scope 1&2)	40 %	2015	Finland Scope 1 and 2
	Carbon neutral chemistry (Scope 1&2)	1 %	2015	
	Fast development (Feedstock)	38 %	2015	Finland Upstream scope 3
	Carbon neutral chemistry (Feedstock)	−59 %	2015	
CEFIC21	High electrification	0 %	2019	Europe Cradle-to-gate
	Fostering circularity	0 %	2019	
	Sustainable biomass	0 %	2019	
	CO_2 capture	0 %	2019	
GIND21	Proposed path	0 %	–	Germany All industries Emissions occurring within Germany
JRC17	Prospective scenario	85 %	2013	EU 26 chemical compounds Scope 1 and 2
NGOV18	Transition agenda	–	2020	Netherlands
ECF19	New processes (Plastics)	0 %	2015	EU Plastics Emissions from refining, cracking and other foreground processes, polymerisation and blending, electricity, and end-of-life (CO_2 only)
	Circular economy (Plastics)	0 %	2015	
	Carbon capture (Plastics)	0 %	2015	
	New processes (Ammonia)	0 %	2015	EU Ammonia Emissions from ammonia synthesis, H_2 production and electricity (CO_2 only)
	Circular economy (Ammonia)	0 %	2015	
	Carbon capture (Ammonia)	5 %	2015	
ACA21a	Circular carbon pathway	0 %	–	Global Plastics Cradle-to-grave
ACA21b	1.5 °C case	0 %	2017	Global Chemical/ petrochemical sector Life cycle (CO_2 only)

to note how the emission scopes vary widely along multiple different aspects, mainly regarding (i) geographical scope, (ii) product scope (e.g., plastics and fertilizers or a number of largest products from the industry), (iii) life cycle scope (e.g., scope 1 and 2 or full life cycle emissions) and (iv) greenhouse gas emission scope (e.g., only considering carbon dioxide emissions). The roadmaps often focus on scope 1 and 2 emissions and only half consider emissions from end-of-life treatment or waste incineration in some way. Varying scopes also affect how negative emissions are accounted for and assumptions vary widely. This for example explains the negative remaining emissions shown in CEFIC17 and FCHEM20, who use a cradle-to-gate and upstream scope 3 perspective respectively. The purposes of the roadmaps also range from illustrating technological options and potentials for industry to reach net-zero to vision documents and brochures announcing ambitions and discussing conditions for transition (mainly CHEME18 and CEFIC19).

Use of technologies and strategies

The strategies used in the roadmap pathways to reduce emissions are summarised in Fig. 1. Other strategies may also be discussed and assumed in the roadmaps but their contribution to the overall emission reduction is not quantified therein. Fig. 1 shows that the use of the different strategies varies widely and there is no clearly preferred strategy. Rather, the preferred path is to use various combinations of several of the above-described strategies for decarbonisation.

Changes of feedstock

Almost all pathways utilise plastic recycling to some extent, the only exceptions being CEFIC17, and the TP and BIO scenario from PORT18. CEFIC17 did not include recycling since the emission reduction potential had not been quantified in the source material and it would require a thorough life cycle investigation. The extent of the recycling varies between the pathways from 7 % to 63 % of the feedstock (Fig. A.1), but the corresponding emission reductions are not quantified. The effect on emission reductions is generally low compared to other strategies. Recycled feedstock is used to a larger extent in the non-industry roadmaps.

Biomass is used as feedstock in all roadmaps except EC17 and the TP

Roadmap codename	Pathway	Remaining emissions by 2050	Recycling	Biomass	CCU/H_2	Electrification	Electricity emission factor	Renewable energy (non-electricity)	CCS	Efficiency improvements	Other	Production growth effect	Reference year
CEFIC17	Intermediate	58%	0%	11%	26%	27%	nq[1]	nq	0%	12%	9%[2]	-41%	2015
	Ambitious	23%	0%	13%	53%	24%	nq[1]	nq	0%	8%	19%[2]	-41%	2015
	Maximum	-106%	0%	25%	145%	25%	nq[1]	nq	0%	2%	49%[2]	-41%	2015
NCHEM18	Circular & biobased	4%	8%	59%	1%	0%	12%	11%	0%	3%	9%[4]	-7%	2005
	Electrification	4%	7%	3%	58%	nq[3]	11%	9%	0%	5%	9%[4]	-7%	2005
	CCS	40%	7%	3%	1%	0%	11%	0%	30%	5%	9%[4]	-7%	2005
	2030 compliance at least cost	4%	8%	37%	1%	nq[3]	11%	11%	18%	7%	9%[4]	-7%	2005
	Direct action & high-value applications	5%	7%	28%	11%		11%	5%	23%	7%	9%[4]	-7%	2005
PORT18	Technical progress (TP)	26%	0%	0%	0%	nq	nq	nq	nq	nq	-	nq	2015
	Biomass and CCS (BIO)	2%	0%	nq	0%	nq	nq	nq	nq	nm	-	nq	2015
	Closed carbon cycle (CYC)	2%	nq	0%	0%	nq	nq	nq	0%	nm	-	nq	2015
CHEME18	Proposed plan	0%	nq	nq	nq	nq	nq	nq	nq	nq	-	nq	-
CEFIC19	Plausible estimate	50%	nq	nq	nq	nq	nq	nm	nq	nm	-	nq	2015
GCHEM19	Technology pathway	39%	nq	nq	nq	nq	nq	nq	0%	nq	-	nq	2020
	Greenhouse gas neutrality pathway	3%	nq	nq	nq	nq	nq	nq	0%	nq	-	nq	2020
FCHEM20	Fast development (Scope 1&2)	40%	0%	0%	15%	12%	29%	13%	6%[5]	17%	-	-31%	2015
	Carbon neutral chemistry (Scope 1&2)	1%	3%		25%	27%	27%	19%	15%[5]	16%	-	-31%	2015
	Fast development (Feedstock)	38%	nq	nq	nq	nm	nm	nm	nm	nm	-	nq	2015
	Carbon neutral chemistry (Feedstock)	-59%	nq	nq	nq	nm	nm	nm	nm	nm	-	nq	2015
CEFIC21	High electrification	0%	nq	31%[6]	2%	nq	16%	nq[7]	6%	nq	28% & 16%[8]	-	2019
	Fostering circularity	0%	nq	19%[6]	3%	nq	13%	nq[7]	17%	nq	30% & 17%[8]	-	2019
	Sustainable biomass	0%	nq	27%[6]	2%	nq	13%	nq[7]	17%	nq	28% & 13%[8]	-	2019
	CO_2 capture	0%	nq	31%[6]	0%	0%	12%	nq[7]	45%	nq	0% & 12%[8]	-	2019
GIND21	Proposed path	0%	nq	nq	nq	nq	nq	nq	0%	nq	-	nq	-
EC17	Prospective scenario	85%	nq	0%	nm	nm	nm	nm	nq	nq	-	nq	2013
NGOV18	Transition agenda	nq	nq	nq	nq	nm	nm	nm	nm	nm	-	nq	2020
ECF19	New processes (Pla)	0%	nq	nq	0%	nq	nq	nq	0%	nq	-	-11%	2015
	Circular economy (Pla)	0%	nq	nq	0%	nq	nq	nq	0%	nq	-	-11%	2015
	Carbon capture (Pla)	0%	nq	nq	0%	nq	nq	nq	34%	nq	-	-11%	2015
	New processes (Amm)	0%	2%	0%	-	61%[9]	nq	nq	0%	9%	-	27%	2015
	Circular economy (Amm)	0%	5%	0%	-	50%[9]	nq	nq	0%	18%	-	27%	2015
	Carbon capture (Amm)	5%	2%	0%	-	18%[9]	nq	nq	39%	9%	-	27%	2015
ACA21a	Circular carbon pathway (combo)	nq	nq	nq	nq	nm	nq	nq	nq	nm	-	nq	-
ACA21b	1.5 °C case	0%	11%	6%	25%[10]	nq	33%	7%	68%	70%	-	-115%	2017

Fig. 1. Remaining emissions and greenhouse gas emission reduction strategies by share. Numbers are presented as percentage of emissions during reference year, so that the sum of a row represents the 100 % of emissions from the reference year (including any rounding errors). "Production growth effect" represents the emission reduction if no strategy is used, as portrayed in the roadmap, and is typically a result of assumed changed production volumes. Emission reductions are given a green colour and remaining or increased emission are given a red colour. A deeper colour corresponds to a larger absolute value. Gray is used if the value is zero or if the strategy is not mentioned ("nm"), and yellow is used if the strategy is mentioned but not quantified ("nq"). Notes: [1]Included in electrification [2]H_2 for ammonia/urea [3]Included in renewable energy [4]N_2O [5]All carbon capture [6]All biogenic carbon removal, i.e. both for feedstock and energy [7]Included in biomass [8]Reductions of other direct emissions & upstream and imported emissions [9]Includes H_2 via water electrolysis [10]H_2 feedstocks including ammonia.

and CYC scenarios in PORT18. The use of biomass as feedstock contributes between <3 % and 59 % to the reduction of emissions and is used for 1 % up to 42 % of the feedstock, although most often in the order of 30 %. CEFIC17 however uses exceptionally low amounts of around 4 % even in the most ambitious scenario. They state that the routes to produce olefins and aromatics from biomass requires large amounts of feedstock and are expensive compared to the emission avoidance and is thus an inefficient use of biomass. There is also a high emphasis of the risk of unsustainable use of biomass in the roadmaps.

Carbon dioxide is used as feedstock in most of the roadmaps. It is important to note that there is an overlap between the CCU and hydrogen strategy since transforming the carbon dioxide to olefins requires addition of hydrogen, while at the same time, hydrogen is also used unrelated to CCU as feedstock for ammonia. CCU/hydrogen strategies contribution to emission reduction and feedstock, when used, is very varying, and multiple examples exist both of a few percent and of more than 50 % of emission reduction. A few roadmaps explicitly avoid CCU as a mitigation strategy and/or source of feedstock. ECF19 and GIND21 reason that CCU is incompatible with net-zero since it might only delay the emissions rather than avoid them. PORT18 similarly notes that CCU is only carbon neutral as long as the captured carbon remains in a cycle of use and recycling. On the other hand, FCHEM20 and CEFIC17 consider CCU a better alternative compared to CCS since it closes the carbon cycle and makes use of captured carbon. The use of electrolytic hydrogen gas for CCU requires large amounts of low-carbon electricity, and CCU thus becomes a significant contributor to the use of electricity.

Most roadmaps assume a continued use of fossil feedstock. Especially in pathways not aimed at carbon neutrality, the share of fossil feedstock is often around 50 % of the total feedstock. The continued use of fossil feedstock either means that lower emission reductions are reached, and/or that strategies like CCS are used to a larger extent. Net-zero emissions are however still reached in the case of CEFIC21, the carbon capture pathway of ECF19, and ACA21b despite the continued use of fossil feedstock. CEFIC21 uses a cradle-to-gate perspective and downstream emissions are thus not accounted for. ECF19 and ACA21b use a life cycle perspective and use CCS to mitigate the emissions from the remaining fossil feedstock. There are however several examples of roadmaps where 0 or <10 % of the feedstock is fossil.

Energy related strategies and energy use

The scope 1 and 2 emissions are mitigated by switching energy sources from fossil to low-carbon sources, but also through the decreased emission factor of the electricity used. It includes electrification of processes and alternative heat sources including electricity, geothermal, solar or biomass energy. It also relates to hydrogen through the electricity needed for production through electrolysis. Energy related strategies often account for large shares of the emission reductions. Almost all roadmaps that quantify energy sources use electricity to a large extent, often accounting for >50 % of the energy use.

Electricity consumption is expected to increase in almost all roadmaps (EC17 being the exception) and often makes up the majority of the energy use. The roadmaps often show a 5-fold increase, but even 10-fold increases are sometimes expected. The most important factor for the electricity demand increase is hydrogen production via water electrolysis, which often accounts for around 80 % of electricity demand in the most demanding pathways. Apart from electricity, other renewable heat sources are used in some roadmaps, contributing to reduced emissions of around 10 %. Using biomass and biofuels for heat and steam is the main contributor, but solar and geothermal heat are mentioned as well. The use of biomass for energy is modest in the roadmaps for 2050, where its use as feedstock is prioritised instead.

Like with fossil feedstock, fossil resources for energy remains in many of the roadmaps, often representing around 10–30 % of total energy demand (Fig. A.2). In some cases, e.g., FCHEM20, emissions are still reduced by switching to less emission intensive variants, the main example being switches to natural gas. Again, less ambitious pathways and CCS-type pathways (where emissions remain low as the fossil carbon is captured) tend to have higher amounts of fossil energy sources left, but fossils remain in net-zero pathways as well. As with fossil feedstock, this is explained by the use of CCS and limited emission scopes.

CCS

There are about as many pathways that avoid using CCS as there are that use it. In many roadmaps the strategy is limited to the pathway that specifically focuses on it, and some roadmaps avoid it altogether. Where used, it contributes to emission reductions in the range of 6 to 68 %. The roadmaps identify that the least expensive and easiest application of CCS is to process emissions, mainly on crackers, but also on other higher purity processes like fossil methane reforming and ammonia production. Some apply CCS to waste incinerators at the product's end-of-life, thus reducing scope 3 emissions. CCS-type pathways tend to allow larger amounts of fossil resources to remain in use as pointed out previously, and more of the existing production units can remain intact.

Efficiency and system measures

The contribution of efficiency improvements to emission reductions is assumed to be around 10 %, mainly due to improved energy efficiency. Continuous process and energy efficiency improvements are often expected, typically expressed as assumptions of e.g., 0.5 % improvement per year. Most roadmaps furthermore address material efficiency, more commonly in terms of process improvements than measures for increased use intensity, such as circular business models, reuse, designing for circularity and measures to enable the transfer of materials for reuse. The non-industry roadmaps ECF19 and NGOV18 explore these types of measures in more detail but overall point to the same types of measures.

Although demand-side measures are recognised as important in the scientific literature [55,56], only the non-industry roadmaps. ECF19 and ACA21b assume or explore decreased production. Rather, the general assumption of demand is typically made as annual production growth rates, often 0.5 %−1 %, where the assumption of such growth is sometimes justified by referring to literature. Industrial symbiosis and sector integration solutions are often mentioned or implied, mainly as an integration of heat and carbon dioxide, but some also discuss integration of carbon monoxide and hydrogen as well as demand-side response services to the energy sector. Only ACA21b discusses geographical relocation, where it contributes 2 % to the total emission reduction.

Investments and costs

Estimations of investments and production costs in the roadmaps are shown in Tables A.4 and A.5 respectively, as well as comparisons to baseline levels where possible. It shows how the economic feasibility may be one of, if not the main barrier for realising a transition to net-zero emissions under current conditions. The estimations for investments vary from CEFIC17 showing increases of 700 to 1200 % compared to the BAU case, to CEFIC21 and GCHEM19 presenting increases in the range of 11 to 60 % depending on pathway, compared to current investments and a reference pathway respectively. Most pathways, however, imply increases in investment costs of around 100 to 200 %. The roadmaps may vary in how they account for investments made within as opposed to outside the industry's own operation, for instance, if investments for water electrolysis are included or if the cost of hydrogen is instead counted as a production cost. Carbon capture type pathways and pathways with lower ambition typically turn out to have lower investment costs when a roadmap document compares different pathways.

Costs for energy and feedstock constitute a significantly larger share of the total costs compared to investments. These energy and feedstock costs are estimated to be around five times higher than investment costs, but for some pathways they are as much as 20 times higher. They are also assumed to increase in the pathways compared to the current level, typically by around 20 to 80 %, although different estimations show more than doubled costs or sometimes lowered costs. Also here, CCS pathways and less ambitious pathways tend to show lower costs. However, ECF19 shows mechanical recycling to be the least expensive production route and ACA21a finds that the operational costs are in the same range in a circular carbon pathway as in a linear pathway with CCS, using a global and life cycle perspective. Economic feasibility is also affected by risks, both for investments in new technology and reinvestments in current processes. There are risks for example with regards to resource availability and prices as well as regulatory conditions, as pointed out in several roadmaps. Some also bring up the risks of lock-ins and stranded assets if investments are made but conditions do not turn out as expected.

Dependency on other actors and stakeholders

It is very common for the roadmaps to express how reaching the net-zero target is highly dependent on several surrounding factors that are at least partly under the control of other actors. Fig. 2 is a visualisation summarising the main dependencies mentioned in the roadmaps as identified in the qualitative assessment made in this study. Each key concept displayed was identified as a reoccurring theme and appeared in multiple roadmaps. The bottom line communicated is that a transition will not happen unless it is economically justifiable under the given framework conditions. Governments and policymakers as well as energy and feedstock availability are particularly emphasised dependencies, but other businesses are also mentioned at times. Furthermore, the pathways rely partly on non-commercialized technologies, implying a dependency on further R&D in order to follow the described path. The role of the public, consumers and civil society is on the other hand less discussed. The most emphasised dependencies are described below in more detail.

Government and policy

One of the most commonly requested conditions from governments and policymakers is a global level playing field. In the absence of such a framework, governments are asked for compensatory measures to remain competitive. Policy measures also relate to creating an enabling framework in general by providing clarity, removing legislative obstacles, investments in infrastructure and R&D funding for demonstration and scale-up. The roadmaps also point to a need for these changes to be long-term, reliable, and consistent over time.

Examples mentioned with regard to an enabling policy framework include showing direction by developing strategies and visions for biomass and hydrogen resources as well as innovation and investment frameworks. Requests are also made for legislative recognition of technologies and identified opportunities which could enable transition, for example removing obstacles to the movement of waste across borders. Another central topic in the roadmaps concerns competitiveness, and in

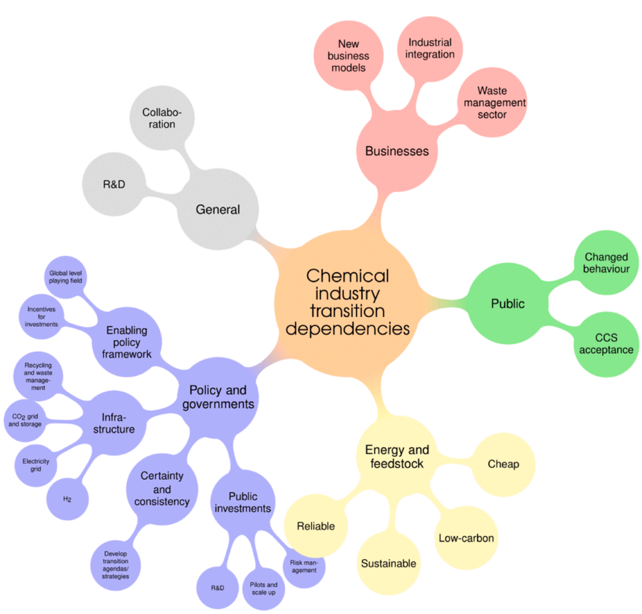

Fig. 2. Chemical industry transition is enabled or challenged depending on various surrounding factors and actors noted in the roadmaps. Most pronounced are factors relating to policy and government (purple) as well as energy and resource availability (yellow), but the public (green) and other businesses (pink) can also affect the ease of decarbonisation. Collaboration and R&D (grey) are also needed and apply generally to all affected actors.

the absence of equal environmental legislation across the globe, enforcing EU legislation at the border and carbon border taxes are brought up as alternatives. The EU ETS is seen as an important tool which should be expanded, but compensations are requested for any global competitive disadvantages. At the same time, the EU ETS is also sometimes pointed out to not be sufficient incentive to spur transition, which in part may depend on a low assumed emission allowance price. Other ways mentioned for creating more enabling economic conditions are for example lowering taxes on renewable energy, creating lead markets, and allowing state aid to be used for sector transformation measures. Public investments are also commonly requested, mainly for R&D including pilots, demonstrations, and commercialisation, but also risk sharing. Highlighted is also the need for new and improved infrastructure and planning for carbon dioxide grids, transport and storage, electric grids and energy storage, hydrogen infrastructure as well as waste handling and recycling.

Energy and feedstock availability

The question of electricity availability stands out as one of, if not the most significant dependency. The need for large amounts of reliable, inexpensive, and low carbon electricity is at a level far from what is available today. GCHEM19, which assumes an electricity price of 40 €/MWh, states that the industry cannot reach greenhouse gas neutrality by 2050 if the electricity price is 60 €/MWh. For comparison, the average price of electricity in the EU recently has been about 80–90 €/MWh [69], with fossil fuels representing 37 % of the electricity production [70].

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

Collaborations and the industry's own role

Several roadmaps identify a strong need for collaboration and coordination. This is for example with governments, research, the energy sector, other industries in the cluster, and internationally coordinated efforts and coordination across the product value chains. It also includes a deeper integration with the waste management sector. Overall, it involves a coordinated system level transition. Cooperation is not new to the sector. The plastics industry was historically developed as a way of making use of residual streams from fuel production [57]. However, the level of collaboration and the integration with new types of actors is more of a fundamental change. This can both be an accelerator if the different actors manage to help each other overcome hurdles in the transition, but may also risk falling short if the responsibility becomes too distributed and vague.

While the chemical industry's transition is clearly dependent on the initiatives and actions of other actors to provide enabling conditions, whether or how the industry itself can act to help create more enabling conditions is rarely discussed in the roadmaps. The role of the chemical industry could thus be interpreted as limited to implementing processes following market and legislative incentives, being open and cooperative and following the technology development. However, there are a few notable examples that point to a greater sense of agency. NCHEM18 notes the role of leadership from top management and the industry's role of actively reaching out for cooperation and partnerships and taking a leading role. PORT18 provides recommendations to the port industries, including identifying networking opportunities and low-risk investments as well as pressuring policymakers to provide investment certainty. FCHEM20 gives solutions directed at the chemical industry in both the short- and long-term, such as own purchase and installations of low-carbon energy, own R&D and marketing. Joint ventures with energy and recycling sectors are also mentioned.

Timelines, specificity and concretion

The roadmaps' level of readiness and specificity in early action is illustrated in Fig. 3 through eight aspects divided into three categories. The figure is an illustration of the results from the qualitative assessment made in this study, and the ratings are based on the authors' expert judgement when noting if, how clearly, and at what level of detail the roadmaps fulfilled the aspects in comparison to one another. First, aspects regarding the presentation of a timeline are reviewed, which gives indications of the considered path towards the target vision. Secondly, the roadmaps are assessed with regard to specificity in strategical choices and challenges, which is how a roadmap can show the level of knowledge and considerations taken into account in the pathway. Finally, a focus is placed on recommendations given in the roadmap, as these point out a starting point and next steps for action, potentially setting the industry on the specified path towards the envisioned goal.

Most roadmaps contain timelines until 2050 in the form of interval-based model results (aspect 1). These can be interpreted as indications of key actions by industry but are generally not meant to dictate them, and it may not be meaningful to specify exact plans until 2050 due to uncertainties. It may thus be more relevant to have a timeline for the short term (aspect 2), when conditions are more predictable. This is less common, although there are a few notable exceptions. These are all on a national or smaller scale. FCHEM20 shows the most applied approach for beginning the transition, with sketches of year-by-year action plans both at company level and a more general level. Some roadmaps give indications for timelines by presenting technology readiness levels or other ways to show when technologies could be in use (aspect 3). These estimates generally tend to align between roadmaps although they are not identical and can be difficult to compare between the roadmaps. The least specific in terms of timeline are the academic, global scope roadmaps which only present an end-state in 2050, and documents such as CHEME18, CEFIC19 and NGOV18 which serve a partly different purpose than the model-based roadmaps.

The roadmaps are generally specific and detailed when it comes to identifying and describing technological options (aspect 4). It shows that the available technologies have been mapped and these are explained to the reader at a level high enough to give context for the roadmapping. However, when it comes to which technologies are actually assumed to be installed in the pathways (aspect 5), the roadmaps are not always as clear and detailed. When the pathways are described, the technologies and strategies assumed are often more generalized.

Uncertainties and challenges (aspect 6) regarding the strategies are often brought up to some extent and are described for all or some of the strategies. It is mainly assessed in a broader sense, for example by discussing biomass and electricity availability or technology development although some assess uncertainties and challenges on a more detailed level, by technology. They may describe the specific policy, cost, or development issues for each technology. Exploring different pathways with different technology focuses is a way to manage future uncertainties and it is an approach which several of the roadmaps take. Identification of issues and difficulties that may arise is a crucial part of making a plan that can be followed in practice. Challenges must be identified in order to be managed or worked around, rather than being used as an argument to reduce decarbonisation ambition.

Recommendations for future measures (aspects 7 and 8) are important to enable continued action. The recommendations in the roadmaps are to a much larger extent directed at government agencies and policymakers than to the chemical industries, with various requests and suggestions as described in Section 4.4. The recommendations also vary in terms of precision, ranging from broader statements such as "*New technologies must be recognised as progress in regulations and must not be hampered by additional obstacles.*" [29] to precise suggestions as for example "*Based on the port's Decarbonisation Roadmap, the Port Authority should:* [...] *Develop exclusion criteria for new* CO_2-intensive *investments in the area (in cases where it has the authority to grant or deny investments).*" [71]. Recommendations can be used as an opportunity to show agency as industrial actors, act proactively and prepare the industry. Some roadmaps (e.g., NCHEM18, PORT18 and FCHEM20) for example point towards collaborations with companies and sectors which would be highly relevant partners in a future transition or preparing when and how regions, clusters or units could be converted. Potentially, recommendations for the industry could also be aimed at suggesting actions to achieve the framework conditions they require to decarbonise. The chemical industry's influence on climate policy through lobbying efforts is never brought up as such, but as the business model may be different when carbon neutral, suggestions for how to adapt the industry's approach towards climate and energy policy may be relevant.

Discussion

The roadmaps show large variations across all aspects that they were evaluated against, i.e., ambition level, technology and feedstock strategies, investment needs and costs, agency and dependency on other actors, and timeline and concretion. Furthermore, the large dependencies described present a dimension of decarbonisation requiring

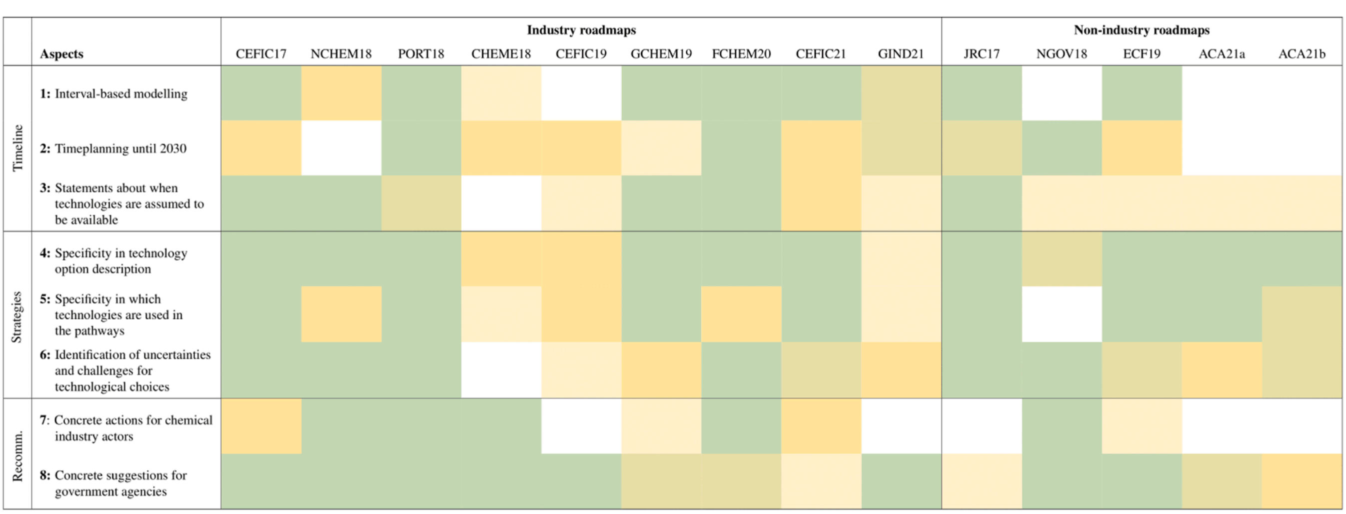

Fig. 3. Qualitative evaluation of concretion and maturity in the roadmaps. Aspects 1–8 are colour graded based on to which extent they are present in the roadmaps according to: white - Not at all; light yellow - Very minor indications; yellow - To a small degree, with low specificity; lime green - To a larger degree, but with some vagueness; green - To a higher degree.

attention and development of solutions. Lastly, a number of gaps were identified which require consideration in the assessment and development of roadmaps.

Large variations

There is a large variation in terms of emphasis on different technology options or strategies across the roadmaps. One observation is that the roadmaps make different technical assumptions, for example of costs and availability of technologies. They also use vastly different methodological approaches, ranging from quantitative optimization modelling to qualitative descriptions based on expert assessments. How scope 3 emissions and captured or stored emissions are accounted for may also create a wider range of conclusions. Another reason for the variety is the presentation of a wider breadth of possibilities in explorative pathways (e.g., NCHEM18 and CEFIC21), that illustrate possible, but not necessarily plausible scenarios. Lastly, the assumptions, approaches and choices of pathways may also be shaped by the varying narratives and preferences applied. This can for example take its form in which technologies, options and kinds of framework conditions are considered.

Exploring and displaying the wide range of options potentially available may be seen as an advantage since it signifies an awareness of the many available possibilities. However, when the variations between different roadmaps and scenarios are too vast, it also creates uncertainty concerning in which direction the chemical industry will or should be moving. This might in turn make it difficult for involved actors to interpret what actions should be taken. The uncertainty is especially reflected in the roadmaps with a larger geographical scope, while more regional or cluster level roadmaps tend to include more detailed recommendations and descriptions of strategies and technologies as well as more ambitious targets. Possibly, the range of options is in these cases mainly an opportunity, as it allows adaptability depending on regional and local circumstances in terms of access to different feedstocks and energy. As the particular opportunities and options may be specified more locally or on a case-by-case basis, future permit procedures could make it mandatory for companies or industrial clusters to develop decarbonisation roadmaps.

Large dependencies

Many of the roadmaps state that a decarbonisation in the chemical industry is heavily dependent on the development in other sectors (e.g., zero-emissions electricity) and of infrastructure (e.g., for collecting and sorting waste, or CCS). This signals that much of the responsibility and heavy lifting for decarbonisation falls on other sectors. However, as a key player, the chemical industry cannot remain passive in its development. For example, electrification will have profound effects on the power sector and this new sectoral coupling implies that the chemical industry should work closely with energy companies to ensure reliable access to electricity. This may involve long-term power purchase agreements, own investments in power production, and offering demand flexibility through hydrogen or other energy storage. Similarly, chemical recycling means that the industry becomes part of a new circular economy system, and it must engage with new actors in shaping that system. Clusters and companies seeking to decarbonise will need to gather knowledge, coordinate, and cooperate with actors across whole value chains, and use their economic and political influence to help enable the transition.

Gaps

Roadmaps should always be compatible with overall climate objectives. As previously noted, not all roadmaps identified in this study are aimed at net-zero or close to net-zero emission targets. While it is almost never explicitly stated in the roadmaps, it is important to remember that not aiming for net-zero implies either that it does not intend for the EU target to be reached, or that other sectors are expected to reach negative emissions compensating for those left in the chemical industry. Furthermore, several roadmaps also allow continued use of large amounts of fossil resources while in contrast, others, as noted above, conclude that even measures like CCU are not compatible with a net-zero pathway. Future roadmaps would benefit from a more explicit recognition of what strategies are viable in a net-zero context. For example, those aiming to reduce emissions by switching to natural gas could evaluate if this can be compatible with the long-term goal or if it creates lock-ins that prevent net-zero solutions. It is also important to include the upstream as well as downstream scope 3 emissions when developing roadmaps. This to ensure that system level targets are reached, and that important opportunities are considered even when not under the direct influence of today's chemical industry. If and how and if the scope 3 emissions are included varies a lot between the roadmaps, and while they may be more difficult to assess than scope 1 and 2, they are often significant and should also be assessed and mitigated.

It has been observed that strategies on a system level are less commonly assessed than others. Such strategies include industrial symbiosis, material efficiency, relocation and demand reductions that contribute to lower energy and overall resource use. Exploring the options for decreased use is important, especially from a broader societal resource perspective. However, the roadmaps from industry are rather about showing how the industry can maintain their position and adapt to fit into a net-zero future, than about avoiding emissions by avoiding growth in production. Since strategies like these are rarely considered more than qualitatively, there could be an untapped potential worth investigating quantitatively.

Maturity in terms of planning for the next few years and recommendations for early actions are also missing from many of the roadmaps. There is a lacking signal of agency and urgency from the industry as has been discussed above. When commissioning roadmaps, this could be one of the questions to investigate in greater depth. There may here be an opportunity to leverage the chemical industry's well developed lobbying apparatus for net-zero solutions in the chemical sector as well as future coupled sectors using a different approach than the previously partly obstructive one.

We have discussed the gaps that have been identified in the roadmaps that do exist, but it should be pointed out that more chemical industry actors, clusters and countries exist for which there are no roadmaps at all. Preparing for significantly reducing emissions, exploring alternatives, opportunities, and challenges by creating roadmaps will be necessary for all industries in the coming years. This work should begin as soon as possible and there is plenty of knowledge and information to be gathered from previous works such as the roadmaps evaluated in this paper. Based on our analysis and to summarize our conclusions regarding gaps, we propose that future roadmaps should take special care to include the following aspects:

- Targeting a fully net-zero emissions chemical industry, also including scope 3 emissions, in order to be in line with the overall net-zero target for the EU,
- Considering the potential, limitations and feasible combinations of all main supply-side strategies, i.e., switching feedstock to recycled material, sustainable biomass, and sustainable captured carbon and hydrogen, switching energy sources to sustainable and low-carbon energy sources, particularly via electrification, CCS, energetic as well as material efficiency improvements,
- Considering demand-side strategies and measures to ensure a sustainable level of production,
- Focusing on agency and implementation of the roadmap by specifying well-defined early actions to be taken by all relevant actors, and by defining plausible paths, intermediate goals and steps to reach the target on time,

· Forming pathways that are robust and allow for flexibility by identifying and acknowledging challenges, opportunities and uncertainties.

Our assessment of roadmaps suggests that the European chemical industry has not yet fully embraced the implications of net-zero emission targets, or the urgency to address climate change. The narrative in several roadmaps is one in which industry adapts to and operates under frameworks provided by governments without reflecting on its own role, responsibility, and agency in the transition. Central elements of this narrative are that governments should provide financial support, green electricity as well as gas and CCS infrastructures, and not impose measures that may lead to an "unfair" playing field that threatens competitiveness. But fairness also dictates that Europe should take the lead in combating climate change, and Europe has adopted a net-zero emission target. This leads to an equation that industry and government must solve together. To retain credibility, industry should develop strategies for zero emissions across the whole value chain and engage proactively in shaping policies and markets rather than lobby against attempts at stricter climate policy.

Conclusions

It is only in recent years that the chemical industry has started to openly explore and communicate strategies for decarbonisation. A total of 14 chemical industry decarbonisation roadmaps published between 2017 and 2021 were assessed and compared. Although they vary in terms of ambition level, scope of emissions covered and purpose, this allowed us to explore how the European chemical industry envisions and communicates its role in decarbonisation. The roadmaps put different emphasis on different mitigation options and use scenarios to explore different pathways mainly considering scope 1 and 2 emissions. They are mostly focused on supply-side options, i.e., switching from fossil feedstock and energy to recycled plastics, biomass, renewable electricity, hydrogen and synthetic fuels and feedstock, as well as CCS. They also vary widely in terms of the importance they assign to different supply-side options. The common omission of scope 3 emissions is problematic given the relatively high upstream as well as downstream chemical industry emissions. Options to reduce demand, through for example material efficiency or avoiding certain uses, are less explored. The roadmaps done by or for industry actors generally emphasize barriers, uncertainties, and risks such as high investment cost, increased production cost, low technology readiness levels, low availability of cheap renewable electricity, development of CCU and CCS infrastructure, and carbon leakage. In this context, they also underline the need for governments and other actors to create enabling and favourable conditions for decarbonisation whereas the role and responsibility of the chemical industry goes rather unnoticed. In combination with mixed climate mitigation ambitions in the roadmaps this leads us to the conclusion that the chemical industry does not yet have a strong and shared vision for pathways to net-zero emissions, including the necessity of scope 3 zero emissions, nor have they fully accepted their own responsibility and agency in making such a transition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgement

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Appendix

Roadmap codename	Pathway	Fossil	Recycling	Biomass	H_2 and/or CCU
CEFIC17	Intermediate	75%	0%	3%	23%
	Ambitious	53%	0%	4%	43%
	Maximum	4%	0%	4%	92%
NCHEM18	Circular & biobased	nq	nq	nq	nq
	Electrification	nq	nq	nq	nq
	CCS	nq	nq	nq	nq
	2030 compliance at least cost	nq	nq	nq	nq
	Direct action & high-value applications	nq	nq	nq	nq
PORT18	Technical progress (TP)	nq	0%	0%	0%
	Biomass and CCS (BIO)	nq	0%	nq	0%
	Closed carbon cycle (CYC)	0%	nq	nq	0%
CHEME18	Proposed plan	0%	nq	nq	nq
CEFIC19	Plausible estimate	nq	nq	nq	nq
GCHEM19	Technology pathway	46%	12%	29%	14%
	Greenhouse gas neutrality pathway	6%	11%	28%	55%
FCHEM20	Fast development (Scope 1&2)	nq	nq	nq	nq
	Carbon neutral chemistry (Scope 1&2)	nm	nq	nq	nq
	Fast development (Feedstock)	44%	27%	27%	2%
	Carbon neutral chemistry (Feedstock)	9%	41%	42%	8%
CEFIC21	High electrification	60%	8%	27%	5%
	Fostering circularity	54%	19%	17%	10%
	Sustainable biomass	53%	7%	35%	5%
	CO_2 capture	88%	11%	1%	0%
GIND21	Proposed path	0%	18%+12%	0%	70%
EC17	Prospective scenario	100%	nq	0%	nq
NGOV18	Transition agenda	44%	31%+10%	15%	0%
ECF19	New processes (Pla)	0%	15%+47%	38%	0%
	Circular economy (Pla)	0%	25%+38%	37%	0%
	Carbon capture (Pla)	38%	15%+14%	33%	0%
ACA21a	Circular carbon pathway	1%	19%+25%	38%	17%
ACA21b	1.5 °C case	36%	nq	25%	39%

Fig. A.1. Feedstock used in the pathways, as shares of total feedstock base for the products specified in the roadmaps. Note that this may vary between roadmaps so the values may not be fully comparable. For roadmaps presenting mechanical and chemical recycling separately, this table shows mechanical recycling as the first value and chemical as the second. Alternative feedstocks are given a green colour and fossil feedstocks are given a red colour. A deeper colour corresponds to a larger share. Gray is used if the value is zero, and yellow is used if the feedstock source is mentioned but not quantified ("nq").

Roadmap codename	Pathway	Fossil	Waste material	Biomass	H_2	Electricity	Other/ Non-separable	Note
CEFIC17	Intermediate	65%	0%	5%	nq[1]	30%	nq	Energy+feedstock
	Ambitious	44%	0%	7%	nq[1]	50%	nq	Energy+feedstock
	Maximum	3%	0%	7%	nq[1]	90%	nq	Energy+feedstock
NCHEM18	Circular & biobased	nq	nq	nq	0%	nq	nq	
	Electrification	nq	nq	nq	nq	nq	nq	
	CCS	nq	nq	nq	0%	nq	nq	
	2030 compliance at least cost	nq	nq	nq	0%	nq	nq	
	Direct action & high-value applications	nq	nq	nq	nq	nq	nq	
PORT18	Technical progress (TP)	76%	0%	0%	nq[1]	24%	nm	Energy
	Biomass and CCS (BIO)	21%	7%	7%	nq[1]	64%	nq	Energy
	Closed carbon cycle (CYC)	5%	nq	0%	nq[1]	80%	15%[2]	Energy
CHEME18	Proposed plan	0%	nm	nq	nq	nq	nq	
CEFIC19	Plausible estimate	nq	nm	nq	nq	nq	nq	
GCHEM19	Technology pathway	21%	4%	21%	nq[1]	48%	5%[3]	Energy+feedstock
	Greenhouse gas neutrality pathway	2%	2%	11%	nq[1]	81%	3%[3]	Energy+feedstock
FCHEM20	Fast development (Scope 1&2)	nq	nm	nq	nq	55%	nm	Electricity+heat
	Carbon neutral chemistry (Scope 1&2)	nq	nm	nq	nq	74%	nm	Electricity+heat
	Fast development (Feedstock)	nm	nm	nm	nm	nq	nm	Electricity+heat
	Carbon neutral chemistry (Feedstock)	nm	nm	nm	nm	nq	nm	Electricity+heat
CEFIC21	High electrification	12%	nm	0%	nq[1]	88%	nm	Energy
	Fostering circularity	9%	nm	1%	36%[4]	55%	nm	Energy
	Sustainable biomass	10%	nm	2%	34%[4]	54%	nm	Energy
	CO_2 capture	19%	nm	41%	9%[4]	31%	nm	Energy
GIND21	Proposed path	0%	2%	11%	2%	76%	8%[5]	Energy
EC17	Prospective scenario	88%	nm	0%	nq	12%	nm	Energy
NGOV18	Transition agenda	nm	nq	nm	nm	nm	nm	
ECF19	New processes (Pla)	0%	45%	29%	nq[1]	29%	nm	Energy+feedstock
	Circular economy (Pla)	0%	46%	29%	nq[1]	26%	nm	Energy+feedstock
	Carbon capture (Pla)	33%	20%	22%	nq[1]	26%	nm	Energy+feedstock
	New processes (Amm)	nq	nm	nm	nq	nq	nm	
	Circular economy (Amm)	nq	nm	nm	nq	nq	nm	
	Carbon capture (Amm)	nq	nm	nm	nq	nq	nm	
ACA21a	Circular carbon pathway	0%	nq	35%[6]	nq[1]	65%[6]	nm	Energy+feedstock
ACA21b	1.5 °C case	24%	nq	28%	19%	20%[7]	9%[8]	Energy

Fig. A.2. Energy sources used in the pathways, as shares of total energy use. Alternative energy sources are given a green colour and fossil energy sources are given a red colour. A deeper colour corresponds to a larger share. Gray is used if the value is zero or if the energy source is not mentioned ("nm"), and yellow is used if the energy source is mentioned but not quantified ("nq"). Notes: [1] Included in electricity [2]Other is steam from undefinable and mixed sources [3]Energy from district heating [4] H_2 is from market, own H_2 production counted in electricity. Electricity also includes electricity for H_2 from market production [5] 7 % district heating +1 % ambient heat [6]Two alternatives are given in the roadmap, the values here correspond to the given feedstock values, but the second alternative representing a "feasibility point" relating to available resources would mean 81 % and 19 % for biomass and electricity respectively) [7] Excluding electricity for H_2 [8]2 % solar thermal, 7 % district heating.

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

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

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

Roadmap codename	Feedstock classified as
	Fossil:
CEFIC17	Naphtha
	Heavy oil
	Natural gas
GCHEM19	Fossile Rohstoffe
FCHEM20	Fossil
CEFIC21	Naphtha
	Crude oil

(*continued on next page*)

Table A.2 (*continued*)

Roadmap codename	Feedstock classified as
	LNG
	Fuel oil
NGOV18	Virgin (fossil raw material)
ECF19	Electric steam cracking
	Electric steam cracking with CCS
	Steam cracking with CCS
ACA21a	Fossil resources
ACA21b	Oil
	Gas
	Coal
	Recycling:
GCHEM19	Kunststoffabfälle
FCHEM20	Recycled
CEFIC21	Mechanical+chemical
GIND21	Mechanisches Recycling
	Chemisches Recycling
NGOV18	Mechanically recycled
	Chemically recycled
ECF19	Mechanical recycling
	Chemical recycling (incl. steam cracking)
ACA21a	Mechanical recycling
	Chemical recycling
ACA21b	(Recycled)*
	Biomass:
CEFIC17	Biomass
GCHEM19	Biomasse
FCHEM20	Renewable
CEFIC21	Lignocellulosic biomass (for bioethanol)
	Agricultural residues (for biomethane)
	Sugar crops (for bioethanol)
	Woody biomass (for bionaphtha)
GIND21	Syn. Naphtha im elektr. Steamcracker
	Methanol-to-X
NGOV18	Bio-based
ECF19	Bio based production
ACA21a	Biomass Utilization
ACA21b	Biomass
	H_2 and/or CCU:
CEFIC17	CO_2 feed
GCHEM19	CO_2
FCHEM20	Carbon from CCU, power-to-H_2
CEFIC21	CCU
ACA21a	Carbon Capture and Utilization
ACA21b	Green hydrogen feedstocks

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

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

Roadmap codename	Energy source classified as
	Fossil:
CEFIC17	Naphtha
	Heavy oil
	Natural gas
PORT18	Naphtha
	Pet coke
	NG
	Refinery gas
	Steam (*generation from fossil sources)
GCHEM19	Rohstoffe fossil
	Brennstoffe (fossil)
CEFIC21	Fuel oil
	NG
ECF19	Fossil fuels
ACA21b	Fossil fuel
	Waste material:
PORT18	Steam (*generation from waste)
GCHEM19	Rohstoffe Abfallkunststoffe
GIND21	Müllverbrennung

(*continued on next page*)

Table A.3 (*continued*)

Roadmap codename	Energy source classified as
ECF19	End-of-life plastics
	Biomass:
CEFIC17	Biomass
PORT18	Steam (*generation from biomass)
GCHEM19	Rohstoffe Biomasse
	Brennstoffe (erneubar)
CEFIC21	Woody biomass
	Agr. Residues
GIND21	Biomasse
ECF19	Biomass
ACA21a	Biomass
ACA21b	Bioenergy
	H_2:
CEFIC21	H_2 from market
GIND21	Grüne Gase
ACA21b	Green hydrogen
	Electricity:
CEFIC17	Electricity
PORT18	Electricity
GCHEM19	Strom
CEFIC21	Electricity
	Electricity for H_2 from market production
GIND21	Strom
ECF19	Electricity
ACA21a	Renewable electricity
ACA21b	Electricity (excluding green hydrogen production)
	Other/Non-separable:
PORT18	Steam (*Energy source not specified)
GCHEM19	Fernwärme, extern
GIND21	Fernwärme
ACA21b	Solar thermal
	District heating

Table A.4
Investment costs in the different pathways for the different roadmaps.

Roadmap codename	Pathway	Total investments over period (bill €)	Average per year (bill €/year)	% increase	Compared to	Peak around	2 most significant investment costs
CEFIC17	BAU	72.3	2.1	**0**	BAU	–	Ethylene Propylene
	Intermediate	594	17	**710**	BAU	–	Methanol Ethylene
	Ambitious	672	19.2	**810**	BAU	–	Methanol Ethylene
	Maximum	934	26.7	**1170**	BAU	–	Methanol Ethylene
NCHEM18	Circular & biobased	24.5[1]	0.8[1]	**–**	–	After 2030	Alternative feedstock Renewable energy (geothermal+biomass boilers)
	Electrification	91.3[1]	2.8[1]	**–**	–	After 2030	Alternative feedstock, energy efficiency
	CCS	12.4[1]	0.4[1]	**–**	–	After 2030	CCS Closure of material chains
	2030 compliance at least cost	16.2[1]	0.5[1]	**–**	–	After 2030	Energy efficiency Closure of materials chain
	Direct action & high-value applications	24.5[1]	0.7[1]	**–**	–	After 2030	Alternative feedstock Energy efficiency
PORT18	BAU	–	–	**–**	–	–	–
	Technical progress	–	–	**–**	–	–	–
	Biomass and CCS	–	–	**–**	–	–	–
	Closed carbon cycle	–	–	**–**	–	–	–
CHEME18	Proposed plan	–	–	**–**	–	–	–
CEFIC19	Plausible estimate	–	–	**–**	–	–	–
GCHEM19	Reference pathway	210	7	**0**	ref	–	–
	Technology pathway	233.5	7.8	**11**	ref	2050 or later	Additional investments for HVCs: Electrolysis and Fischer-Tropsch for naphtha Biomass gasification and Fischer-Tropsch for naphtha
	Greenhouse gas neutrality pathway	278	9.3	**32**	ref	2040s	Additional investments for HVCs: Electrolysis and Fischer-Tropsch for naphtha Electric crackers for HVC production from naphtha

(*continued on next page*)

Table A.4 (*continued*)

Roadmap codename	Pathway	Total investments over period (bill €)	Average per year (bill €/year)	% increase	Compared to	Peak around	2 most significant investment costs
FCHEM20	*Scope 1&2:*						
	BAU	34	1.0	**0**	BAU	Continuous increase	BAU fixed BAU R&D
	Fast development	50	1.4	**48**	BAU	2030–2035	BAU fixed BAU R&D (of additional: New technology (mainly bio-based feedstock production, chemical recycling and electrification of heat) Asset conversion)
	Carbon neutral chemistry scope	58	1.7	**72**	BAU	2030–2035	BAU fixed BAU R&D (of additional: New technology Asset conversion)
	Feedstock:						
	BAU	1	<0.1	**0**	BAU		
	Fast development	28[2]	0.8[2]	**2700**	BAU	2040	
	Carbon neutral chemistry	42[2]	1.2[2]	**4100**	BAU	2040–2045	
CEFIC21	High electrification	280[1]	8.8[1]	**45**	Current annual investment 20 bill €	2045[3]	Biomass feedstock technologies (mainly gasification) H_2 related processes (mainly alkaline electrolysis and methane pyrolysis)
	Fostering circularity	288[1]	9.0[1]	**46**	Current annual investment 20 bill €	2050 or later[3]	Biomass feedstock technologies (almost only gasification) H_2 related processes (mainly alkaline electrolysis and methane pyrolysis)
	Sustainable biomass	350[1]	10.9[1]	**56**	Current annual investment 20 bill €	2050 or later[3]	Biomass feedstock technologies (mainly gasification) H_2 related processes (mainly alkaline electrolysis and methane pyrolysis)
	CO_2 capture	160[1]	5.0[1]	**26**	Current annual investment 20 bill €	2035 and 2045[3]	CO_2 capture, transport, and storage technologies Conventional technologies
GIND21	Proposed path	–	–	**–**	–	–	–
EC17	Prospective scenario	–	–	**–**	–	–	–
NGOV18	Transition agenda	<<0.1[4]		**–**	–	–	"Prevention, more with less and avoidance of leakage" "Increased renewable supply and demand"
ECF19	*Plastics:*						
	Baseline	–	2	**0**	Baseline	Constant	
	New processes	–	6.0	**200**	Baseline	2040	–
	Circular economy	–	5.2	**160**	Baseline	2035	–
	Carbon capture	–	4.4	**120**	Baseline	2030	–
	Ammonia:						
	Baseline	–	0.6	**0**	Baseline	Constant	
	New processes	–	0.7	**17**	Baseline	2030	–
	Circular economy	–	0.6	**6**	Baseline	2030	–
	Carbon capture	–	0.8	**26**	Baseline	2030	–
ACA21a	Linear carbon pathway	–	–	**–**	–	–	–
	Circular carbon pathway	–	–	**–**	–	–	–
ACA21b	Planned Energy Scenario	1950[5]		**0**	Planned Energy Scenario	–	Fossil fuel based production Energy recovery
	1.5 °C case	4500[5]	140[5]	**131**	Planned Energy Scenario	–	Renewables based hydrogen feedstock Energy efficiency

[1] Additional costs.
[2] Partly overlap with scope 1 and 2 investments.
[3] Peak capacity deployment.
[4] Only cost of proposed government actions, until 2030.
[5] USD.

Table A.5
Costs for energy, feedstock and operation in the different pathways.

Roadmap codename	Pathway	Average per year (bill €/year)	% increase	Compared to	Note	2 most significant investment costs
CEFIC17	BAU	103	**0**	BAU	Production costs	–

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Table A.5 (*continued*)

Roadmap codename	Pathway	Average per year (bill €/year)	% increase	Compared to	Note	2 most significant investment costs
	Intermediate	107	**4**	BAU	Production costs	–
	Ambitious	108	**5**	BAU	Production costs	–
	Maximum	110	**7**	BAU	Production costs	–
NCHEM18	Circular & biobased	12.6	**110**	2015	Energy, feedstock	Biodiesel Wood
	Electrification	10.8	**80**	2015	Energy, feedstock	Electricity Wood
	CCS	5.5	**−8.3**	2015	Energy, feedstock	Fossil oil Natural gas
	2030 compliance at least cost	10.0	**65**	2015	Energy, feedstock	Biodiesel Wood
	Direct action & high-value applications	9.0	**50**	2015	Energy, feedstock	Biodiesel Electricity
PORT18	BAU	–	**–**	–	–	–
	Technical progress	–	**–**	–	–	–
	Biomass and CCS	–	**–**	–	–	–
	Closed carbon cycle	–	**–**	–	–	–
CHEME18	Proposed plan	–	**–**	–	–	–
CEFIC19	Plausible estimate	–	**–**	–	–	–
GCHEM19	Reference pathway	23.2	**0.87**	2020 (incl. specialty chemicals)	Energy, feedstock, emission certificates	Fossil raw material Fuel costs
	Technology pathway	26.5	**18**	2020 (excl. Specialty chemicals)	Energy, feedstock, emission certificates	Electricity Fossil raw material
	Greenhouse gas neutrality pathway	36	**61**	2020 (excl. Specialty chemicals)	Energy, feedstock, emission certificates	Electricity Biomass/plastic waste/CO_2 material costs
FCHEM20	*Scope 1&2:*					
	BAU	0.4	**11**	2015	Electricity	–
	Fast development	0.9	**170**	2015	Electricity	–
	Carbon neutral chemistry	1.6	**360**	2015	Electricity	–
	Feedstock:					
	BAU	13.2	**30**	2015	Main raw material costs	Fossil
	Fast development	14.2	**40**	2015	Main raw material costs	Fossil Renewable
	Carbon neutral chemistry	13.8	**35**	2015	Main raw material costs	Renewable Recycled
CEFIC21	High electrification	100.6	**110***	2019	Energy, feedstock, opex until 2050 *Only energy+feedstock	–
	Fostering circularity	91.0	**92***	2019	Energy, feedstock, opex until 2050 *Only energy+feedstock	–
	Sustainable biomass	98.4	**120***	2019	Energy, feedstock, opex until 2050 *Only energy+feedstock	–
	CO_2 capture	95.0	**83***	2019	Energy, feedstock, opex until 2050 *Only energy+feedstock	–
GIND21	Proposed path	–	**–**	–	–	–
EC17	Prospective scenario	–	**–**	–	–	–
NGOV18	Transition agenda	–	**–**	–	–	–
ECF19	*Plastics:*					
	Baseline	1.2*	**0**	Current process	Production costs incl. capex and downstream *€/tonne	–
	New processes	1.5–1.8*	**20–46**	Current process	Production costs depending on technology, incl. capex and downstream *€/tonne	–
	Circular economy	1.5–1.8*	**20–46**	Current process	Production costs depending on technology, incl. capex and downstream *€/tonne	–
	Carbon capture	1.5–1.8*	**20–46**	Current process	Production costs depending on technology, incl. capex and downstream *€/tonne	–
	Ammonia:					
	Baseline	354*	**0**	Current process	Production costs incl. capex and downstream *€/tonne	–
	New processes	418–553*	**18–56**	Current process	Production costs depending on technology incl. capex and downstream, at 40 €/MWh electricity *€/tonne	–
	Circular economy	418–553*	**18–56**	Current process	Production costs depending on technology incl. capex and downstream, at 40 €/MWh electricity *€/tonne	–

(*continued on next page*)

Table A.5 (*continued*)

Roadmap codename	Pathway	Average per year (bill €/year)	% increase	Compared to	Note	2 most significant investment costs
	Carbon capture	418–553*	**18–56**	Current process	Production costs depending on technology incl. capex and downstream, at 40 €/MWh electricity *€/tonne	–
ACA21a	Linear carbon pathway	822–1366*	**same range**	Baseline with only CCS	Operational costs incl. EoL *USD	Oil Energy recovery
	Circular carbon pathway	839–1110*	**same range**	Baseline with only CCS	Operational costs incl. EoL *USD	Biomass or chemical recycling, depending on electricity price
ACA21b	Planned Energy Scenario	860*	**0**	–	Energy, feedstock *USD	
	1.5 °C case	1170*	**36 %**	total energy & feedstock cost in for sector in 2050 (860 bill USD)	*"Total mitigation cost" (310 bill UDS) + Planned Energy Scenario energy+feedstock, USD	CCS for combustion and processes, H_2-based chemicals/Energy efficiency

References

[1] European Commission. COM/2011/0112 final 2011.
[2] European Commission, Secretariat-General. COM/2019/640 final 2019.
[3] M. Amer, T.U. Daim, Application of technology roadmaps for renewable energy sector, Technol Forecast Soc Change 77 (2010) 1355–1370, https://doi.org/10.1016/j.techfore.2010.05.002.
[4] W. Deason, Comparison of 100% renewable energy system scenarios with a focus on flexibility and cost, Renew. Sustain. Energy Rev. 82 (2018) 3168–3178, https://doi.org/10.1016/j.rser.2017.10.026.
[5] Element Energy, Cambridge econometrics. Towards fossil-free energy in 2050. 2019.
[6] Fuel Cells and Hydrogen 2 Joint Undertaking, Hydrogen Roadmap Europe, 2019, https://doi.org/10.2843/249013. Luxembourg.
[7] S. Samadi, C. Barthel, Meta-Analysis of Industry Sector Transformation Strategies in German, European and Global Deep Decarbonisation Scenarios, 2020.
[8] O.W. Johnson, G. Mete, F. Sanchez, Z. Shawoo, S. Talebian, Toward climate-neutral heavy industry: an analysis of industry transition roadmaps, Appl. Sci. 11 (2021), https://doi.org/10.3390/app11125375.
[9] EEA. EU-28 Industrial pollution profile 2020 2020.
[10] Cefic. 2022 Facts and figures of the European chemical industry 2022.
[11] BCG. Klimapfade 2.0: Ein Wirtschaftsprogramm für Klima und Zukunft 2021.
[12] A. Boulamanti, J.A. Moya, Energy Efficiency and GHG emissions: Prospective scenarios For the Chemical and Petrochemical Industry, Publications Office of the European Union, Luxembourg (Luxembourg), 2017, https://doi.org/10.2760/630308.
[13] IEA. The future of petrochemicals 2018.
[14] Material Economics. Industrial transformation 2050: pathways to net-zero emissions from EU heavy industry 2019.
[15] M. Borup, N. Brown, K. Konrad, H Van Lente, The sociology of expectations in science and technology, Technol. Anal. Strateg. Manag. 18 (2006) 285–298, https://doi.org/10.1080/09537320600777002.
[16] J. Cochran, T. Mai, M. Bazilian, Meta-analysis of high penetration renewable energy scenarios, Renew. Sustain. Energy Rev. 29 (2014) 246–253, https://doi.org/10.1016/j.rser.2013.08.089.
[17] M. Densing, E. Panos, S. Hirschberg, Meta-analysis of energy scenario studies: example of electricity scenarios for Switzerland, Energy 109 (2016) 998–1015, https://doi.org/10.1016/j.energy.2016.05.020.
[18] J. Dixon, K. Bell, S. Brush, Which way to net zero? a comparative analysis of seven UK 2050 decarbonisation pathways, Renew. Sustain. Energy Trans. 2 (2022), 100016, https://doi.org/10.1016/j.rset.2021.100016.
[19] T. Naegler, C. Sutardhio, A. Weidlich, T. Pregger, Exploring long-term strategies for the german energy transition–a review of multi-Sector energy scenarios, Renew. Sustain. Energy Trans. 1 (2021), 100010, https://doi.org/10.1016/j.rset.2021.100010.
[20] T. Gerres, J.P. Chaves Ávila, P.L. Llamas, T.G San Román, A review of cross-sector decarbonisation potentials in the European energy intensive industry, J. Clean. Prod. 210 (2019) 585–601, https://doi.org/10.1016/j.jclepro.2018.11.036.
[21] IEA. Energy technology perspectives 2020. Paris: 2020.
[22] Industry Transition Tracker n.d. https://www.industrytransition.org/industry-transition-tracker/ (Accessed July 5, 2022).
[23] T.A Kappel*, Perspectives on roadmaps: how organizations talk about the future, J. Product Innov. Manag. 18 (2001) 39–50, https://doi.org/10.1111/1540-5885.1810039.
[24] A. Bazzanella, F. Ausfelder, Low carbon energy and feedstock for the European chemical industry: technology study. DECHEMA, Gesellschaft für Chemische Technik und Biotechnologie eV, 2017.
[25] Stork M., de Beer J., Lintmeijer N., den Ouden B. Chemistry for Climate: acting on the need for speed-Roadmap for the Dutch Chemical Industry towards 2050 2018.
[26] S. Samadi, C. Schneider, S. Lechtenböhmer, Deep decarbonisation pathways for the industrial cluster of the Port of Rotterdam. Leading the low-carbon transition : ECEEE Industrial Summer Study ; 11-13 June 2018, Berlin, Germany, in: Proceedings, Stockholm: European Council for an Energy Efficient Economy, 2018, pp. 399–409.
[27] Chemelot. We have more than just a plan! 2018.
[28] Cefic. Molecular managers; A journey into the Future of Europe with the European Chemical Industry 2019.
[29] Verband der Chemischen Industrie e. V. (VCI). Working towards a greenhouse gas neutral chemical industry in Germany 2019.
[30] Pöyry. Roadmap to reach carbon neutral industry by 2045 2020.
[31] Deloitte, iC2050 Project Report, 2021.
[32] BCG, Climate Paths 2.0: a Program for Climate and Germany's, Future Development (2021).
[33] Transition agenda Plastics 2018.
[34] R. Meys, A. Kätelhön, M. Bachmann, B. Winter, C. Zibunas, S. Suh, et al., Achieving net-zero greenhouse gas emission plastics by a circular carbon economy, Science 374 (2021) 71–76.
[35] D. Saygin, D. Gielen, Zero-emission pathway for the global chemical and petrochemical sector, Energies 14 (2021) 3772.
[36] L.S. Nowell, J.M. Norris, D.E. White, N.J. Moules, Thematic analysis, Int. J. Qual. Methods 16 (2017), https://doi.org/10.1177/1609406917733847.
[37] I.A. Bashmakov, L.J. Nilsson, A. Acquaye, C. Bataille, J.M. Cullen, S. de la Rue du Can, et al., Industry. In IPCC, 2022: climate change 2022: mitigation of climate change, in: Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, 2022, https://doi.org/10.1017/9781009157926.013.
[38] Plastics Europe. Plastics - the facts 2021 2021.
[39] K. Ragaert, L. Delva, K. Van Geem, Mechanical and chemical recycling of solid plastic waste, Waste Manage. 69 (2017) 24–58, https://doi.org/10.1016/j.wasman.2017.07.044.
[40] F. Bauer, T.D. Nielsen, L.J. Nilsson, E. Palm, K. Ericsson, A. Fråne, et al., Plastics and climate change—breaking carbon lock-ins through three mitigation pathways, One Earth 5 (2022) 361–376, https://doi.org/10.1016/j.oneear.2022.03.007.
[41] J. Huang, A. Veksha, W.P. Chan, A. Giannis, G. Lisak, Chemical recycling of plastic waste for sustainable material management: a prospective review on catalysts and processes, Renew. Sustain. Energy Rev. 154 (2022), 111866, https://doi.org/10.1016/j.rser.2021.111866.
[42] J. Huang, A. Veksha, W.P. Chan, A. Giannis, G. Lisak, Chemical recycling of plastic waste for sustainable material management: a prospective review on catalysts and processes, Renew. Sustain. Energy Rev. 154 (2022).
[43] R. Hatti-Kaul, L.J. Nilsson, B. Zhang, N. Rehnberg, S. Lundmark, Designing biobased recyclable polymers for plastics, Trends Biotechnol. 38 (2020) 50–67, https://doi.org/10.1016/j.tibtech.2019.04.011.
[44] IEA. Technology roadmap - energy and GHG reductions in the chemical industry via catalytic processes 2013.
[45] M. Babiker, G. Berndes, K. Blok, B. Cohen, A. Cowie, O. Geden, et al., Cross-Sectoral Perspectives. In IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel On Climate Change, Cambridge and, Cambridge University Press, New York, 2022, https://doi.org/10.1017/9781009157926.005.
[46] E. Palm, L.J. Nilsson, M. Åhman, Electricity-based plastics and their potential demand for electricity and carbon dioxide, J. Clean. Prod. 129 (2016) 548–555, https://doi.org/10.1016/j.jclepro.2016.03.158.
[47] E. Palm, A. Nikoleris, Conflicting expectations on carbon dioxide utilisation, Technol. Anal. Strateg. Manag. 33 (2021) 217–228, https://doi.org/10.1080/09537325.2020.1810225.
[48] Z. Yuan, M.R. Eden, R. Gani, Toward the development and deployment of large-scale carbon dioxide capture and conversion processes, Ind. Eng. Chem. Res. 55 (2016) 3383–3419, https://doi.org/10.1021/acs.iecr.5b03277.
[49] European Commission, Directorate-general for energy. COM/2020/301 final 2020.

[50] M. Bui, C.S. Adjiman, A. Bardow, E.J. Anthony, A. Boston, S. Brown, et al., Carbon capture and storage (CCS): the way forward, Energy Environ. Sci. 11 (2018) 1062–1176.
[51] S. L'Orange Seigo, S. Dohle, M Siegrist, Public perception of carbon capture and storage (CCS): a review, Renew. Sustain. Energy Rev. 38 (2014) 848–863, https://doi.org/10.1016/j.rser.2014.07.017.
[52] G.J. Nabuurs, R. Mrabet, A. Abu Hatab, M. Bustamante, H. Clark, P. Havlík, et al., Agriculture, Forestry and Other Land Uses (AFOLU). In IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel On Climate Change, Cambridge University Press, Cambridge and New York, 2022, https://doi.org/10.1017/9781009157926.009.
[53] Cefic. European chemistry for growth; Unlocking a competitive, low carbon and energy efficient future 2013.
[54] Wiertzema Holger, Svensson Elin, S. Harvey, Bottom–up assessment framework for electrification options in energy-intensive process industries, in: PROCEL Omställning Mot Koldioxidfria Industriella Processer Genom Ökad Elektrifiering Frontiers in Energy Research, 8, 2020.
[55] F. Creutzig, J. Roy, P. Devine-Wright, J. Díaz-José, F.W. Geels, A. Grubler, et al., Demand, Services and Social Aspects of Mitigation. Climate Change 2022 - Mitigation of Climate Change, Cambridge University Press, 2023, pp. 503–612, https://doi.org/10.1017/9781009157926.007.
[56] F. Meng, A. Wagner, A.B. Kremer, D. Kanazawa, J.J. Leung, P. Goult, et al., Planet-compatible pathways for transitioning the chemical industry, Proc. Natl Acad. Sci. 120 (2023), https://doi.org/10.1073/pnas.2218294120.
[57] Bauer F., Ericsson K., Hasselbalch J., Nielsen T., Nilsson L.J. Climate innovations in the plastic industry: prospects for decarbonisation 2018.
[58] P.G. Levi, J.M. Cullen, Mapping global flows of chemicals: from fossil fuel feedstocks to chemical products, Environ. Sci. Technol. 52 (2018) 1725–1734, https://doi.org/10.1021/acs.est.7b04573.
[59] CDP. Cascading commitments: driving ambitious action through supply chain engagement 2019.
[60] UNEP. Intergovernmental Negotiating Committee on Plastic Pollution n.d. https://www.unep.org/inc-plastic-pollution (Accessed September 28, 2023).
[61] UNEP. Zero draft text of the international legally binding instrument on plastic pollution, including in the marine environment. Nairobi 2023.
[62] Nilsson K. Nordregio news 1 2016 : industrial symbiosis 2016:12.
[63] B. Fagan-Watson, B. Elliott, T. Watson, Lobbying By Trade Associations On EU Climate Policy, 2015. London.
[64] LobbyFacts. lobbyfacts.eu n.d. https://www.lobbyfacts.eu/ (Accessed July 13, 2022).
[65] J. Markard, D. Rosenbloom, Political conflict and climate policy: the European emissions trading system as a Trojan Horse for the low-carbon transition? Climate Policy 20 (2020) 1092–1111, https://doi.org/10.1080/14693062.2020.1763901.
[66] A. Michaelowa, The politics of climate change in Germany: ambition versus lobby power, Wiley Interdiscip. Rev. Clim. Change 4 (2013) 315–320, https://doi.org/10.1002/wcc.224.
[67] InfluenceMap. European Chemical Industry Council (Cefic) n.d. https://lobbymap.org/influencer/CEFIC-d9d3710f40561dc4376930da7e0c5942/projectlink/European-Chemical-Industry-Council-CEFIC-In-Climate-Change (Accessed July 13, 2022).
[68] Cambridge University Press. agency. Cambridge advanced learner's dictionary & thesaurus n.d. https://dictionary.cambridge.org/dictionary/english/agency (Accessed September 28, 2023).
[69] Eurostat. Electricity prices for non-household consumers - bi-annual data (from 2007 onwards) 2022.
[70] Jones D. EU power sector in 2020, 2021.
[71] Samadi S., Lechtenböhmer S., Schneider C., Arnold K., Fischedick M., Schüwer D., et al. Decarbonization pathways for the industrial cluster of the port of Rotterdam 2016.