Pathways for the global chemical industry to climate neutrality

This report was written by ICIS and Carbon Minds and represents the outcome of a study commissioned by the International Council of Chemical Associations.

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Publication Details

ONE SENTENCE SUMMARY

This report uses the latest scientific modeling approaches and industrial expertise to identify four pathways and key enablers for the global chemical industry to reach climate neutrality.

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1 PREFACE

In the climate neutrality statement published in 2021, the International Council of Chemical Associations (ICCA) stated its support for the Paris Agreement and the ambition of the chemical industry to achieve climate neutrality by mid-century. To align with this statement, ICCA has commissioned this study to identify pathways and key enablers for the global chemical industry to reach climate neutrality.

The unique nature of the chemical industry leads to specific challenges in reaching climate neutrality. In particular, the chemical industry is a major manufacturing sector that is comprised of complex and energy-intensive operations that manufacture carbon-containing products that support our modern way of life.

Using a scientific modeling approach, this study explores different pathways that could lead to climate neutrality in a cost-minimal manner, giving particular focus on feedstock selection, sourcing and end-of-life management. These pathways consider uncertainties in future resource availability, the role of recycling, and other enabling technologies. In addition, the study also identifies key enablers necessary for the global chemical industry to reach climate neutrality.

The study is conducted at a globally aggregated level by ICIS and Carbon Minds. However, we trust the report will shed light on individual chemical companies, along with local and regional chemical associations, to work toward climate neutrality, although their pathways will ultimately reflect regional characteristics that are beyond the scope of this report.

2 EXECUTIVE SUMMARY

The International Council of Chemical Associations (ICCA), the global voice of the chemical industry, supports the Paris Agreement and the ambition to achieve climate neutrality by mid-century[1]. To reaffirm this ambition, ICCA has commissioned a study to identify potential pathways and key enablers (e.g., access to resources, infrastructure, and policies) for the global chemical industry to achieve climate neutrality[2]. This executive summary presents the key findings of the study.

BACKGROUND: TWO OF THE MAJOR CHALLENGES THE GLOBAL CHEMICAL INDUSTRY MUST OVERCOME: REDUCING GREENHOUSE GAS EMISSIONS FROM CARBON FEEDSTOCK[3] AND ENERGY USE.

The chemical industry today faces an environmental challenge due to the greenhouse gas (GHG) emissions generated by converting chemical feedstock (i.e., raw material to produce chemical products) into valuable carbon-containing products.. Chemical products frequently rely on carbon as a building block, making carbon-containing feedstock a critical input. Additionally, to convert these feedstocks into products, the chemical industry requires a large amount of process energy. Thus, GHG emissions are released in multiple steps across the chemical industry's value chain. These emissions can be primarily divided into feedstock-related and process energy-related emissions.

Feedstock, Process, and End-of-life Related Emissions (emissions related to Carbon Feedstock). Currently, most of the carbon-containing feedstock used in the chemical industry are fossil-based, including natural gas, coal, naphtha, and ethane. The extraction and refining processes for these feedstocks release GHGs, such as methane and CO_2. Emissions of GHG also occur during the conversion processes of these feedstock into chemical products. Additionally, at the end of the life cycle, if chemical products are not recycled and incinerated without CCS, the stored carbon is also released back into the atmosphere as GHG emissions.

Energy-Related Emissions. Chemical production is energy-intensive, often necessitating reaction temperatures above 500 degrees Celsius. These temperatures typically require fuel combustion, which, if unabated, leads to direct GHG emissions. Beyond using fuel combustion as a source of energy, grid electricity is also commonly used to power equipment and

[1] https://icca-chem.org/news/icca-statement-on-climate-policy/

[2] Climate neutrality in this study is defined according to IPCC's net-zero emissions definition. Therefore, climate neutrality is achieved when "anthropogenic emissions of greenhouse gases (GHG) to the atmosphere are balanced by anthropogenic removals over a specified period". These greenhouse gas emissions include carbon dioxide, methane, carbon monoxide, and nitrous oxides among others. IPCC (2018), https://doi.org/10.1017/9781009157940.008.

[3] Carbon feedstock as a terminology is used, since most chemical products use carbon as a backbone of their chemical structure. This carbon can originate from fossil resources, biomass, recycling plastic waste or CO_2.

operations in the chemical industry.

Thus, achieving climate neutrality in the chemical industry necessitates overcoming the dual challenge of reducing both process energy-related emissions and those stemming from the use of carbon-containing feedstock. The primary focus of this report is on emissions related to carbon feedstock, while energy-related emissions are included in the modeling and addressed at a high level.

METHODOLOGY: A COMBINATION OF SCIENTIFIC MODELING AND INDUSTRY EXPERTISE IS USED TO ANALYZE POTENTIAL PATHWAYS TOWARD A CLIMATE-NEUTRAL CHEMICAL INDUSTRY.

This project uses a scientific modeling approach, which has been previously applied in various peer-reviewed publications that assess a climate-neutral chemical industry[4]. Parts of these peer-reviewed publications have been reprinted in the industry chapter of the latest report of the Intergovernmental Panel on Climate Change (IPCC)[5]. The scientific modeling approach uses a life cycle assessment in combination with cost-minimization to create and assess pathways to climate neutrality for the chemical industry. To do so, technical, environmental, and economic parameters validated by industry experts are used.

This study covers eighteen large-volume chemicals[6] with an increasing projected global demand until mid-century. Per the life cycle approach, emissions from all major sources are accounted for, including the ones associated with (1) supply of process energy, (2) extraction of fossil resources, (3) production of chemical feedstock, (4) operation of chemical plants, and, finally, (5) the end-of-life of the products in the scope[7]. Along the value chain, the study considers emissions of all GHGs according to the IPCC, including CO_2 and methane[8]. This study does not include use phase emissions, to focus on activities closely related to the chemical industry.

To meet the production volume of large-volume chemicals, a wide set of production technologies is considered in a technology-neutral approach to ensure an economical transition to climate neutrality. This approach promotes flexibility by considering all available

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[4] Raoul Meys et al., Science (2021), https://doi.org/10.1126/science.abg9853; Arne Kätelhön et al., Proceedings of the National Academy of Sciences (2019), https://doi.org/10.1073/pnas.1821029116; Christian Zibunas et al., Computers & Chemical Engineering (2022), https://doi.org/10.1016/j.compchemeng.2022.107798.

[5] Bashmakov et al., 2022: Industry. 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 https://doi.org/10.1017/9781009157926.013.

[6] Methanol, ethylene, propylene, benzene, xylenes, toluene, styrene, chlorine, ammonia, hydrogen, ethylene oxide, ethylene glycol, LDPE, LLDPE, HDPE, PP, PET, PVC. Other chemicals that are part of these value chains (framed as "embedded products") have also been included.

[7] The life cycle assessment-based approach takes into consideration emissions from scope 1, 2 and 3. For scope 3, categories 3.1 and 3.12 are considered from the GHG Protocol for "purchased goods and "end-of-life" treatment, respectively. (Martin Barrow et al., https://ghgprotocol.org/scope-3-calculation-guidance-2)

[8] Intergovernmental Panel on Climate Change (IPCC), 2013, The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report, https://doi.org/10.1017/CBO9781107415324.

technologies[9] while minimizing capital expenditures and operating costs. Limiting certain technological choices would restrict the chemical industry's ability to address the challenges related to achieving climate neutrality and lead to higher costs, potentially making climate-neutral chemical products more expensive and delaying the wider societal shift to climate neutrality. Based on the unique combination of scientific modeling and industry expertise, results for multiple climate-neutral pathways are identified.

FINDING #1: MULTIPLE CLIMATE-NEUTRAL PATHWAYS EXIST FOR THE GLOBAL CHEMICAL INDUSTRY.

In navigating the complex landscape of the chemical industry's shift towards climate neutrality, a critical factor is the uncertainty surrounding the future availability of key resources such as biomass and carbon capture and storage capacities. To address this uncertainty and explore the range of possible futures, this study has developed four distinct scenarios based on the scientific modeling approach and industry feedback. These scenarios are crafted to represent varying resource availabilities and technological advancements, providing a nuanced and informed perspective on the industry's path forward. For each of the scenarios, a cost-minimal pathway to climate neutrality is calculated (cf. Figure 1).

	PATHWAY 1	PATHWAY 2	PATHWAY 3	PATHWAY 4
SCENARIO DESCRIPTION				
ACCESS TO BIOMASS	ABUNDANT	ABUNDANT	LIMITED	LIMITED
ACCESS TO CCS	ABUNDANT	LIMITED	ABUNDANT	LIMITED
COMMON IN ALL PATHWAYS	ACCESS TO NET-ZERO ENERGY, TECHNOLOGY AVAILABILITY, PLASTIC WASTE & FOSSIL FEEDSTOCK & OTHER AVAILABILITIES			

PATHWAY RESULTS

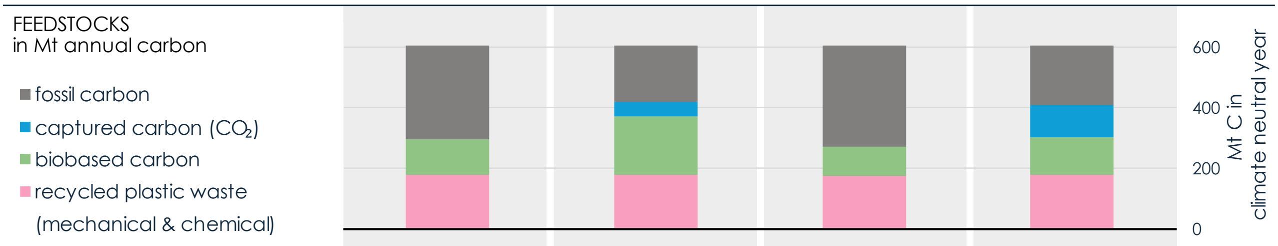

Figure 1: Scenario definitions and key results for four climate-neutral pathways for the climate-neutral year. The feedstock results highlight the universal role of plastic waste in addressing end-of-life emissions and reducing plastic pollution across all pathways. Additionally, the figure shows the varied use of biomass and fossil resources as carbon feedstocks in each pathway. Pathways #2 and #4, which have limited access to carbon capture storage (CCS), utilize carbon dioxide combined with low-emission hydrogen as an alternative carbon feedstock source.

The results highlight that no single fixed global pathway to climate neutrality exists and that pathways can vary depending on available resources, which are uncertain at present.

[9] We consider technologies with a technology readiness level above 6.

Each pathway leverages mitigation strategies in different combinations, reflecting adaptations to the available resources. Despite its global scope without regional granularity, the results show that varying access to key resources will result in differing pathways across regions and countries. Key solutions such as recycling technologies (mechanical and chemical), fossil feedstocks with carbon capture and storage (CCS), and biomass are, however, essential in all pathways.

FINDING #2: THE GLOBAL CHEMICAL INDUSTRY NEEDS ENABLERS FOR CLIMATE NEUTRALITY.

This study has developed four pathways that could lead the chemical industry to climate neutrality. Each pathway considers a combination of solutions, such as recycling and biomass as a feedstock. To unlock the potential, the chemical industry needs enablers from outside the chemical industry, which are also described in more detail in Chapter 8.

Access to plastic waste. Recycling reduces emissions from incineration and mismanaged waste. Currently, only 9% of global plastic waste is recycled[10]. To combat mismanaged plastic waste and achieve climate neutrality, recycling rates must significantly increase worldwide, supported by improved waste collection, sorting and distribution infrastructure, economic and market incentives, and implementing laws and policies.

Additionally, integrating chemical recycling alongside mechanical recycling is crucial. While mechanical recycling is resource-efficient, chemical recycling can handle a wider range of plastic wastes and overcome issues like polymer degradation. Using sorted plastic waste as a valuable feedstock, the chemical industry can reduce potential environmental impacts from incinerating plastic or mismanagement of plastic waste.

Sustainably sourced biomass. Biomass captures carbon dioxide from the atmosphere during its growth and can be transformed into various chemical products. This makes it a valuable feedstock to help the chemical industry reduce the overall GHG emissions particularly from its value chain including end-of-life incineration via CO_2 uptake during plant growth.

However, biomass must be sourced in a sustainable manner to avoid deforestation and biodiversity loss. Additionally, competition with food to support a growing global population must be avoided. Ultimately, for the chemical industry to utilize biomass, it must have reliable and affordable access to sustainably sourced biomass.

Low-emission hydrogen. Scalable alternatives to mitigate GHG emissions from current hydrogen production include water electrolysis powered by low-emission electricity and methane reforming with CCS. Low-emission hydrogen could reduce the GHG emissions associated with high-volume chemicals such as ammonia and methanol.

Furthermore, low-emission hydrogen supports carbon circularity by enabling the production of chemicals from captured CO_2, from industrial point sources (i.e., high volume or high

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[10] OECD, 2022, Global Plastics Outlook: Policy Scenarios to 2060, https://doi.org/10.1787/aa1edf33-en.

concentration emission from power plants or industries), or air through Carbon Capture and Utilization (CCU), thereby reducing CO_2 emission to the atmosphere or reducing atmospheric CO_2. Given the potential of low-emission hydrogen, the chemical industry requires supportive policy frameworks and permit processes to incentivize investment.

Fossil feedstock and adequately regulated carbon storage. All four pathways utilize fossil feedstocks in combination with CCS. To contribute to climate neutrality, CCS captures CO_2 at various points in the chemical value chain, including from end-of-life product incineration, and then transports CO_2 to long-term geological storage sites.

However, CCS implementation faces challenges, including lengthy planning and construction periods, substantial initial capital requirements for developing transport and storage infrastructure, and the need for public and stakeholder acceptance. Effective CCS deployment requires robust and durable policy support to facilitate investment in infrastructure and enhance public and stakeholder trust.

Affordable low-emission energy. As the industry transitions towards climate neutrality, low-emission energy becomes indispensable in production processes that require low-, mid-, and high-temperature heat and electricity. Different sources, including renewables, fossil fuels with CCS, and nuclear, can provide low-emission energy.

The exact combination of these sources will vary depending on locally available resources and the type of chemical reactions (e.g., those requiring low or high temperature), but each requires significant investment and policy support to enable such investment.

3 CHEMICAL PRODUCTS SUPPORT OUR LIFESTYLE

The chemical industry is responsible for the production of a multitude of products that are part of our everyday life as illustrated in Figure 2, right side. These products underpin society as we know it today, being present in sectors such as consumer goods, building and construction, agriculture, automotive, textile, healthcare, and many others. The chemical industry supports these sectors by providing raw materials, finished products, and enablers for other manufacturing activities.

The production processes in the chemical industry are based on a complex transformation value chain. Most of these processes start from the same building blocks, often referred to as basic chemicals (e.g., ethylene, propylene, mixed xylenes, benzene, ammonia, hydrogen, chlorine, and methanol). Using these basic chemicals, a diverse range of chemical derivatives and polymers (e.g., polypropylene, polyethylene, PET, PVC) is produced.

The products covered in this study are shown in Figure 2, left side. These products were chosen because of their importance in the chemical industry. According to an internal analysis, these products represent over 90% of the basic chemicals produced by the industry, while the derivatives and polymers included in the scope are responsible for over 70% of the consumption of these basic chemicals.

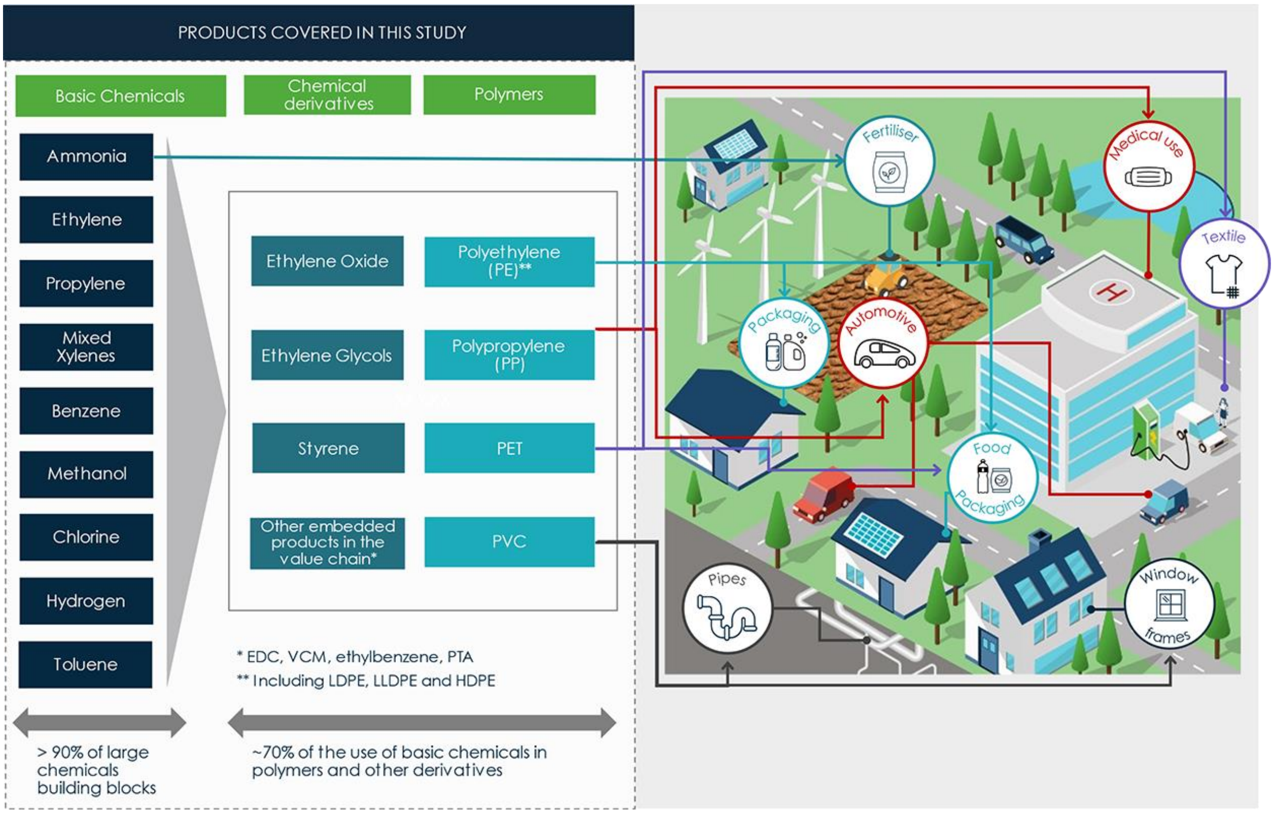

Figure 2: How different chemical products covered in this study are used in our daily lives. This image is not intended to be comprehensive about the products' applications.

Thanks to its role as a major manufacturing sector that supports and enables activities in several other sectors, the chemical industry is also an important contributor to the global economy. In 2017, the chemical industry accounted for $ 5.7 trillion through direct, indirect, and induced benefits, which represent 7% of global GDP. The sector is also responsible for supporting 120 million jobs worldwide, directly and indirectly.[11]

In addition to its importance for society and the global economy, the chemical industry can also play an essential role in the transition to climate neutrality, going beyond reducing GHG emissions associated with its own operations. By supplying low-impact, energy-saving, and emissions-reducing solutions, such as materials to improve insulation and lightweight, the chemical industry can support other sectors in reducing their GHG footprint and achieving climate neutrality.

[11] ICCA and Oxford Economics, 2019, "Catalyzing Growth and Addressing Our Worlds Sustainability Challenges Report."

4 A TWO-FOLD CHALLENGE: REDUCING EMISSIONS FROM FEEDSTOCK AND ENERGY USE

To provide a clearer understanding of how GHG emissions are distributed across the chemical value chain, an overview is presented in Figure 3. The chemical value chain starts from resource supply (energy and feedstock), followed by conversion processes, use phase, and end-of-life of chemical products. Within each of these stages, GHG emissions are released.[12]

The breakdown of GHG emissions according to the lifecycle stages was determined by Meng et al. for 2020 and is illustrated in Figure 3. The supply of feedstock and energy to the chemical industry represents a GHG emissions share of around 27% of the total chemical value chain in 2020. GHG emissions due to the conversion of feedstocks into chemical products (including the emissions from process energy) account for 46%. While GHG emissions from the resource supply and conversion processes can be determined with reasonable effort, the emissions related to product use and end-of-life can be more challenging to tackle, given the products' different applications in multiple sectors. Although challenging, end-of-life has been assessed as 27% of the total GHG emissions.[13]

Specifically, these GHG emissions in the various life cycle stages can be assigned to (1) feedstock and end-of-life-related and (2) process energy-related emissions.

Feedstock, Process, and End-of-life related emissions. Because most chemical products contain carbon, carbon is indispensable regardless of the type of feedstock used to make chemical products. As such, the chemical industry needs feedstock that contains carbon. The supply of fossil feedstock, for example, involves extraction and refining processes that release GHG, such as methane and CO_2. For biobased feedstocks, upstream sourcing would include the CO_2 uptake from the atmosphere and GHG emissions associated with the cultivation and processing for feedstock use. After the supply of feedstocks to the chemical industry, these feedstocks are processed in conversion processes to chemical products. During the conversion processes, GHG emissions could occur as well. Additionally, at the end of the life cycle, if chemical products such as plastics are incinerated, the stored carbon can be released back into the atmosphere as GHG emissions if the emissions are not

[12] The study uses a life cycle assessment-based approach. Some readers, however, might be more familiar with the methodologies of the GHG Protocol. The GHG Protocol subdivides GHG emissions into Scope 1, 2, and 3 categories. The underlying methodologies for life cycle assessments and GHG Protocol cannot be cleanly translated into each other. However, approximately, the values provided in Figure 3 can be categorized as the following: (1) the conversion process emissions correspond to a chemical company's Scope 1, (2) the indirect GHG emissions from a chemical company's purchased power, heating/cooling, or steam to Scope 2, and (3) the indirect feedstock supply and end-of-life emissions to Scope 3.1 and 3.12, respectively. Scope 3.1 and 3.12 represent direct emissions by other entities in the value chain that are upstream and downstream of chemical companies.

[13] Fanran Meng et al., *Proceedings of the National Academy of Sciences* https://doi.org/10.1073/pnas.2218294120.

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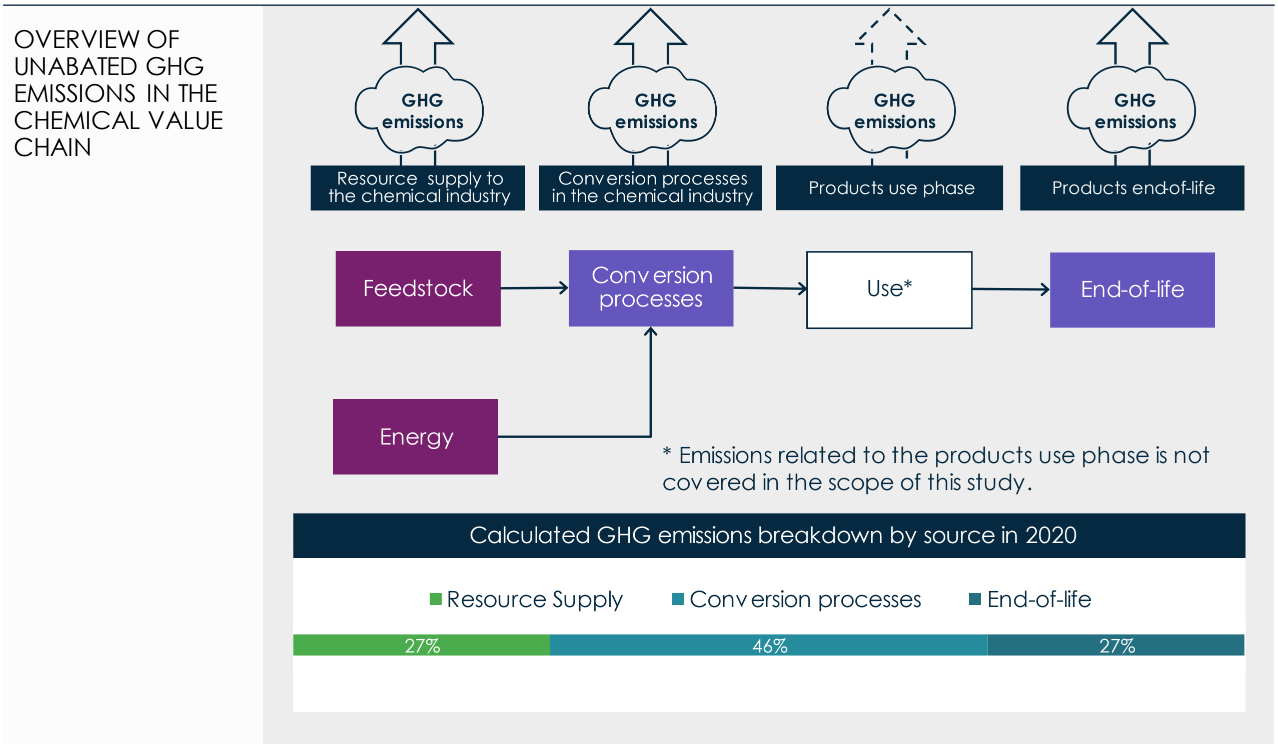

Figure 3: Overview of where the chemical industry's GHG emissions take place in the chemical value chain[14]. This study focuses on steps closely related to the chemical industry's activities. As such, it does not include the use phase of the products.

Energy-related emissions. Process energy presents an equally important input for chemical value chains since chemical production is energy-intensive, often necessitating reaction temperatures above 500 degrees Celsius. These high temperatures typically require fuel combustion. Sourcing and combustion of fuels can contribute to GHG emissions, if unabated. Besides thermal energy, the chemical industry also requires electricity. Electricity is commonly used to power equipment and operations in the chemical industry, and if it is powered by unabated fossil fuel, it also contributes to GHG emissions on a life cycle basis. Most of the production technologies in use by the chemical industry globally have been optimized to improve efficiency and resource consumption. However, most chemicals and polymer production currently rely heavily on unabated fossil-based feedstocks and energy, resulting in a GHG emissions reduction challenges.

Given the impact of feedstock-related and energy-related GHG emissions on the chemical industry, the use of alternative sources of energy and feedstock and abatement technologies represent a crucial part of the pool of feasible solutions for reducing GHG emissions and achieving climate-neutral operations (please see BOX 1).

[14] Fanran Meng et al., *Proceedings of the National Academy of Sciences* https://doi.org/10.1073/pnas.2218294120.

What does the term "climate neutral" mean in this study?

In this study, "climate neutrality" is defined according to IPCC's "net-zero emissions" definition. In other words, climate neutrality is achieved when "anthropogenic emissions and removals of greenhouse gases (GHG) to the atmosphere are balanced over a specified period of time," and therefore, there is no change in atmospheric GHG concentration. These GHG emissions include carbon dioxide, methane, carbon monoxide, and nitrous oxides, among others. In the context of the chemical industry, achieving climate-neutral operations indicates that GHG emissions resulting from the industry's key activities are reduced and that residual emissions are balanced via carbon absorption. A description of the scope of the GHG emissions covered in the study can be found in *Chapter 5 – The Scope of the Study*.

5 THE SCOPE OF THE STUDY

The scope of this study has been designed to provide the global chemical industry with a clear view of the challenges and opportunities for a global transition to climate-neutral operations. To do so, this study has combined academic rigor with market and industry expertise, leveraging the best available data and a robust modeling methodology to model cost-minimal pathways for the chemical industry to achieve climate neutrality. The key input parameters considered in the study are shown below:

Global chemical demand for key chemicals – The chemical industry is complex as it produces thousands of different chemical products globally, using many different manufacturing inputs, processes, and technologies. Table 1 lists the 18 products included in the scope of this study. They represent the industry's key building blocks and the largest polymers produced globally. Additionally, all intermediate products in the value chain of the 18 chemicals in scope are considered as well.

Table 1: List of products covered in the study. Intermediate products of the value chains have also been covered.

Ammonia	Methanol	Polypropylene (PP)
Benzene	Mixed xylenes	Polyethylene (LDPE)
Chlorine	Toluene	Polyethylene (LLDPE)
Ethylene	Styrene	Polyethylene (HDPE)
Ethylene glycol	Propylene	Polyvinylchloride (PVC)
Ethylene oxide	Hydrogen	Polyethylene terephthalate (PET)

Since this study focuses on achieving climate neutrality by mid-century, it is important to consider a forward-looking view of how demand for these products is expected to evolve globally. The product demand data used in this study is based on ICIS's long-term forecast, which covers each one of the products indicated in the above table. ICIS's methodology is based on an integrated analysis framework, starting with the end-use demand for chemical products, which in turn builds demand for intermediates, base chemicals, feedstock, and eventually crude oil and NGLs. Thanks to the presence of chemical products in diverse sectors of the global economy, macroeconomics (e.g., GDP growth) and demographics (e.g., population growth) have always been important drivers for chemical demand. However, product-specific factors such as shifts in applications and regulatory landscape are also important factors that have been accounted for in the forecast, together with trends in the corresponding end-use sectors.

As shown in Figure 4, demand for chemicals is expected to continue growing over the next decades, driven by global population growth, economic development, and an ever-evolving range of new applications. Demand for the four largest polymers[15] currently used globally is expected to grow at an annual average growth rate (CAGR) of 2.2% from 2020 to mid-century, in line with the expected GDP growth for the same period, but also considering specific developments in the key future applications. The demand for these polymers is expected to increase from 328 Mt in 2020 to 625 Mt by the climate-neutral year, while demand for basic chemicals[16] is expected to grow at 1.8% CAGR, increasing from 460 Mt to 796 Mt. This growth rate is lower than that of polymers due to enhanced recycling among other factors.

Ammonia, methanol, and hydrogen, key products today and in the future, are expected to grow at a CAGR of 2.4%, reaching 692 million tons over the same period. Demand for these products is assumed to be boosted by emerging applications related to energy transition, such as the use of methanol and ammonia as marine fuels and for power generation in some regions.

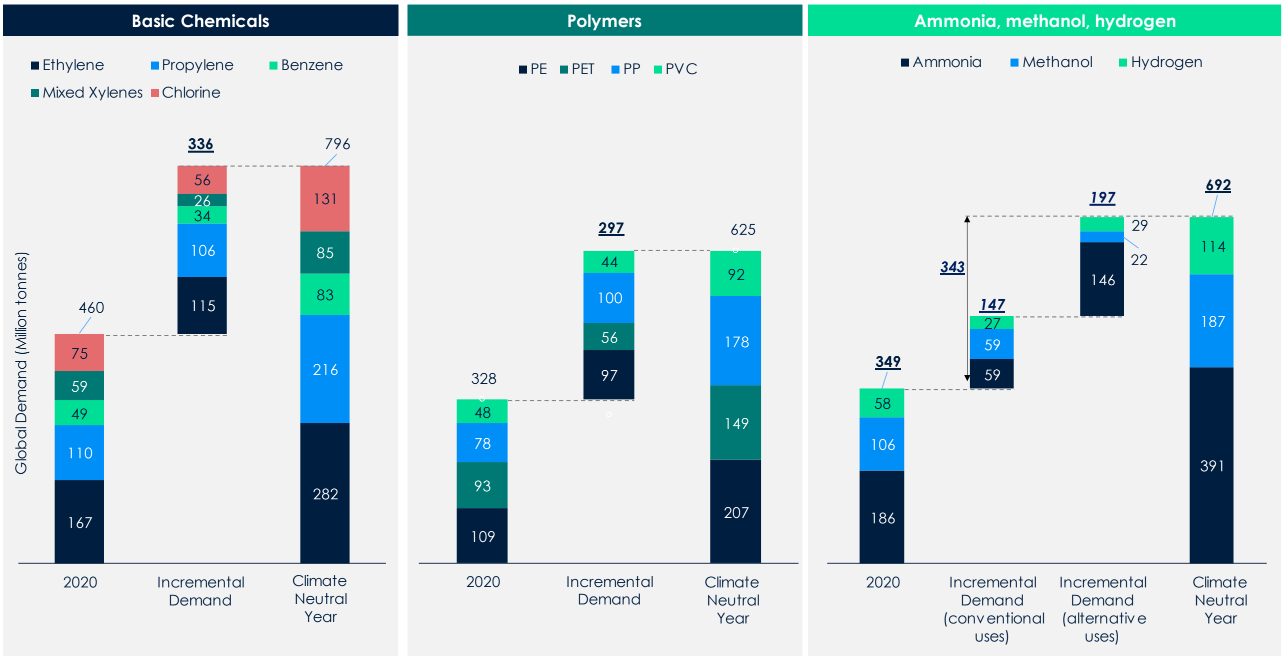

Figure 4: Chemicals and polymers demand forecast assumed in this study. The demand outlook considered in this study is based on ICIS's long-term forecast. The remaining products under the study scope, such as ethylene glycol, ethylene oxide, styrene, and toluene, are considered intermediates and have not been included in this chart for simplicity.

A global industry focus. This study focuses on providing a view of how the chemical industry can achieve climate neutrality at a globally aggregated level.

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[15] Four largest polymers: Polyethylene (PE), Polypropylene (PP), Polyethylene Terephthalate (PET) and Polyvinyl Chloride (PVC).

[16] Basic chemicals: ethylene, propylene, benzene, mixed xylenes, chlorine.

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Multiple potential pathways for the chemical industry to achieve climate neutrality. While the chemical industry aims to achieve climate-neutral operations globally, there is great uncertainty regarding the future availability of resources that are key for the industry's transition to climate neutrality. As a result, different cost-minimal pathways were studied, considering different assumptions on the availability of key resources.

Life Cycle Impact Assessment (LCIA) method and emissions scope. The GHGs considered in this study include carbon dioxide, methane, and nitrous oxides, among others, following IPCC[17]. The life-cycle assessment-based approach utilized in the study considers GHG emissions for extraction and/or cultivation of resources, manufacturing, and end-of-life. Please note that use phase emissions are excluded from the study.[18]

Conventional and alternative technologies to achieve climate neutrality. The transition to climate neutrality will require the chemical industry to leverage not only the conventional, well-established production processes but also alternative technologies focused on reducing emissions. While numerous different processes are currently being developed, this study focuses on alternative technologies characterized by high technology readiness levels that were selected via discussions with industry representatives. The alternative technologies considered in the study are summarized below in Figure 5.

Alternative technologies considered

End-of-life Technologies

Recycling
- Mechanical Recycling
- Chemical Recycling

Other
- Incineration with energy recovery
- Incineration with energy recovery and CCS
- Landfilling

CO_2 and H_2 Technologies

Carbon Capture and Utilization (CCU)
- CO_2 capture from industrial point sources
- CO_2 capture via direct air capture (DAC)
- Hydrogen via electrolysis
- Hydrogen production via natural gas including CCS
- CO_2 to methane
- CO_2 to methanol
- Methanol to olefins/BTX

Carbon Capture and Storage (CCS)
- CCS with CO_2 from industrial point sources
- Hydrogen production via natural gas with CCS

Biomass Technologies

Biomass fermentation
- Bioethanol via fermentation
- Ethanol dehydration to ethylene

Biomass gasification
- Biomass gasification to syngas
- Methanol to olefins/BTX

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[17] Intergovernmental Panel on Climate Change (IPCC), 2013, The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report, https://doi.org/10.1017/CBO9781107415324.

[18] The study uses a life cycle assessment-based approach. Some readers, however, might be more familiar with the methodologies of the GHG Protocol. The GHG Protocol subdivides GHG emissions into Scope 1, 2, and 3 categories. The underlying methodologies for life cycle assessments and GHG Protocol cannot be cleanly translated into each other. However, approximately, the following categories are included in the study: (1) direct Scope 1 emissions of all chemical company processes covered, (2) indirect Scope 2 emissions from purchased power, heating/cooling, and steam, (3) indirect Scope 3.1 emissions from the feedstock supply, and (4) indirect Scope 3.12 emission of the end-of-life emissions. Scope 3.1 nad 3.12 represent direct emissions by other entities in the value chain that are upstream and downstream of individual chemical companies.

Figure 5: Alternative technologies considered in the study.

Capital expenditures (CAPEX) and operating costs (OPEX). Economics is a crucial factor in the transition to climate neutrality. Both CAPEX and OPEX were estimated in the modeling. Best-available references have been used, including feedstock market prices in the case of OPEX. See Chapter 7 under annual operating costs & cumulative capital expenditures for more information about the costs.

Climate-neutral pathways definition

Four different pathways for the chemical industry to achieve climate neutrality have been modeled in this study, showing that there is not one single global pathway but multiple potential pathways. As the different availability of key resources leads to different pathways, it is reasonable for each region to implement a different strategy according to the availability of key resources in the region, the installed infrastructure, economic factors, and the policy landscape in place.

For each scenario, a different set of assumptions regarding the availability of biomass and CCS was used to factor in uncertainty regarding the future availability of these resources on a global scale for the chemical industry. Plastic waste, however, was assumed to be a resource equally available across all the pathways. Plastic recycling is considered essential in reducing mismanaged plastic waste and GHG emissions from unabated incineration. Therefore, ambitious recycling rates have been assumed across all the pathways. To enable all the pathways, full access to low-emission electricity was assumed. The pathways are described below and summarized in Figure 6.

- **Pathway #1: Abundant biomass and CCS** – in this pathway, biomass and carbon capture and storage (CCS) are assumed to be abundantly available for the chemical industry;
- **Pathway #2: Abundant biomass and limited CCS** – in contrast with pathway #1, this pathway assumes that the availability of CCS for the chemical industry is limited, while biomass availability is the same as in pathway 1;
- **Pathway #3: Abundant CCS and limited biomass** – this pathway assumes that the availability of biomass is limited, while CCS capacity is the same as in pathway 1;
- **Pathway #4: Limited biomass and CCS** – pathway 4 represents the case where the availability of both biomass and CCS for the chemical industry is limited.

Considering these different resource availabilities, we determined the optimal production process mix to meet the global demand for chemicals while minimizing costs and gradually limiting GHG emissions so that climate-neutral operations can be achieved by the mid-century. The results obtained are shown in Chapter 7.

	PATHWAY 1	PATHWAY 2	PATHWAY 3	PATHWAY 4
	SCENARIO DESCRIPTION			
ACCESS TO BIOMASS	ABUNDANT	ABUNDANT	LIMITED	LIMITED
ACCESS TO CCS	ABUNDANT	LIMITED	ABUNDANT	LIMITED
COMMON IN ALL PATHWAYS	ACCESS TO NET-ZERO ENERGY, TECHNOLOGY AVAILABILITY, PLASTIC WASTE & FOSSIL FEEDSTOCK & OTHER AVAILABILITIES			

Figure 6: Summary of resource availability in different pathways.

6 MODELING CLIMATE-NEUTRAL PATHWAYS – THE SCIENTIFIC BASIS

This study combines broad industry expert knowledge from various chemical production regions with a scientific modeling approach. Central to this scientific modeling approach is the use of a scientific life cycle assessment-based cost-minimization methodology tailored for the chemical industry. This methodology has already been used for several peer-reviewed journal articles in prestigious journals such as Science, PNAS, or Nature[19]. Moreover, previous results based on this scientific modeling approach have been reprinted in Chapter 11 for Industry in the latest report by the Intergovernmental Panel on Climate Change in 2022 (IPCC)[20]. While a full description of the modeling approach can be provided upon adequate request, a simplified description is provided below.

In essence, the scientific modeling approach identifies cost-minimal climate-neutral pathways for the global chemical industry over a certain timeframe, i.e., from a reference year until the year in which climate neutrality is achieved. The determination of these cost-minimal pathways is done by using a linear cost-minimization model, which minimizes the total costs of all processes across the life cycle of the chemical products in scope to achieve a certain annual greenhouse gas emission target. The total costs in each year include capital expenditures (CAPEX) and operating costs (OPEX). CAPEX covers all investments relating to the plant itself and the infrastructure required to operate the plant, while OPEX covers both variable and fixed operating costs. Variable operating costs in the model reflect market prices for feedstocks, energy, and utilities sourced externally from the chemical industry. Fixed operating costs include expenses such as maintenance, general administration, plant overhead, taxes, insurance, laboratory services, and other related costs.

The scientific modeling approach accounts for all GHG emissions defined by the IPCC, such as CO_2 and methane,[21] while assuming annual emission limits. The annual emission limit refers to the GHG emissions every year during the timeline and is based on the agreed assumptions of ICCA, Carbon Minds, and ICIS.

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[19] Raoul Meys et al., Science (2021), https://doi.org/10.1126/science.abg9853; Arne Kätelhön et al., Proceedings of the National Academy of Sciences (2019), https://doi.org/10.1073/pnas.1821029116; Christian Zibunas et al., Computers & Chemical Engineering (2022), https://doi.org/10.1016/j.compchemeng.2022.107798.

[20] Bashmakov et al., 2022: Industry. 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 https://doi.org/10.1017/9781009157926.013.

[21] Intergovernmental Panel on Climate Change (IPCC), 2013, The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report, https://doi.org/10.1017/CBO9781107415324.

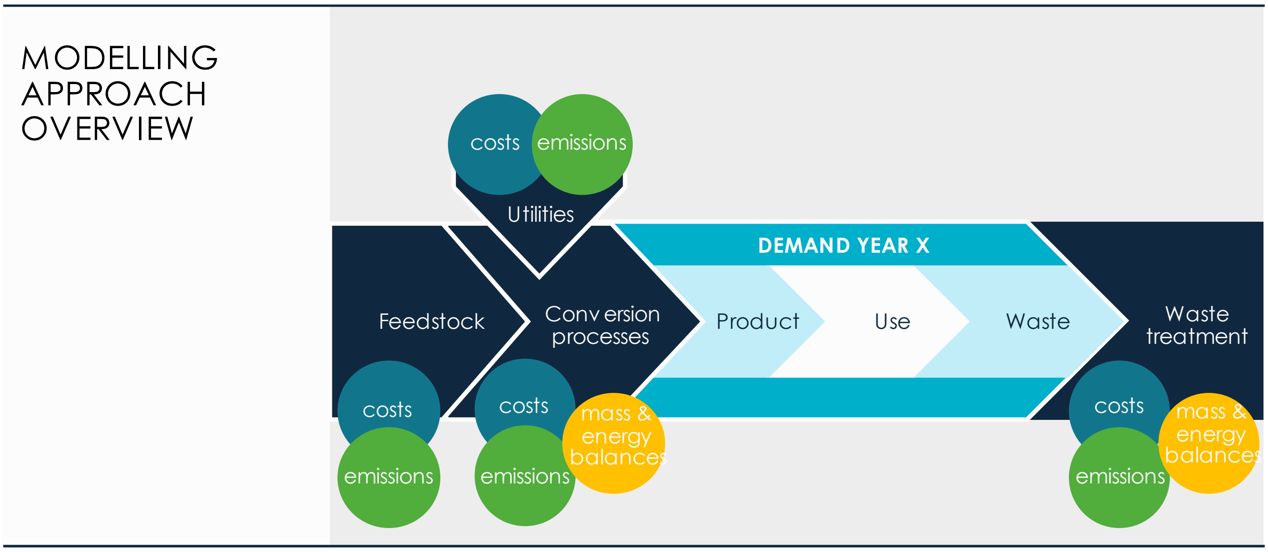

Figure 7: Scientific modeling approach for cost-minimal climate-neutral pathways for chemical value chains.

To achieve realistic climate-neutral pathways, this scientific modeling approach also utilizes detailed models of the chemical value chain each year, from feedstock over chemical production to waste treatment (cf. Figure 7). These models are based on detailed mass and energy balances for feedstock, conversion processes, and waste treatment associated with the 18 chemicals in scope. For instance, methanol can be produced from synthesis gas, using electricity, steam, and thermal energy to provide process energy, as well as utilities such as cooling and process water. As feedstock, methanol production requires coal or natural gas, for example. Both process energy and feedstock are produced by other processes in the model, meaning that supply processes will be used to supply these in a cost-minimal manner. Thus, the detailed mass and energy balances are used to find the exact combination or processes to fulfill the final demand and emission limitations throughout the timeline without leaving any supply of a feedstock or energy source unaccounted for.

While each year has a specific annual demand for chemical products and waste as well as a certain emission limitation, the value chains are defined on an annual basis. Between the years, "mathematical linkages" account for the temporal dependencies between the years.[22] These temporal dependencies, for instance, ensure that only capacities built until a specific year are operational in subsequent years.

Finally, the expected availability of alternative feedstock, such as biomass and sorted plastic waste, as well as the expected CCS capacities, are included on a yearly basis in the scientific modeling approach to reflect different boundary conditions in the future. These boundary conditions, for instance, reflect situations in which a certain technology or

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[22] Christian Zibunas et al., Computers & Chemical Engineering (2022), https://doi.org/10.1016/j.compchemeng.2022.107798.

feedstock is not available or available in lower amounts than expected. In this way, the scientific modeling approach enables the development of various scenarios and assumptions to represent different future chemical industry setups.

While the scientific modeling approach is comprehensive and capable of identifying multiple climate-neutral pathways for the chemical industry, the scope of this study is focused on four possible cost-minimal climate-neutral pathways. For each one of these, results obtained from the model, including GHG emissions, the breakdown of carbon feedstock by type, the energy demand, and the cumulative costs, are shown for a climate-neutral chemical industry in mid-century.

7 MULTIPLE CLIMATE-NEUTRAL PATHWAYS EXIST FOR THE GLOBAL CHEMICAL INDUSTRY

Our results show that climate neutrality for the global chemical industry is possible via all four pathways. These four pathways represent the diversity of products and production processes used across the chemical sector, as well as uncertainty in future feedstock availability, policies, infrastructure, and economics, e.g., prices of resources and energy. All these parameters are likely to vary across regions. For this reason, the global and regional chemical industry cannot be represented by one single climate-neutral pathway and one single set of results. Figure 8 provides a high-level overview of pathway-specific parameters, such as access to uncertain key resources like CCS and biomass, as well as parameters common among all pathways. All subsequent results of this study are shown for a climate-neutral year, defined as a specific year in the mid-century in which climate neutrality is achieved. For this climate-neutral year, we highlight how climate neutrality is achieved, the total process energy demand, the carbon feedstock consumption, the annual OPEX, and the cumulative CAPEX.

	PATHWAY 1	PATHWAY 2	PATHWAY 3	PATHWAY 4
	SCENARIO DESCRIPTION			
ACCESS TO BIOMASS	ABUNDANT	ABUNDANT	LIMITED	LIMITED
ACCESS TO CCS	ABUNDANT	LIMITED	ABUNDANT	LIMITED
COMMON IN ALL PATHWAYS	ACCESS TO NET-ZERO ENERGY, TECHNOLOGY AVAILABILITY, PLASTIC WASTE & FOSSIL FEEDSTOCK & OTHER AVAILABILITIES			

Figure 8: Description of individual climate-neutral pathways.

ACHIEVING CLIMATE NEUTRALITY

Figure 9 presents a snapshot of how emissions and absorption into/from the atmosphere balance when the global chemical industry reaches climate neutrality across various pathways. The figure provides a detailed comparison with dual bars for each pathway: one bar representing the greenhouse gas emissions and the other bar the greenhouse gas emission absorption in giga-ton (Gt) CO_2-equivalents[23]. For example, if biobased (or DAC-CCU) chemicals are produced and incinerated in the climate-neutral year, the absorption (from plant growth or DAC-CCU) will be shown as a negative bar, and the emission will be shown as a positive bar to end up in net-zero GHG emissions. In contrast, because CCS does not

[23] CO_2-equivalents, or carbon dioxide equivalent, is a metric used to compare the emissions of various greenhouse gases based on their global warming potential relative to that of carbon dioxide. Intergovernmental Panel on Climate Change (IPCC), 2013, The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report, https://doi.org/10.1017/CBO9781107415324.

emit or absorb emissions into/from the atmosphere, it does not appear in either bar and is shown separately. The first bar represents feedstock and energy-related GHG emissions. Feedstock-related emissions include GHG related to the supply of feedstocks (extraction and refining processes), the conversion processes from feedstocks to chemicals, and the end-of-life. Energy-related emissions stem from the supply of energy in the chemical value chains. In Figure 9, the energy-related and feedstock-related emissions from extraction and refining processes are summarized as GHG emissions from resource supply. Therefore, the emissions bar reflects only the residual emissions — those not captured, utilized, or stored within the industry. These residual emissions may result from incomplete capture due to technological limitations or limited capture rates, economic viability of CO_2 capture, or other non-captured greenhouse gas emissions. To achieve climate neutrality, it is essential to deal with residual emissions that are not captured. The right bar in Figure 9 illustrates the CO_2 absorbed from the atmosphere, primarily through mechanisms like biomass growth and direct air capture. This captured CO_2, whether sourced from biomass or directly from the air, serves as a critical carbon feedstock in the pathways. Distinct from the residual emissions mitigated through CO_2 absorption mechanisms, the CO_2 that is captured from processes is sequestered in geological formations. This is quantified in Figure 9, where the annual amount of geological CO_2 storage is depicted beneath the bar diagram for each individual pathway.

Within our model, CO_2 geological storage capacity serves as a pivotal constraint. Despite the existence of extensive geological formations suitable for storage, the projected capacity is significantly influenced by various challenges. These include the difficulties associated with planning and constructing storage facilities, the substantial initial investments required, and the imperative for regulatory frameworks to support the development of CO_2 transport and storage infrastructure. According to the Energy Transitions Commission (ETC), the potential capacity for geological storage, including the use of enhanced oil recovery techniques, could reach up to 5 Gt per year of CO_2[24]. Nevertheless, not all this capacity will be directly available to the chemical industry. Our model conservatively assigns 25% to 50% of the total CO_2 storage capacity to the chemical industry, based on a comprehensive process of screening scientific literature and engaging in discussions with industry stakeholders. This method is intended to clarify the uncertainty surrounding the potential availability of CO_2 storage against the backdrop of projected capacities, emphasizing the critical gap between theoretical potential and actual availability. The distinction in CCS capacity plays a crucial role in shaping the emission profiles and mitigation strategies across the four pathways. Pathways 1 ("Abundant biomass & CCS") and 3 ("Abundant CCS") leverage a more generous CCS capacity, enabling a higher volume of CO_2 to be captured and stored. The annual capacity of about 2.5 Gt CO_2 storage is fully utilized in both pathways. This advantage translates into reduced atmospheric emissions, with the bulk of these emissions stemming from the conversion processes within the chemical value chain and the supply

[24] Energy Transitions Commission, "Carbon Capture, Utilisation and Storage in the Energy Transition: Vital but Limited," 2022, https://www.energy-transitions.org/publications/carbon-capture-use-storage-vital-but-limited/.

of resources. In pathways 1 and 3, the high CO_2 storage use leads to CO_2 absorption via biomass only, with no CO_2 directly absorbed from the atmosphere via Direct Air Capture.

In contrast, pathways 2 ("Abundant biomass and limited CCS") and 4 ("Limited biomass & CCS") must cope with stricter CCS restrictions. These restrictions lead to comparatively higher emissions, which are particularly noticeable in the end-of-life phase of the industry's value chain. While pathway 4 ("Limited biomass & CCS") still majorly uses its storage capacities for end-of-life emissions from the incineration of chemicals and plastics, the GHG emissions from the end-of-life phase are lower compared to pathway 2. In pathway 2 ("Abundant biomass and limited CCS"), the 1.1 Gt CO_2 storage capacity is mainly used to store biogenic CO_2 emissions from fermentation and gasification of biomass. To avoid these restrictions and still achieve climate neutrality, the dependence on biomass growth and the strategic application of direct air capture increases compared to pathways 1 and 3.

Adhering to a technology-neutral approach, our model does not impose a cap on direct air capture capabilities, recognizing its potential scalability and flexibility. However, the use of biomass, while crucial for the chemical industry as a renewable carbon feedstock, presents its own set of challenges. These include land competition, which poses risks to food security amid a growing global population and threatens biodiversity. Consequently, biomass is treated as a constrained resource within our model to ensure its sustainable utilization. Through an extensive review of scientific literature and a comprehensive stakeholder engagement process, we have determined the sustainable availability of biomass to be between 8.5 EJ and 37.4 EJ per year for the pathways with less and more abundant biomass, respectively. This constraint ensures that the use of biomass in the chemical industry remains within sustainable limits, reflecting a careful balance between environmental, social, and industrial needs.

Pathway 2 capitalizes on its abundant access to biomass resources, enabling it to accommodate relatively higher residual emissions within its strategy toward climate neutrality. This abundant biomass access serves as a robust buffer, effectively absorbing greater amounts of CO_2 through natural processes. In contrast, pathway 4, constrained by limited biomass, must adopt a more stringent approach to emissions management. This limited access to biomass carbon feedstock in pathway 4 necessitates a reduction in residual emissions and a greater reliance on direct air capture technologies. These technologies are essential for supplementing the pathway's carbon feedstock requirements, ensuring that the chemical industry can achieve climate neutrality by compensating for the shortfall in biomass-derived carbon.

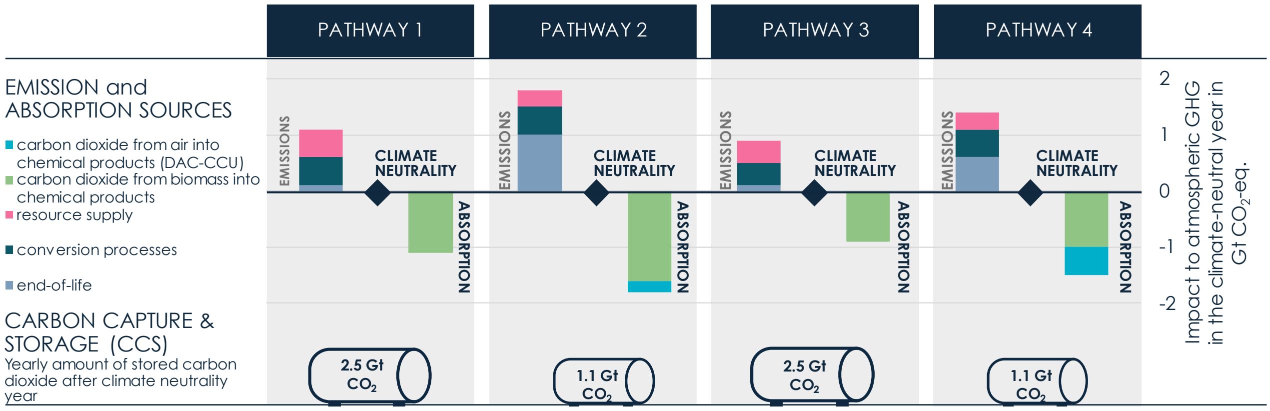


Figure 9: Top figure - Impact on atmospheric GHG in the climate neutrality year. Residual emissions from life-cycle stages are balanced by CO_2 absorption from biomass growth or from air directly via direct air capture. Bottom figure – Yearly amount of stored carbon dioxide in geological formations when the climate neutrality year is reached.

CARBON FEEDSTOCKS CONSUMPTION

Figure 10 shows the breakdown by source of carbon to produce the carbon-containing basic chemicals (ethylene, propylene, benzene, toluene, xylenes, and methanol) in the climate-neutral year. This total amount of basic chemicals consists of approximately. 600 Mt of carbon, as shown on the y-axis. These basic chemicals are used to produce all other carbon-based products in scope, such as polyethylene or polypropylene. Besides the basic chemicals, the carbon feedstock required to produce ammonia is shown. While ammonia does not contain carbon itself, the hydrogen used to produce ammonia in some pathways is still derived from natural gas, a carbon-containing feedstock. To highlight the differences in the pathways, the sources of carbon are highlighted. These sources comprise recycled carbon, biogenic carbon, air-captured carbon, and fossil carbon.

Recycled carbon results from mechanical and chemical recycling of plastic waste. While chemical recycling replaces chemical feedstocks, such as naphtha, mechanical recycling produces recycled granulates for plastics production. These recycled granulates reduce the amount of basic chemicals required to produce plastics.

Biobased carbon is derived from processing biomass, such as agricultural waste or dedicated energy crops, into valuable feedstocks for chemical production. For instance, ethanol is produced through the fermentation of biomass, which is then dehydrated catalytically to form ethylene, a fundamental building block in the chemical industry. Additionally, biomass can be converted into methanol through a process of gasification into syngas, followed by methanol synthesis. This methanol can then be further processed into olefins and aromatics using methanol-to-olefins/aromatics technologies. This versatility makes biomass a highly adaptable and essential input for various chemical manufacturing processes.

Captured carbon (CCU), sourced from Direct Air Capture (DAC) or industrial point sources, plays a significant role in the reduction of greenhouse gas emissions. Industrial point sources encompass a range of processes such as steam methane reforming for hydrogen production, high CO_2 emitting processes like ethylene oxide production, and biomass conversion processes like fermentation and gasification. Particularly, when CO_2 is captured from biomass conversion, it leads to an increase in carbon utilization efficiency within the system. This captured CO_2 is then combined with low-emission hydrogen to produce valuable CO_2-based chemicals, such as methanol and methane.

Fossil carbon comes from fossil feedstocks, such as naphtha, natural gas, ethane, and propane.

Recycled carbon is used to the maximum extent possible in all pathways, representing 176 to 177 Mt carbon in the climate-neutral year. These amounts are derived from the future recycling rate that is needed to minimize mismanaged plastic waste, according to the OECD's Global Ambition policy scenario[25], although there will be other possible policy sets to achieve this target. The respective recycling rates of the OECD are applied to the plastics in scope[23], polyethylene (LD, LLD, HD), polypropylene, polyethylene terephthalate (PET), and polyvinyl chloride (PVC). Other plastics, such as polystyrene, polyamide, polycarbonates, and polyurethanes, are not covered and, thus, might provide some additional recycling potentials not included in this study. The increase in recycling rates requires the implementation of chemical recycling alongside mechanical recycling. While mechanical recycling is resource-efficient, chemical recycling can handle a wider range of plastic wastes and overcome issues like polymer degradation. Using sorted plastic waste as a valuable feedstock, the chemical industry can greatly reduce its environmental footprint. The environmental benefits of recycling not only refer to GHG emission reductions for the chemical value chain[26] but also mitigate pollution from otherwise mismanaged plastic waste. Therefore, achieving higher recycling rates worldwide, supported by improved waste collection and sorting infrastructure and economic incentives, contributes to climate change mitigation and reduces pollution of ecosystems such as the ocean.

The use of biobased carbon varies among the pathways between 95 to 193 Mt carbon. Biomass availability is limited in pathways 3 and 4 ("Abundant CCS and Limited biomass & CCS"), while pathways 1 and 2 have abundant access to biomass ("Abundant biomass & CCS" and "Abundant biomass"). In all pathways, the fermentation of biomass is used to the maximum extent, delivering 118 Mt carbon in pathways 1 and 2 with abundant biomass and 27 Mt carbon in pathways 3 and 4 with limited access to biomass. In addition to fermentation, pathways 2, 3, and 4 use biomass gasification, representing 75 Mt carbon ("Abundant biomass"), 68 Mt carbon ("Abundant CCS"), and 97 Mt carbon ("Limited

[25] OECD, 2022, Global Plastics Outlook: Policy Scenarios to 2060, https://doi.org/10.1787/aa1edf33-en.

[26] Jeswani, Harish, et al. "Life cycle environmental impacts of chemical recycling via pyrolysis of mixed plastic waste in comparison with mechanical recycling and energy recovery." Science of the Total Environment 769 (2021): 144483.

Hermanns, Ronja, et al. "Comparative life cycle assessment of pyrolysis–recycling Germany's sorted mixed plastic waste." Chemie Ingenieur Technik 95.8 (2023): 1259-1267.

biomass & CCS"). Gasification is mainly used to produce biobased propylene and benzene via methanol-to-olefine and methanol-to-aromatics processes. The utilization of gasification varies between the pathways, influenced by other options to produce propylene and benzene. For instance, in pathway 2 ("Abundant biomass"), only benzene is produced via gasification, while propylene is produced from biobased ethylene from fermentation. In pathway 3, with abundant CCS capacities, benzene, and propylene are produced from fossil feedstocks.

Captured carbon is used in pathways 2 and 4 with limited access to CSS ("Abundant biomass" and "Limited biomass & CCS"), representing 49 and 106 Mt carbon, respectively. In both pathways, methane is produced from captured CO_2 and low-emission hydrogen. This methane goes into the natural gas pipelines and processes and replaces 66% and 80% of the total natural gas demands. In pathway 2 ("Abundant biomass"), the captured carbon is only used for the production of methane (49 Mt carbon), while in pathway 4 ("Limited biomass and CCS"), the captured carbon is used to produce methane (89 Mt carbon) and methanol (17 Mt carbon). Methanol is further used to cover the methanol demand and produce basic chemicals, such as olefins and benzene.

Finally, fossil carbon still presents one of the largest carbon feedstocks in the climate-neutral year with 186 to 335 Mt carbon. These large proportions of fossil feedstocks are only possible through the use of CCS in all pathways (see Figure 10). For this reason, the abundant CCS pathways ("Abundant biomass & CCS", 60% and "Abundant CCS", 63%) use significantly more fossil carbon than the limited CCS pathways ("Abundant biomass", 31% and "Limited biomass & CCS", 33%). However, in all pathways, the CCS is used to the maximum extent, limited due to set limitations of storage capacities ("Abundant biomass" and "Limited biomass & CCS") or due to technical limitations ("Abundant biomass & CCS" and "Abundant CCS"). The maximum utilization of CCS potentials in the pathways with abundant CCS increases the use of fossil carbon so that fossil carbon can also be used for more than just carbon-containing chemicals. Here, fossil carbon is also used to produce natural gas-based ammonia (fossil carbon for ammonia), accounting for 139 and 131 Mt additional fossil carbon demand in the "Abundant biomass & CCS" and "Abundant CCS" pathways, respectively.

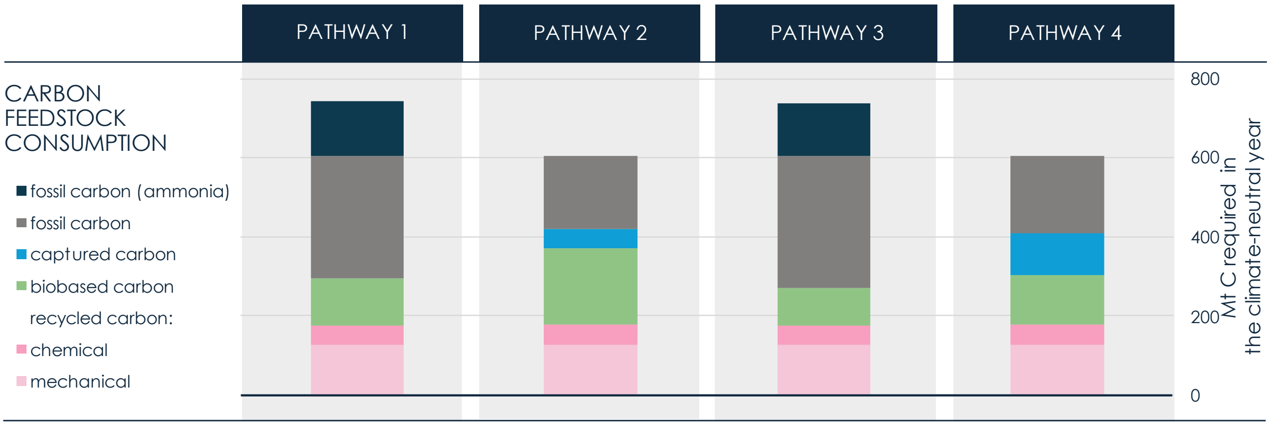


Figure 10: Breakdown of required carbon feedstock consumption in the climate-neutral year to produce the demand for basic chemicals in scope. Carbon feedstocks in the climate-neutral year are measured in Mt carbon, which is defined as recycled carbon (mechanical and chemical), biobased carbon, fossil carbon, and fossil carbon for ammonia production. Note that fossil carbon required for ammonia production in certain pathways, which is not included in Figure 1, is included here.

TOTAL PROCESS ENERGY DEMAND

Figure 11 shows a snapshot of the breakdown of total energy demand, which can be broken down into low-emission electricity and thermal energy in the climate-neutral year. The thermal energy consists of low-, medium-, and high-temperature heat, defined by temperatures under 200°C, between 200°C and 500°C, and above 500°C, respectively. This total process energy demand includes all required energy input for operating the processes in the chemical industry, from the production of basic chemicals via processing to chemical products to end-of-life processes like recycling. The upper diagram of Figure 11 presents the total process energy demand in EJ for the climate-neutral year in each pathway. The bottom of Figure 11 shows the additional electricity demand to produce low-emission hydrogen in each pathway.

The demand for low- and medium-temperature heat remains constant across all pathways. Low- and medium-temperature process energy is employed in numerous chemical processes, e.g., processing basic chemicals to plastics. Additionally, low- and medium-temperature heat is required in emerging processes, such as for the regeneration of CO_2 capture catalysts. Low- and medium-temperature process energy can be supplied from various sources, ranging from direct firing of fossil fuels combined with CCS or biomass, nuclear energy, or low-emission electricity via heat pumps, resistance heaters, or steam boilers.

In contrast, the demand for high-temperature thermal energy differs among the pathways while always representing the biggest portion. High-temperature thermal energy requires combustion to reach desired temperatures, e.g., in steam crackers for the production of basic chemicals. Combustion energy can be provided via several sources, including fossil fuels and fuel gases from chemical processing combined with CCS, biomass, or low-emission hydrogen. Therefore, the best source of energy depends on regional availability and process design. Pathways 1 and 3 show a higher reliance on high-temperature process energy, majorly for the production of ammonia and basic chemicals produced from fossil feedstocks like natural gas or naphtha. Pathways 2 and 4, in contrast, have limited access to CCS and thus require massive additional electricity to produce low-emission hydrogen for ammonia, carbon capture and utilization, and other hydrogen demands.

Low-emission electricity is required in all pathways for operating existing and emerging processes in a climate-neutral chemical industry. Emerging processes demanding low-emission electricity include compressing captured carbon dioxide to high pressure for subsequent transport to and storage in geological formations or electric-driven steam boilers. While low emission electricity is a key requirement for the chemical industry to reach climate neutrality, its supply depends on regional availability.

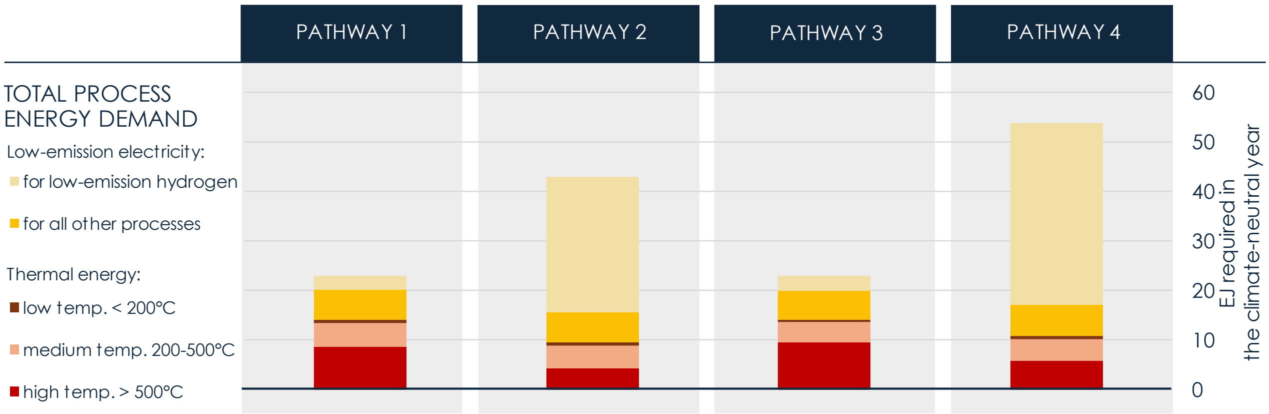


Figure 11: Snapshot of process energy demand in the climate-neutral year in each pathway, showing the sum of the process energy demand by type, from the production of basic chemicals to processing to final products and end-of-life, including recycling, as well as the electricity required to produce low-emission hydrogen for ammonia production, carbon capture and utilization, and other hydrogen demands.

ANNUAL OPERATING COSTS & CUMULATIVE CAPITAL EXPENDITURES

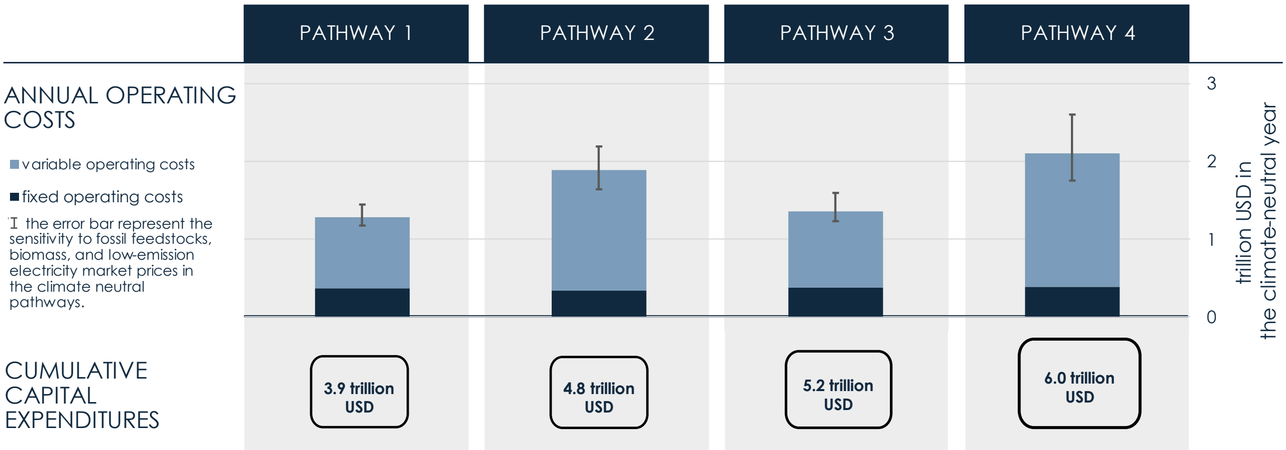
Figure 12 consists of two parts. The annual operating costs in the top part and the cumulative capital expenditure at the bottom part are presented in trillion USD. The annual operating cost diagram shows the annual fixed and variable operating costs for each pathway in the climate-neutral year. The annual fixed operating costs include the fixed costs of all plants operating in the value chain of the 18 chemicals, including the production of all intermediate chemicals, as well as the recycling and waste treatment operations. The variable operating costs include the costs for all resources and energy supplies to the chemical industry, as well as the costs for waste collection and CO_2 storage infrastructure. The error bars show a sensitivity analysis to specific variable costs, including sustainably sourced biomass, low-emission electricity, and fossil feedstocks. In this sensitivity analysis, the expected base case prices of either sustainably sourced biomass, low-emission electricity, or fossil feedstocks were varied by a factor of 0.5 and 1.5. The cumulative capital expenditures represent the sum of all investments done over the modeling timeline until the climate-neutral year.

All pathways show fixed annual operating costs of around 0.4 trillion USD in the climate-neutral year. The fixed operating costs include all costs occurring when operating a plant, such as labor costs, taxes, insurance, maintenance, and other plant overheads. In this study, the fixed costs of all plants in the value chain of the 18 chemicals are included, considering the production of all intermediate chemicals as well as the recycling and other waste treatment operations.

The variable annual operating costs vary between 0.9 to 1.7 trillion USD among the pathways. The variable operating costs are dictated by a few major cost drivers. These cost drivers are the price of low-emission electricity, the price of biomass, and the price of fossil feedstocks, such as naphtha, ethane, propane, and natural gas. While the price of low-emission electricity emerges as a significant cost factor across all pathways, the price for biomass is particularly decisive in pathway 2 ("Abundant biomass"), and the price for fossil feedstocks influence the variable costs of pathways 1 and 3 ("Abundant biomass & CCS" and "Abundant CCS"). Sensitivity analysis regarding the pathway's major cost drivers shows that variable costs range between 0.3 and 0.9 trillion USD, with ranges in the Abundant biomass and Limited biomass & CCS pathways being twice as high as those in the pathways 1 and 3 ("Abundant biomass & CCS" and "Abundant CCS"). The different cost ranges result from the different feedstock prices since fossil feedstocks are assumed to be relatively low-priced compared to other resources, such as biomass.

Comparing the total operating costs of the different pathways, it is noted that pathways 1 and 3 with abundant CCS ("Abundant biomass & CCS" and "Abundant CCS") result in lower costs relative to the other pathways. These lower overall costs can be attributed to the strong use of relatively low-priced fossil feedstocks in combination with CCS. In contrast, the pathways with limited CCS result in comparable higher operating costs, using alternative feedstocks such as biomass, low-emission hydrogen, or captured CO_2 in combination with low-emission hydrogen. In particular, the substantial additional demand for low-emission electricity to produce low-emission hydrogen in these pathways leads to higher costs. Therefore, pathway 4 ("Limited biomass & CCS") presents the highest operating costs. To make the pathway 2 and 4 more cost-competitive according to operating costs, affordable low-emission electricity is required.

Cumulative capital expenditures also vary significantly among the pathways, differing by a factor of 1.5, ranging from 3.9 to 6.0 trillion USD. Here, pathway 2 ("Abundant biomass") and pathway 3 ("Abundant CCS") have capital expenditures in a comparable range of around 5 trillion USD, with the Abundant biomass pathway exhibiting slightly lower capital expenditures of 4.8 trillion USD. Therefore, the development of a chemical industry oriented more to biomass compared to a fossil-oriented one with an advanced carbon capture and storage infrastructure could have similar cumulative capital expenditures. Acknowledgeable in the cumulative capital expenditures is pathway 1 ("Abundant biomass & CCS"), presenting the lowest cumulative capital expenditures (3.9 trillion USD). In this pathway 1, due to the abundant availability of biomass and CCS, the most effective technologies regarding costs and greenhouse gas emission reduction potential can be selected. In other words, it can integrate existing fossil-based technologies and cost-efficient alternative technologies. For instance, the fermentation of biomass requires, compared to biomass gasification, only one-third of capital expenditures. Therefore, fermentation is used on a large scale if biomass is available ("Abundant biomass & CCS" and "Abundant biomass"). In comparison, the Limited biomass & CCS pathway requires the highest cumulative capital expenditures due to the investment in many new technologies and infrastructures.



Note:
- All results, shown in this Figure, are for a midcentury year in which climate neutrality is achieved.
- All results refer to the production demand of the 18 chemicals included in the scope of this report.

Figure 12: Snapshot of costs required to achieve climate neutrality in each pathway. The top figure shows the operating costs in trillion USD in the climate-neutral year divided by the fixed and variable operating costs. The annual fixed operating costs include the fixed costs of all plants operating in the value chain of the 18 chemicals. The annual variable operating costs include the costs for all resources, energy supplies, waste collection, and CO_2 storage infrastructure. Moreover, the error bar shows the sensitivity of the operating cost regarding prices of fossil feedstocks, biomass, and low-emission electricity. The bottom figure represents the cumulative capital expenditures in trillion USD.

8 CLIMATE NEUTRALITY REQUIRES ENABLERS

This study has developed four potential pathways for the chemical industry's transition to climate neutrality. Each pathway consists of a combination of solutions, such as recycling and leveraging CO_2 and biomass as a feedstock. However, to effectively implement these solutions, there are critical enablers that are needed, such as access to plastic waste, sustainably sourced biomass, low-emission hydrogen, adequately regulated carbon capture and storage (CCS), and access to affordable low-emission energy, as well as supportive policies. The sections below explore the role of each one of these enablers that support the industry's transition to climate neutrality, as well as the challenges currently faced, highlighting the need for a multifaceted approach to GHG reduction. The importance of regulatory frameworks and infrastructure development in facilitating these transitions is also stressed, setting the foundation for understanding how the integration of these enablers is crucial for the chemical industry's transition to climate neutrality.

ACCESS TO PLASTIC WASTE

As depicted in Chapter 7, plastic waste plays an important role as carbon feedstock in all pathways. Figure 13 illustrates the lifecycle of plastics from production to their use and end-of-life. At the end-of-life stage, plastic waste can either be landfilled, incinerated with energy recovery, or sent to recycling. While landfilling and incineration of plastic waste will lead to irreversible loss of carbon, recycling processes circulate the plastics' carbon content back to the chemical value chain. Recycling decreases GHG emissions from incineration and curtails pollution from mismanaged waste. In this way, recycling significantly enhances the circular flow of carbon within the chemical industry, providing dual benefits for GHG mitigation strategies.

Mechanical recycling processes plastic waste directly into new raw materials for plastic products without changing the material's chemical structure, effectively keeping the carbon locked within the plastic economy. This process counts on well-established technologies. However, there are some limitations to mechanical recycling. Over successive recycling cycles, polymer properties tend to degrade, potentially restricting their use in certain applications. This can be due to degradation related to processing conditions or to the presence of additives initially used in the virgin material[27]. In comparison to mechanical recycling, chemical recycling is still a nascent industry. However, it addresses some of the challenges faced by mechanical recycling. Chemical recycling breaks down plastic waste into molecular building blocks, which can then be repurposed as feedstock to produce chemicals and plastics with virgin-like properties. In addition, chemical recycling can handle a wider range of plastic waste streams, including mixed and contaminated ones. Despite its advantages, chemical recycling requires more energy throughout the value chain

[27] Ragaert et al., 2017: Mechanical and chemical recycling of solid plastic waste; Waste Management; http://dx.doi.org/10.1016/j.wasman.2017.07.044

to break up the chemical structure and for plastics production. The integration of chemical recycling alongside mechanical recycling is essential to maximize the amount of plastic waste that can be reprocessed into the value chain.

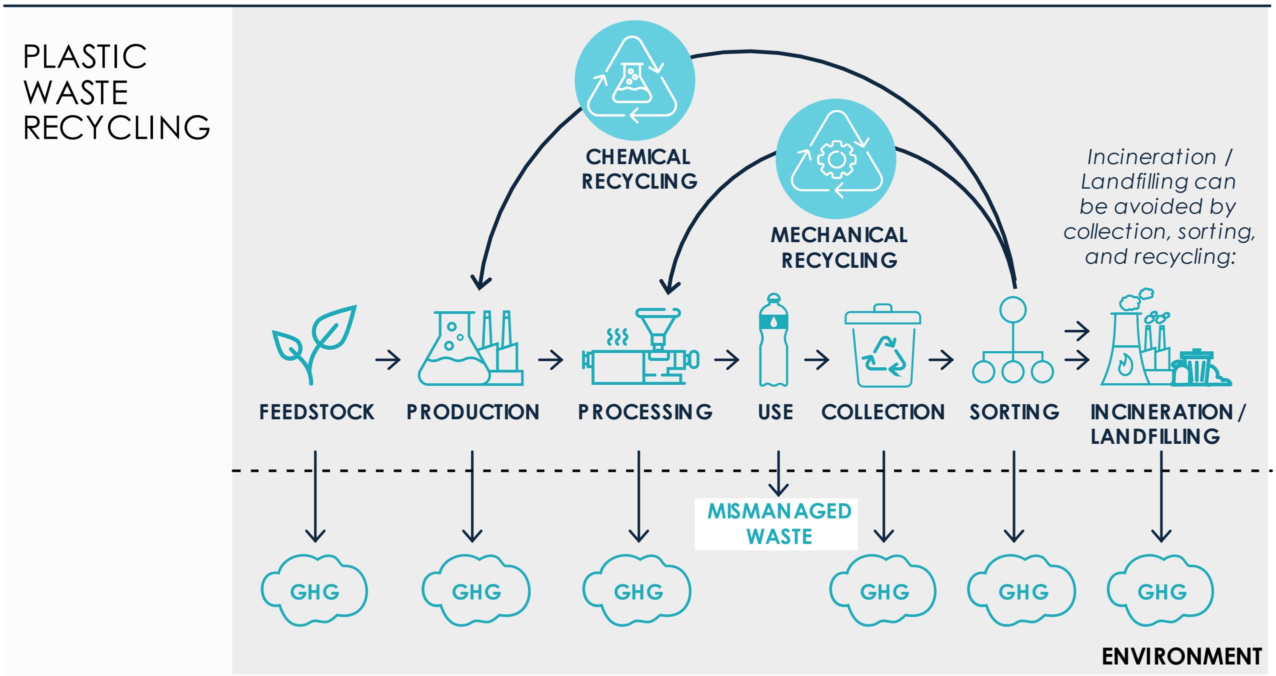


Figure 13: Schematic overview of plastic recycling. The implementation of recycling strategies reduces environmental footprint, diminishes reliance on virgin plastics, and mitigates greenhouse gas emissions across the value chain. Emission from the use phase is outside the scope of this study.

Despite the undeniable advantages of recycling, global recycling rates remain low, with only 9% of plastic waste being recycled and over 22% disposed of improperly[28]. As global demand for plastics continues to grow, increasing recycling rates becomes even more critical to harness the benefits of plastic recycling. This requires supportive policies and investments in advanced infrastructure for plastic waste collection and sorting, which will not only reduce environmental pollution but also ensure that plastic waste is efficiently reintegrated as feedstock within the chemical industry.

In summary, the adoption of mechanical and chemical recycling technologies is vital for advancing climate neutrality within the chemical industry and offers potential opportunities to reduce carbon emissions across the entire chemical value chain. Encouraging recycling provides additional options to potentially reduce the amount and environmental footprint of mismanaged plastics. However, these benefits depend on the introduction of advanced waste management infrastructure, investment in innovative recycling solutions, and adequate policies and incentives to drive these initiatives.

[28] OECD, 2022, Global Plastics Outlook: Policy Scenarios to 2060, https://doi.org/10.1787/aa1edf33-en.

SUSTAINABLY SOURCED BIOMASS

Our results from Chapter 7 underscore the critical role of biomass as a carbon feedstock across all four identified pathways (see Figure 10), emphasizing its substantial role in driving the transition toward climate neutrality. Figure 14 illustrates the principle of circular carbon from biomass. During its growth phase, biomass captures atmospheric CO_2. This biomass can then be utilized in the chemical industry as a feedstock to produce basic chemicals like ethylene via biomass fermentation and subsequent catalytic dehydration and methanol via biomass gasification and subsequent methanol synthesis.

In addition to its role as a feedstock, biomass also serves as an energy source within the chemical industry, supplying high-temperature heat, low-emission electricity, and steam. As biomass moves through the value chain to its end-of-life, the carbon stored within the biobased products is released back into the atmosphere as CO_2 or other GHG, thereby completing the biogenic carbon cycle.

This cycle creates a balance where biogenic carbon captured from the atmosphere is eventually returned, maintaining a circular system. Further integration of carbon capture and storage (CCS) technologies during the chemical conversion processes or at the end-of-life phase allows for the creation of a carbon sink, potentially leading to net negative emissions along the value chain as the captured carbon is not returned to the atmosphere but is instead sequestered.

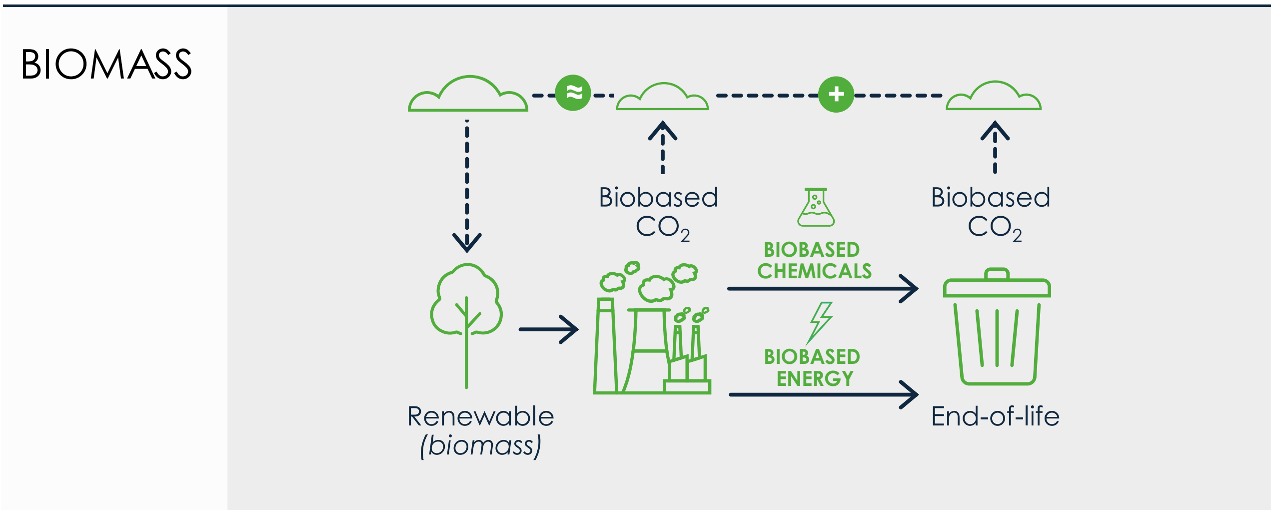


Figure 14: Lifecycle of biomass as a sustainable feedstock in the chemical industry. From CO_2 capture through photosynthesis to the creation of biobased chemicals and energy, and finally to end-of-life, emphasizing the minimal net emissions and the role of biomass in enhancing circular economy practices.

However, despite the potential of using biomass for GHG emissions mitigation, there are challenges in the application of biomass in the chemical industry. Cultivation of biomass requires a delicate balance in land use to avoid risks to food security and deforestation, among other challenges. The Energy Transitions Commission report[29] highlights that sustainable biomass must meet strict criteria to avoid environmental degradation and advocates for its prudent use where no alternatives exist. This framework for sustainable use underlines the tension between the potential supply of biomass for chemical production and the stringent sustainability requirements that must be upheld. A pivotal part of the strategy involves prioritizing biomass use as material or as carbon feedstock, e.g., in the chemical industry. Using biomass as a feedstock or material rather than an energy source is often deemed more advantageous because it retains the carbon content within products, extending carbon storage time.

In addressing the challenges of leveraging biomass for climate neutrality, it is crucial for the chemical industry to secure reliable access to sustainably sourced and economically affordable biomass.

Overall, biomass use stands as a promising approach to mitigate GHG emissions in the chemical industry's value chain. The strategic utilization of biomass, supported by robust infrastructure, innovative technologies, and sustainable practices, is a key factor in the industry's progress toward climate neutrality. However, careful management of resources and alignment with economic and environmental goals are necessary.

LOW-EMISSION HYDROGEN

In addition to biomass and recycling, the results of this study indicate that low-emission hydrogen will play a crucial role in the future climate-neutral chemical industry, underscoring the importance of a diverse feedstock mix. Low-emission hydrogen is a valuable feedstock for reducing GHG emissions associated with ammonia and methanol production. Additionally, low-emission hydrogen can be used to upgrade captured CO_2 into valuable chemical feedstocks, thus closing the carbon loop via Carbon Capture and Utilization (CCU) processes. Figure 15 illustrates the basic principle of CCU, which can leverage CO_2 from either industrial point sources or atmospheric CO_2 via direct air capture (DAC). Feedstocks produced via CCU include methane and methanol, which are used in the production of several other chemical products.

It is important to note that the CO_2 captured earlier and used as feedstock is released back into the atmosphere during processing or at the end of life. If the carbon captured from direct air capture (DAC) is released back into the atmosphere, a carbon cycle is created. When CO_2 capture and storage is further applied to the chemical conversion or end-of-life, a carbon sink can be created, leading to net negative emissions along the value chain, as the carbon is locked out of the atmosphere.

To effectively harness the benefits of low-emission hydrogen within the chemical industry,

[29] Energy Transition Commission (2021), "Bioresources Within A Net-Zero Emissions Economy"; https://www.energy-transitions.org/publications/bioresources-within-a-net-zero-economy/

the chemical industry requires reliable and affordable access to it. Particularly important is the development of robust and low-cost infrastructure for hydrogen production, storage, and transportation, which must be designed to handle hydrogen's unique properties and ensure safe and efficient delivery to users, including minimizing fugitive emissions of hydrogen.

Finally, supportive regulatory frameworks and financial incentives are crucial to incentivize the shift towards low-emission hydrogen, helping to overcome economic barriers and encouraging investment in hydrogen infrastructure and technology. Together, these measures will enable the chemical industry to leverage hydrogen's full potential as a key enabler of climate neutrality.

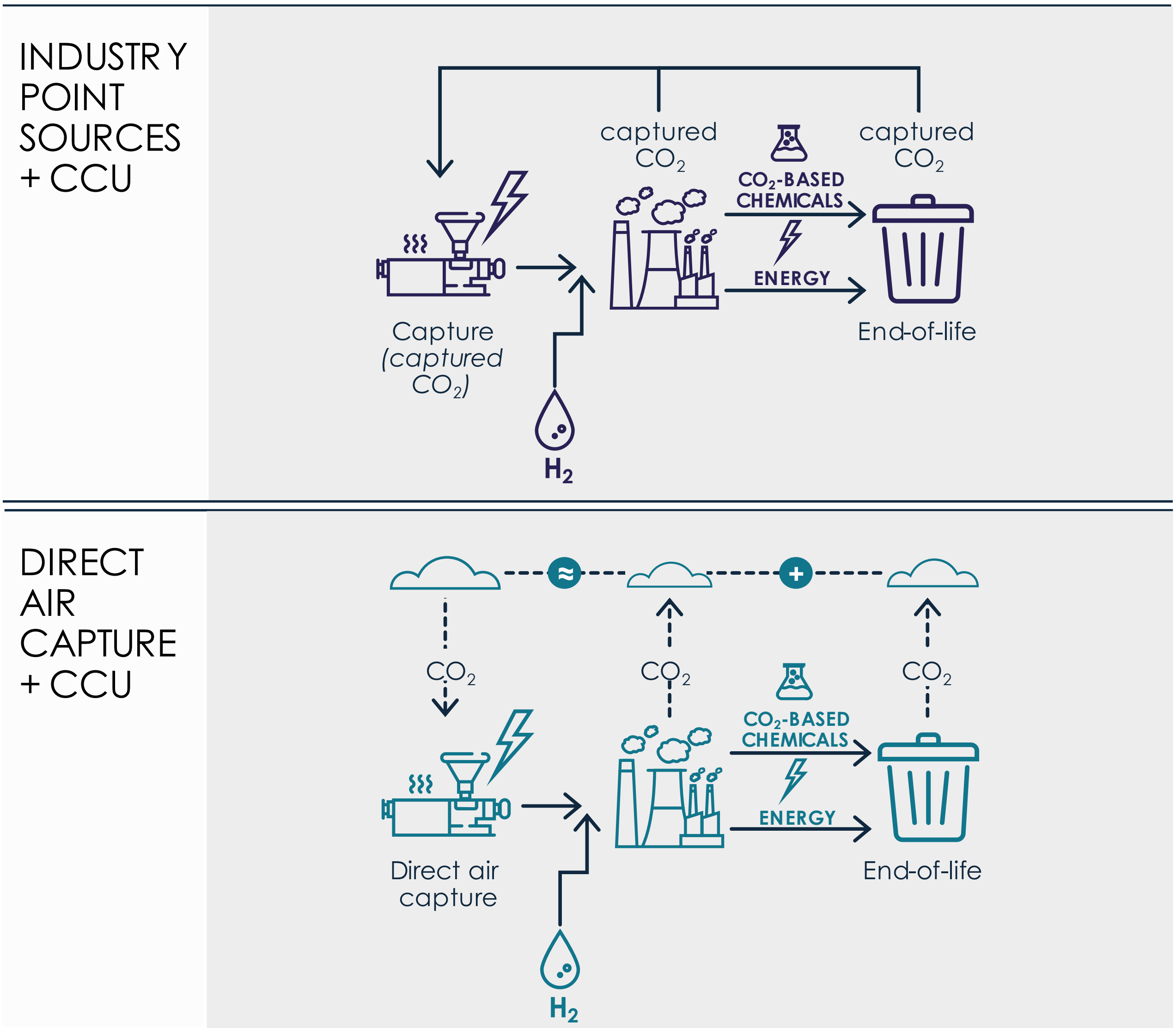


Figure 15: Carbon Capture and Utilization (CCU) via capture of high-concentration industrial point source CO_2 (top) and via direct air capture (bottom) combined with low-emission hydrogen provides valuable basic chemicals minimizing GHG emissions along the value chain. Industrial point sources in the chemical industry include processes with high concentrations of CO_2 in exhaust streams, such as steam methane reforming, production of ethylene oxide, and waste incineration.

FOSSIL FEEDSTOCK AND ADEQUATELY REGULATED CARBON STORAGE

All four pathways utilize fossil feedstocks in combination with Carbon Capture and Storage (CCS) (see Figure 10). The projected continued use of fossil fuels in a climate-neutral chemical industry underscores the importance of comprehensive carbon management strategies, highlighting CCS as an integral component to mitigating environmental footprint.

Figure 16 shows the principle of CO_2 capture and storage. CCS technology captures carbon dioxide (CO_2) emissions at sources along the chemical value chain, preventing CO_2 from being released into the atmosphere. The process of CCS can be broken down into three major steps: capture, transport, and storage. The capture phase involves separating CO_2 from other gases produced at industrial sites, for instance, ethylene oxide production, biomass gasification, and fermentation, or at the end-of-life of chemicals and plastics. Once captured, the CO_2 is compressed and transported, usually via pipelines, to a suitable site for geological storage. This storage occurs deep underground, in rock formations that can securely contain the CO_2, effectively isolating it from the atmosphere.

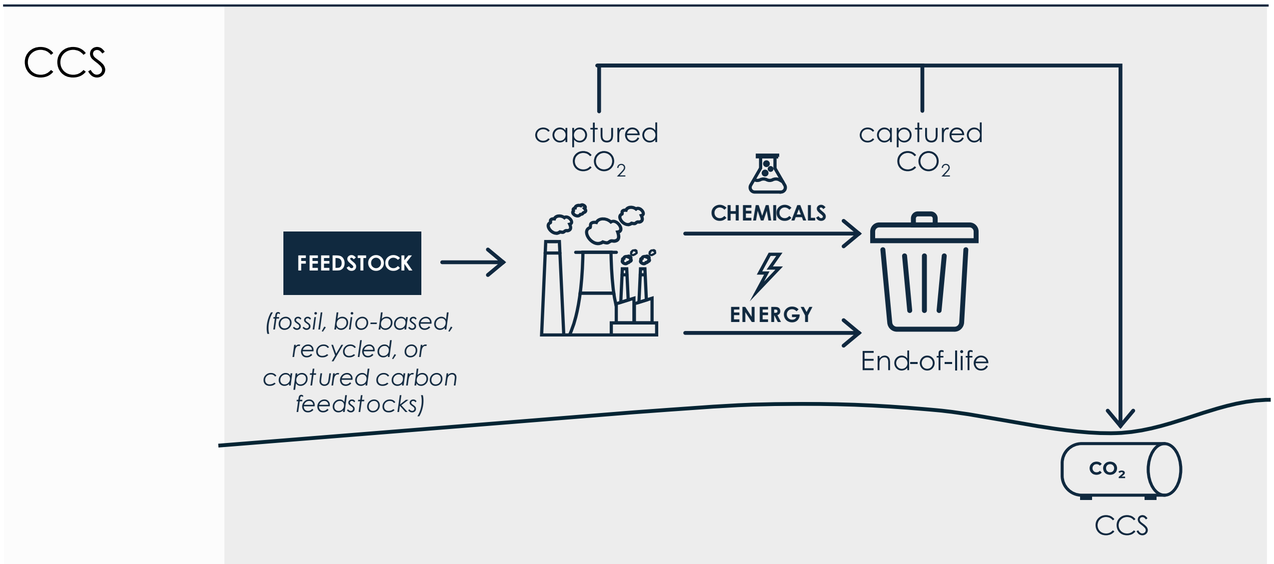


Figure 16: Carbon Capture and Storage (CCS) process in the chemical industry, illustrating the capture of CO_2 emissions from various feedstock sources, including fossil, biobased, recycled, or captured carbon. The diagram shows how CO_2 emitted in the value chain can be captured.

However, despite its potential benefits, the adoption of CCS in the chemical industry faces several challenges. One significant challenge is the extensive lead times required for planning, constructing, and commissioning CCS projects. Additionally, the development of dedicated CO_2 transport and storage infrastructure demands significant upfront investment and regulatory support[30].

To effectively leverage CCS use as an enabler, the chemical industry needs reliable and economical access to CCS. Overcoming the challenges associated with large-scale CCS extension will require streamlined regulatory processes to facilitate project development, investments in CO_2 infrastructure to support transportation and storage needs, and stakeholder engagement that builds trust and acceptance. Furthermore, technological advancements in capture, transport, and storage techniques are vital to improving the efficiency and cost-effectiveness of CCS solutions.

AFFORDABLE LOW EMISSION ENERGY

Our analysis indicates that achieving a climate-neutral chemical industry requires a broad spectrum of process energy, ranging from low- to high-temperature heat and to low-emission electricity (see Chapter 7). To meet these diverse energy needs, a variety of sources can be employed, including fossil fuels with CCS, biomass, low-emission hydrogen, nuclear energy, waste with CCS, and low-emission electricity.

Specifically, in the case of processes operating on high-temperature heat, e.g., existing steam crackers and reformers, combustion is usually required to supply temperatures above 500°C. Fossil fuels are a viable energy source for these processes when combined with Carbon Capture Utilization and Storage (CCUS) technologies. Alternatively, biomass, low-emission hydrogen, and synthetic fuels derived from CO_2 and low-emission hydrogen or biomass also present viable options.

The energy portfolio can be further diversified with sources such as low-emission electricity from nuclear power and energy recovery of plastic waste with CCS, which are suitable for supplying low- to medium-temperature heat as well as steam. Moreover, low-temperature, medium-temperature heat, and steam can be generated through direct electrification using heat pumps, electric boilers, or electrical resistance heaters. Here, it is important to note that the effectiveness of directly electrified process energy depends on the emission factors associated with the consumed electricity. Thus, direct electrification of process energy can only reduce GHG emissions if low-emission electricity is available. As the global energy industry incorporates more renewable energy, managing intermittency becomes crucial to ensure continuous access to reliable electricity and, consequently, process energy.

Overall, the choice of energy sources and technologies will largely depend on regional availability, existing infrastructure, and political incentives. This dependency highlights the need for a coordinated approach that considers local conditions and global environmental targets, ensuring that the chemical industry can meet its climate neutrality goals efficiently and effectively.

[30] Energy Transition Commission (2022), "Carbon Capture, Utilisation and Storage in the Energy Transition: Vital but Limited"; https://www.energy-transitions.org/publications/carbon-capture-use-storage-vital-but-limited/

9 SUMMARY AND CONCLUSIONS

As a major manufacturing sector, the chemical industry produces products that are part of our everyday life and support GHG emission reductions in other sectors. To achieve climate neutrality, the chemical industry faces a dual challenge of reducing GHG emissions from energy consumption and carbon feedstocks (where carbon is a crucial component of most chemical products), both of which are largely fossil-based today. Overcoming this challenge demands innovative solutions and concerted efforts across the chemical value chains and with policymakers.

In this report, we looked at a wide variety of feedstocks used in chemical manufacturing to study quantitative pathways for the global chemical industry to reach climate neutrality by mid-century, using a scientific modeling approach that has been applied in various peer-reviewed publications. We took a technology-neutral and cost-minimal approach to ensure an economical transition to climate neutrality. This approach was chosen since limiting certain technological choices would restrict the chemical industry's ability to address its dual challenge and could potentially make climate-neutral chemical products more expensive and delay the wider societal shift to climate neutrality.

The first key finding of this study is that there are multiple pathways for the global chemical industry to achieve climate neutrality. We identified four pathways that assume a range of factors, including resource availability and technological advancements. These results emphasize the absence of a one-size-fits-all solution, highlighting the need for adaptable strategies tailored to regional contexts and resource availabilities.

The second key finding of this study underscores the crucial role of external enablers in facilitating the chemical industry's transition towards climate neutrality. Access to plastic waste, sustainably sourced biomass, low-emission hydrogen, adequately regulated carbon storage, and affordable and reliable low-emission energy emerge as key enablers to allow the implementation of solutions that can significantly mitigate GHG emissions across the chemical industry's value chains. The chemical industry even has a potential to reduce emissions from other sectors outside its value chains through Carbon Capture and Utilization (CCU). However, unlocking the full potential of these enablers demands comprehensive policy frameworks, robust infrastructure investment, and cross-sectoral stakeholder collaboration.

This study highlights the complexity of the challenge and the necessity for a multifaceted approach that leverages technological innovation, policy support, and industry collaboration. By embracing these findings and supported by the identified enablers, the global chemical industry can pave the way towards climate neutrality, contributing to combating climate change on a global scale.