Defossilising the petrochemical industry

What a switch from fossil to renewable feedstocks may imply for current and future value chains

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Contents

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High-level summary

- Measures to **decarbonise** the chemical industry, such as improved efficiency, electrification or carbon capture and storage, can help to partially reduce the climate impacts of the sector. However, since carbon will remain an important feedstock for most chemical compounds, those levers will need to be complemented by a switch to novel sources of carbon (biogenic or atmospheric). Some voices therefore call for a **"defossilisation"** of the chemical industry.

- Strategies by oil companies to **maximise the production of petrochemical outputs** are expected to be observed in the coming decades, with highly uncertain climate benefits, particularly regarding end-of-life emissions and remaining uses of oil products.

- A shift to renewable sources of carbon would require a **substantial re-engineering of the value chains of the chemical industry**. Processes would need to be tailored to the composition of biogenic molecules, to different storage and transport requirements, and be able to adapt to possible seasonal and daily variations.

- Key questions remain as to **which chemicals should be targeted** by novel feedstock pathways. A combination of both drop-in strategies, targeting the production of chemicals similar to those used today, thus minimising changes to current infrastructures, and dedicated production of novel chemicals in a more resource and energy-efficient manner, warrant further investigation.

- Both bio-based and CO_2-based pathways to chemicals are **resource-intensive**, and a one-to-one replacement of current fossil production capacities through such pathways is likely to lead to very high demand for biomass raw materials and electricity/H_2/CO_2, respectively. On a global scale, these demands would be challenging to meet sustainably.

- Although there are **no agreed-upon pathways** to enable the chemicals industry to meet net zero, and the contribution of different technologies is still uncertain, a **combination or co-evolution of bio-based and CO_2-based** pathways – coupled with **demand reduction** strategies – is likely to increase the overall feasibility and sustainability of the sector's defossilisation.

- A balance must be found between **retrofitting, decommissioning and building new** facilities or individual equipment units within the same plant. For instance, some studies have found steam crackers to be more suited to retrofits than catalytic reformers. Such dynamics should be further analysed and better documented by studies at more detailed regional scales.

- Pathways based on renewable feedstocks are and will remain, at least in the short term, **more expensive** than their fossil-based alternatives. Economic viability may be increased by gradual integration to current processes and supply chains, measures such as subsidies and carbon prices, as well as innovation in related technologies and subsequent cost reductions.

- Developments in **niche markets** and a focus on the chemicals that have the highest feasibility and marketability may act as "market shapers", paving the way to larger-scale transformation of the chemicals industry. Identifying and accelerating those candidates (such as polyurethane) may be a powerful step to scale up novel carbon feedstocks in the chemical industry.

Key barriers

1. **Data availability** – The petrochemical industry is a complex and non-transparent sector, with a large variety of process combinations and plant configurations. Successful transformation of this sector will require a better and more widespread understanding of its processes, supply-demand dynamics, the competitive landscape and more.

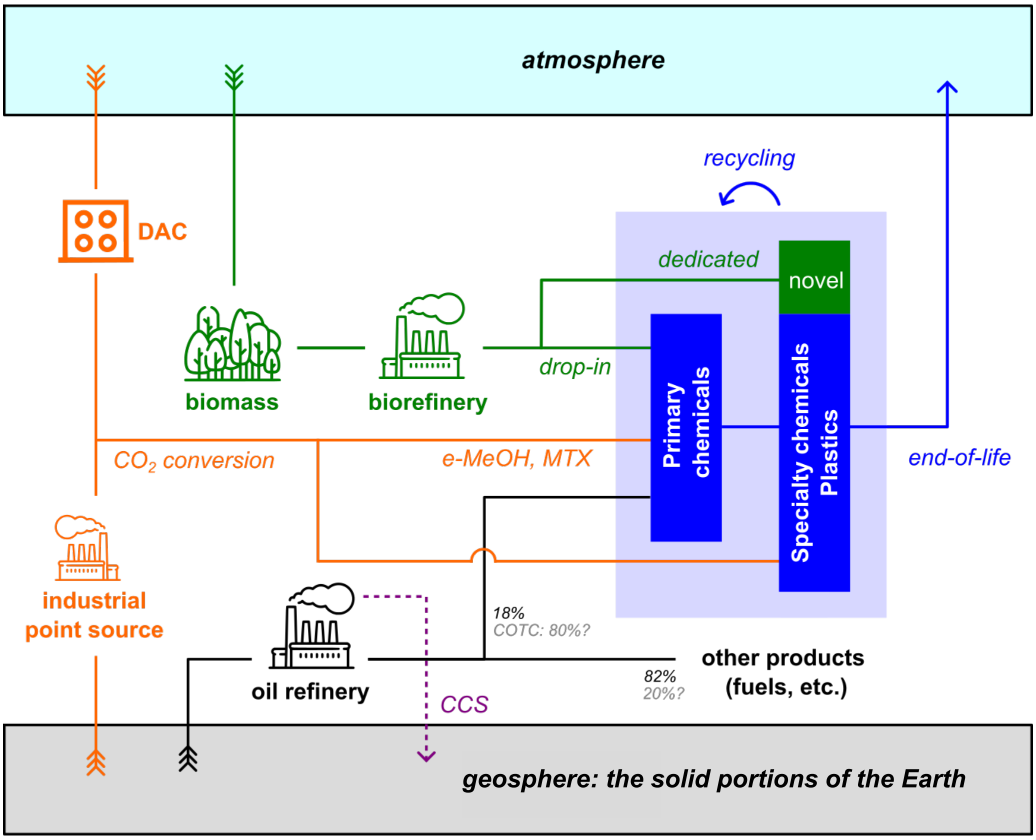
2. **Lifecycle analyses** – Since many technologies are still nascent, life-cycle analyses under operating conditions are lacking, for example for crude-oil-to-chemicals (COTC). This makes it challenging to assess the potential of different decarbonisation strategies for the sector.

3. **Resource trade-offs and allocation** – Although some frameworks have been developed to prioritise carbon capture utilisation and storage (CCUS) or biomass for the most climate-relevant uses, these remain largely conceptual for now. Clear guidelines and, ultimately, policies would enable the right allocation of such limited resources.

4. **Technology developments** – The role that new technologies and innovation can play in decarbonising the chemicals sector is still not well understood. Technologies with a low level of readiness ("low TRL") are typically not included in quantitative analyses or future decarbonisation pathways. More work is needed to understand the technologies, their potential uptake and interlinkages, how to de-risk them, and how to bring down their costs.

5. **Business models** – Better understanding how the energy transition will change the sector is crucial. This includes how players – novel and incumbent – will adapt to the switch to renewable feedstocks, how businesses will reshape their models and how the petrochemical and oil and gas industries will review their respective roles in the transition.

Visual summary



A map of pathways to defossilise the production of chemicals, showing fossil-based (black), bio-based (green) and CO_2-based (orange) pathways. Visual by François de Rochette.

COTC = crude oil to chemicals, CCS = carbon capture and storage, DAC = direct air capture, e-MeOH = e-methanol, MTX = methanol-to-X.

Fossil-based chemicals	Bio-based chemicals	CO_2-based chemicals
Possible solutions – Incremental improvements (electrification and/or decarbonisation of electricity supply, energy efficiency) – Carbon capture and storage (CCUS) – Crude-oil-to-chemicals (COTC) to maximise chemical outputs **Limitations** – Limited potential for further incremental improvements – Large demand for CCUS from other sectors and limited resources – Unknown climate benefits of COTC	**Challenges** – Biomass composition – Expensive production pathways **Large-scale concerns** – Availability of biomass – Biorefinery constructions, retrofits of fossil refineries and facilities – Biomass handling, storage and transport **Key technology developments** *Short-/medium-term* – Biomass pretreatment – Lignin conversion (TRL 5–6) – Catalysts able to handle biosubstrates *Long-term* – Generation 3 biomass processes (TRL 4)	**Challenges** – CO_2 conversion – Expensive production pathways **Large-scale concerns** – Need for large amounts of low-carbon electricity (and H_2) – Need for large amounts of CO_2 – Need for infrastructure and coordination with other industries **Key technology developments** *Short-/medium-term* – More selective catalysts – Methanol-to-X (MTX), especially aromatics (TRL 7) *Long-term* – CO_2 to specialty chemicals (TRL 3–5 depending on chemicals)

TRL = Technological readiness level.

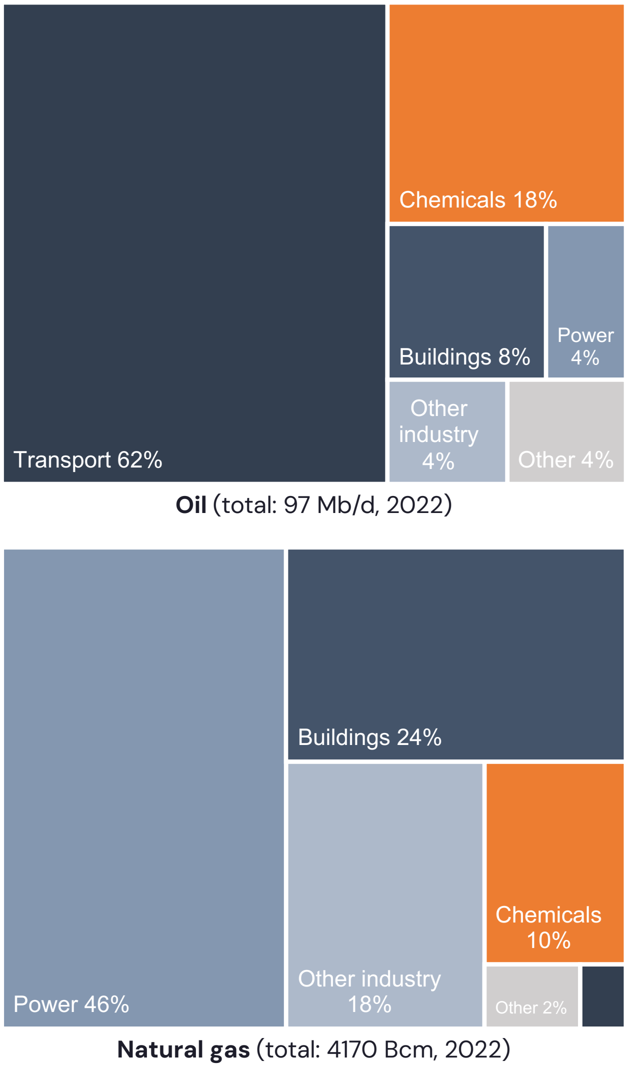
1. Context

Context

As the largest energy consumer and third largest emitter of all industrial sectors, the chemical industry is one of the "hard-to-abate" sectors, for which decarbonisation solutions are not yet mature or not straightforward.

Currently, chemicals are almost exclusively derived from fossil fuels, but crucially, they do not represent a dominating share of current global fossil fuels demand: about **18% of petroleum and 10% of natural gas** [1] is dedicated to manufacturing petrochemicals. Transportation fuels constitute the bulk of oil consumption, while natural gas is mainly used to generate electricity and as a heat source for buildings and industrial applications (see **Figure 1**). With significant transformations such as the electrification of mobility expected to occur in the next decades, oil demand for transportation is likely to shrink. Several players thus envision that chemicals will be the largest driver for oil demand growth over the next few decades [2].

The petrochemical industry emerged in North America and Europe during the second half of the twentieth century. However, in recent decades, production from those regions has stagnated due to the rise of China as a key chemicals industry player over the last few decades. China's petrochemical production is largely derived from coal.



Oil (total: 97 Mb/d, 2022)

Natural gas (total: 4170 Bcm, 2022)

Figure 1. Sectoral breakdowns of global oil and natural gas demand, with highlighted shares for chemicals. Adapted from Energy Transitions Commission, 2023 [1].

A key peculiarity of the chemical sector is that fossil fuels are used both as an **energy source** (around 40%) and as a **material feedstock** (around 60%), with hydrocarbons providing the necessary atomic building blocks (carbon and hydrogen atoms) that constitute most chemical compounds [2]. In that regard, putting the chemical industry on a net zero-aligned trajectory is both a question of **defossilising** its carbon sources as well as decarbonising the sector's energy sources. More than 70% of the climate change we observe today can be attributed to the anthropogenic transfer of fossil carbon from the geosphere to the atmosphere through the extraction of oil, gas and coal, and their later conversion into energy or products. Directly or indirectly sourcing carbon from the atmosphere to produce chemicals would thus provide a key opportunity to stop the sector from contributing to climate change. Two alternative carbon feedstocks are **atmospheric carbon dioxide (CO_2)** captured directly from the air (direct air capture; DAC)[a] and **biomass**.

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[a] For more information, refer to QCF's CDR Evidence Review [3].

Over decades, the petrochemical industry has exploited abundant and cheap fossil sources and has grown into a well-established sector with highly integrated and optimised value chains. Incorporating alternative feedstocks may require no less than a complete reorganisation of the sector, its players, its value chains and its business models.

Scope and aim of this study

This study aims to shed light on the key challenges related to integrating alternative feedstocks into petrochemical processes, and reviews which transformations the industry might face if such feedstocks were to largely or fully substitute fossil carbon sources. The study also explores some possible remaining uses of fossil feedstocks in a net-zero chemical world.

The focus is set on the six carbon-containing **primary chemicals**: methanol (MeOH), light olefins (ethene, propene) and BTX aromatics (benzene, toluene, xylenes). Primary chemicals serve as a base for a huge variety of end products, mainly specialty chemicals and plastics. Olefins and aromatics are commonly referred to as “high-value chemicals” (HVCs).

Appendix 1 – Definitions and key figures, provides facts and figures about conventional chemical production and processes.

Although ammonia (NH_3) represents the biggest share of emissions from primary chemical production (45%) [4], it was not included in the study as it does not contain carbon. (Defossilising ammonia production mainly consists of defossilising the hydrogen used in the Haber-Bosch process.) Furthermore, this study mainly focuses on novel feedstocks for primary chemical production and therefore only partially explores the important and related sustainability levers of substitution, demand reduction and recycling. Although these are essential sustainability levers with economic, technological and societal implications, the wider topic of a circular economy is not within the scope of this study.

Key overarching concepts: “green chemistry” and “renewable carbon”

Several frameworks have been developed to define the key elements on which the transition to a sustainable chemical industry should be based. The concept of **“green chemistry”** emerged from academic experts in the 1990s, notably motivated by researchers from the American Chemical Society. Since then, it has been further explored by a wide variety of industry and engineering players. Green chemistry can be defined as the “design of chemical products and processes to reduce or eliminate the use and generation of hazardous substances” [5], and is commonly referred to based on its **12 key principles** developed by Anastas & Warner in 1998 [6].

The use of alternative and renewable feedstocks is one of the key principles of green chemistry which has been increasingly investigated over the last few years because of its potential to prevent the negative climate and environmental outcomes caused by current production pathways. In that perspective, the concept of **“renewable carbon”** has been gaining importance, advocated by organisations such as the Renewable Carbon Initiative [7], gathering scientific and industrial players. The concept can help in providing a framework for the chemical industry to reduce its reliance on fossil carbon, while acknowledging the difficulties of combining diverse novel carbon sources unified under a common term [8].

2. The past, present (and future?) of fossil-based chemicals production

A brief overview of current production

The term “petrochemicals” originally refers to chemicals produced from petroleum, and is now often used interchangeably with the simpler, shorthand term “chemicals”.

Petrochemicals can be produced from feedstocks derived from oil, natural gas liquids or coal (**Figure 2**). Oil refining allows the separation of crude oil, which is a complex mixture of many hydrocarbons, into several “fractions” for further processing; natural gas is purified and further processed; coal is usually gasified into syngas. Following these initial purification steps, more chemical reactions (such as cracking or reforming) are used to convert such hydrocarbons into more reactive “primary chemicals“.

Primary chemicals serve as precursors to larger and/or more molecularly complex chemicals, such as “specialty chemicals” and polymers (**Figure 2**).

A highly integrated industry with optimised value chains

Historically initiated to generate value from the by-products of refining operations, the petrochemical industry has grown into a highly self-sufficient, integrated and efficient industrial sector. [10] As the industry is already extremely optimised, any transformational innovations in processes or business models will likely encounter significant hurdles. Pathways for the sector to reach net zero emissions may require incremental or step-change innovations.

Incremental and conventional mitigation levers

A first route to reduce petrochemical industry emissions consists of **optimising** current fossil-based processes, using the Best Available Techniques (BATs) to improve heat and energy

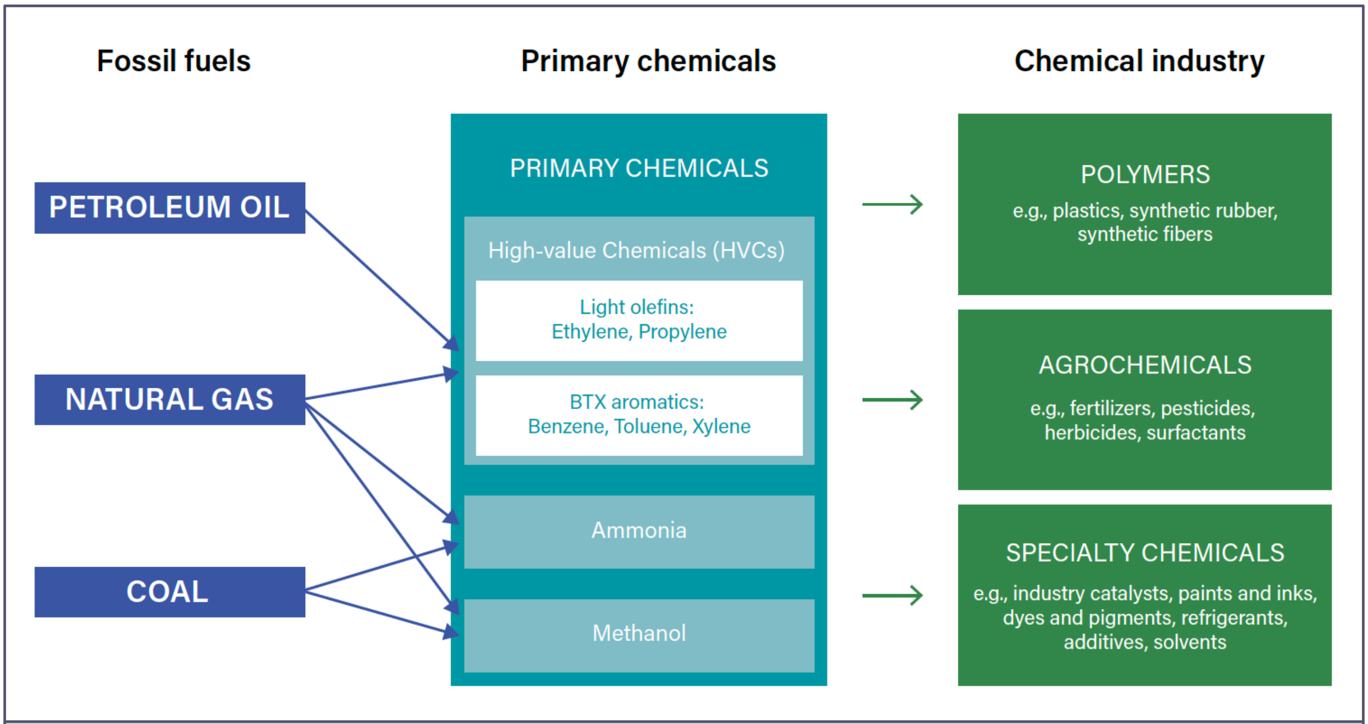


Figure 2. Processing of fossil feedstocks into primary chemicals and products. Image from World Resources Institute, 2024 [9] CC BY 4.0.

integration (e.g. through Combined Heat and Power, CHP) or to switch to lower-carbon heat sources for equipment units such as steam crackers [11], [12]. Such incremental measures have already enabled some significant decoupling between emissions and production in the past: at the European level, emissions of the chemical industry have decreased by 55% since 1990, while production increased by 43% [13]. However, while further gains may still be expected, many processes have reached close to their highest feedstock efficiency levels [14].

Electrification of processes with low-carbon power will be a critical pathway to reduce emissions from most refinery equipment. This is most easily applied to low-temperature processes (150–350 °C) such as boilers and through the use of heat pumps, which are industrially available (TRL ≥ 8) and more energy-efficient than combustion-based processes. Progress still needs to be made to enable the electrification of higher-temperature equipment – above 350 °C up to 800–900 °C [15] – but recent analyses have shown that technologies to achieve this are advancing rapidly [16], [17].

Such incremental strategies focusing on energy sources will be crucial to reduce the emissions of the sector, with a potential combined emissions reduction contribution of 12–40% according to various scenarios [18]. However, a focus on process emissions alone will not be enough to fully abate current emissions, and they do not address the fossil feedstock issue – the key focus of this study.

Carbon capture utilisation and storage (CCUS) within the chemical industry

Technical challenges

Captured carbon from a concentrated point source may be used as a feedstock for another chemical process (CCU) or stored (CCS). Carbon capture is not the same as carbon dioxide removal (CDR; for more information on that, refer to QCF's CDR Evidence Review [3]). This next section will focus on technical challenges related to carbon capture as they are pertinent for carbon capture, utilisation and storage (henceforth referred to as CCUS for simplicity).

However, capturing CO_2 from refineries and chemical plants is not as straightforward as it may seem. Contrary to the emissions of cement plants for instance, which occur at only two sources (the precalciner and the kiln), refineries tend to present a **large number of emissions sources**, often exceeding a hundred [19]. Capturing emissions might thus require prioritising the largest and most highly concentrated CO_2 point sources, such as steam crackers or steam reformers. The success of this approach would largely depend on the specific configuration of a given refinery. For instance, about a quarter of US refineries do not comprise a steam cracker or reformer [19]. Therefore, a focus on CCUS integration with steam cracking/reforming units could leave a significant portion of emissions from multiple small-scale units unabated – up to 30% of emissions from large conversion refineries may remain unaddressed [20]. **Re-engineering** may be required to generate combined stacks of CO_2 sources for refineries to achieve more complete carbon capture coverage [21].

Some **general challenges** related to carbon capture technologies also apply to the chemical sector. Capture rates approaching 100%, although theoretically possible, may prove difficult to implement in operating conditions due to financial and energetic constraints. Therefore, a more realistic CO_2 capture rate would be 90–95%. Therefore, some form of CDR may be required to compensate for the residual emissions and effectively reach net zero [14].

Overall challenges

Although carbon capture technologies are mature, a key challenge to deploying CCUS at a large scale lies in **organising** the individual technological building blocks and deploying the required infrastructure at the right pace (pipelines, shipping infrastructure) while ensuring a supply/demand match between capture and storage facilities. This is even more challenging because the chemical industry is not the only sector that may require CCUS infrastructure. Other industrial facilities (steel, cement) and some power plants could also become major users of the technology, which, given the different possible bottlenecks along the whole value chain, requires some **priority setting** to ensure that mitigation by CCUS is used in the most cost-effective sectors where alternatives are most limited. Some early methodologies have been developed to assess the appropriateness of CCUS for specific sectors, taking into account criteria such as the availability of alternative technologies, the mitigation potential or the source of CO_2 [22]. In the resulting **"CCS ladder"** (see **Figure 3**), focusing on Europe, steam cracking for high-value chemicals (HVCs; **Figure 3B**) and fluid catalytic cracking (**Figure 3C**) are among the most relevant options for CCUS in the near-term (2030). By 2050 however, they are downgraded in priority due to the hypothetical availability of other decarbonisation technologies.

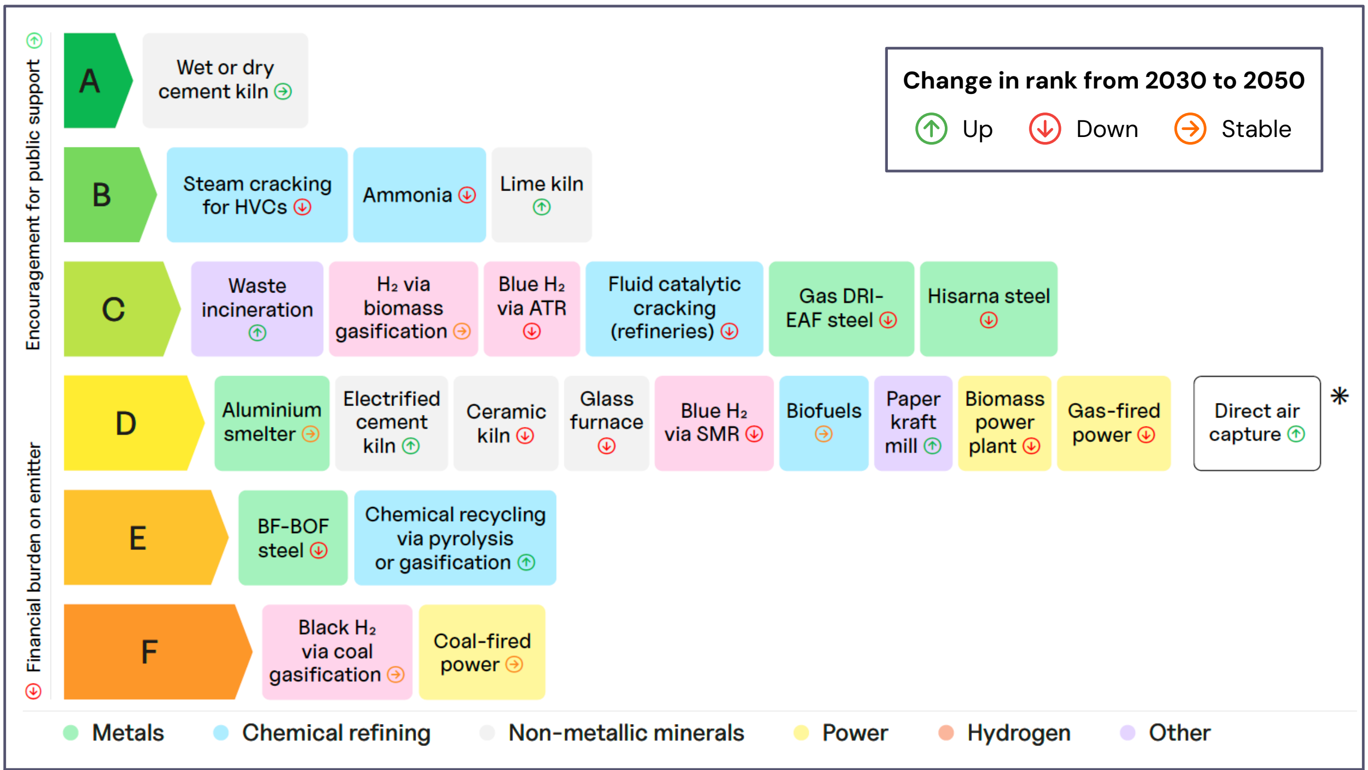


Figure 3. The "CCS ladder" as developed by E3G & Bellona 2023, aiming at establishing a possible prioritisation of CCUS for certain sectors. This figure shows a possible hierarchy of CCUS uses in Europe by 2030. The boxes colour coded in blue are relevant for the chemicals industry. Image from Vangenechten *et al.*, 2023 [22]. CC BY-NC-SA 4.0.

Pathways to maximise chemicals output from oil

Note: although an important share of chemicals are produced from gas-derived products, particularly in certain countries such as the United States, this section focuses on oil-based production pathways only, and on a set of very specific pathways to increase the production of chemicals directly from crude oil.

Rationale

Historically, chemicals have only been a minor by-product of refining operations. Today, on average 10% of a barrel of oil is converted to chemicals – with values ranging between 5 and 20% depending on the systems considered [23].

The oil and petrochemical industries are facing a **dual challenge** [24]. Along with the expected decline of fossil transportation fuels, overall demand for oil refining might also decline. Meanwhile, demand for petroleum-derived chemicals is expected to increase. Therefore, petrochemicals will constitute a higher share of the remaining demand and are likely to become key drivers of oil companies' profitability. Strategies targeting an increase in the ratio of chemicals to fuel output from oil refining are thus gaining momentum among industrials. Generally referred to as **crude oil to chemicals (COTC)**, those are mainly targeting the production of olefins and aromatics.

Conversion pathways

Converting crude oil to chemicals is not straightforward. Direct processing of crude oil in steam crackers has not proven successful until recently due to impurities (especially for heavier feeds) that lead to process issues such as coke formation or fouling [25]. Yet, several approaches are being explored by industrials [24], which include:

- Adapting existing **fluid catalytic cracker (FCC)** technologies to deliver larger petrochemical outputs (olefins and aromatics), for instance by running conventional FCC under more energy intensive conditions to optimise propene production.
- **Refinery reconfigurations**, such as increasing hydrocracking capacity while aiming at a higher yield of light-end feedstock, or altering reforming conditions to maximise aromatics outputs.
- **Direct conversion** through novel technologies that do not rely on traditional units, mostly focusing on utilising (very) light crude oil.

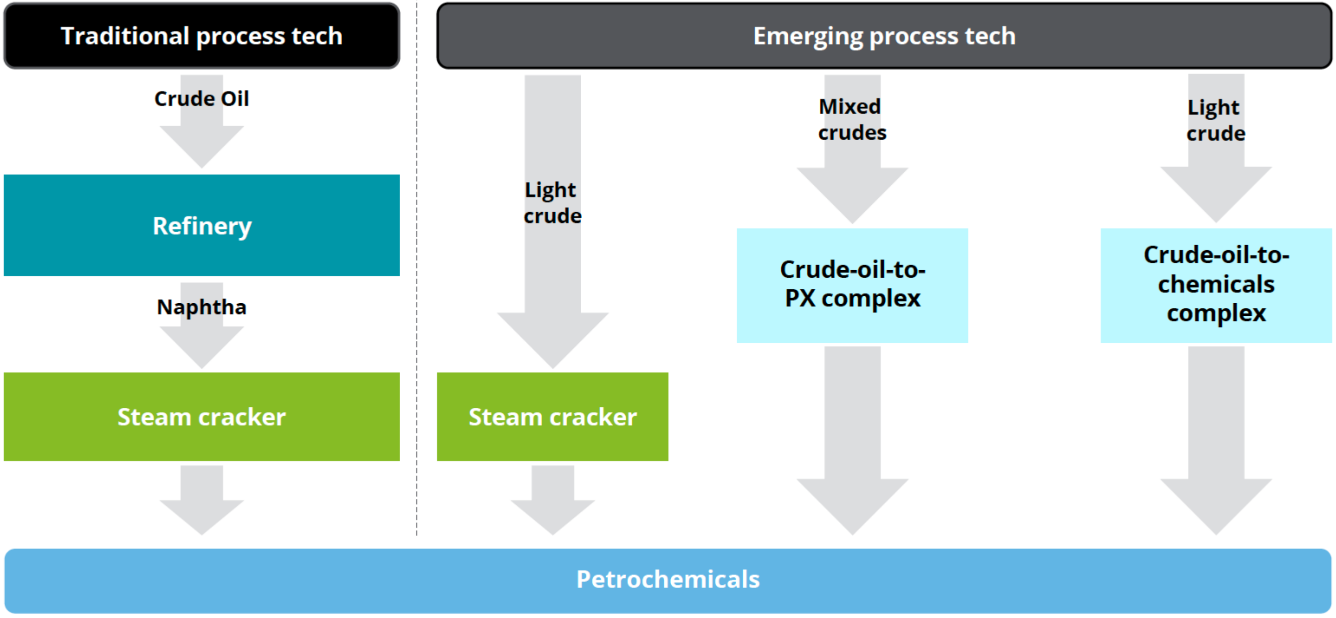


Figure 4. Visualisation of approaches to more direct pathways to producing petrochemicals from crude oil Image from Deloitte, 2021 [26]. A more detailed process is shown in **Figure 14** in Appendix 2. PX = paraxylene.

Possible evolutions

COTC is a nascent field that comes after several decades of increasing integration between refining and petrochemical activities [27], [28]. Depending on the extent to which conventional or novel technologies are developed and combined, petrochemical yields ranging between **40% and 80%** of a barrel of oil have been announced by different industry players, who expect an increase over the next decades as the different technologies develop (**Figure 5**).

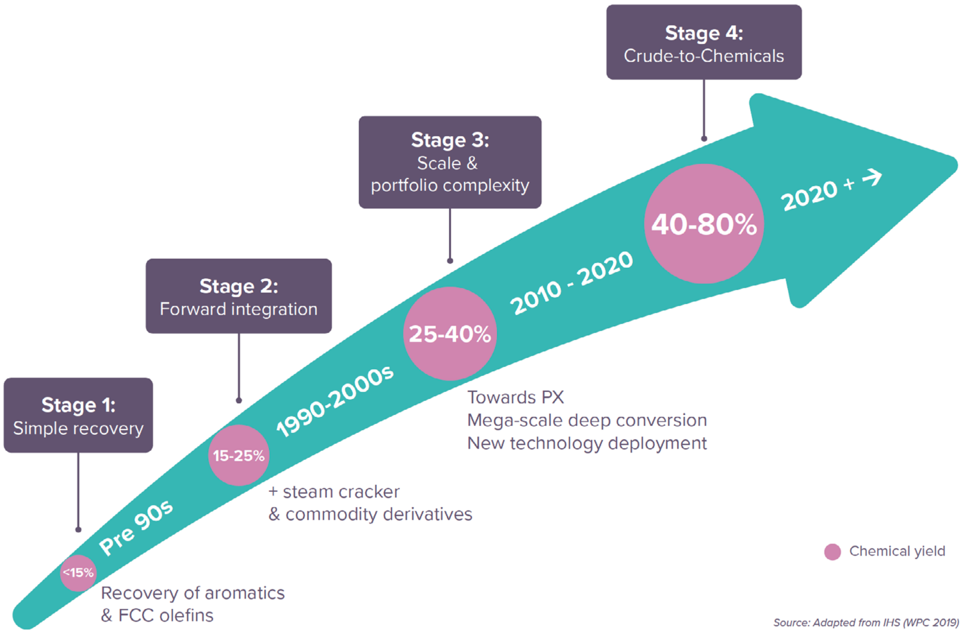


Figure 5. A possible evolution of COTC yields. Image from Axens [28].

For now, much of the activity around COTC has been occurring in the Middle East and in China, South Korea and Japan [29]. Most of these technologies are at a (very) low maturity level, and no single approach has emerged as a game-changer yet – given the variety of possible refinery configurations and strategies, this situation is unlikely to change.

A list of key COTC projects is given in Appendix 2 – Crude oil to chemical projects.

For now COTC has mainly spurred the interest of large oil companies willing to penetrate the petrochemical market [29]. Deloitte highlights that, if deployed, COTC technologies may lead to considerable disruptions of the petrochemical industry, bringing production of chemicals to a refinery scale [30] – a single COTC unit in the Middle East would be able to produce several megatons of chemicals per year. Please refer to **Table 2**, Appendix 1 for an overview of primary chemical production volumes. In that regard, the articulation between the refining and petrochemical sectors remains unclear. Although increased integration has been observed between the refining and the petrochemical industries, they remain very different businesses – refiners focus on a handful of feedstocks sold as bulk commodities, while petrochemical players are involved in much more diverse value chains targeting specific customer segments.

A climate-focused approach?

Currently, it seems that the main motivation behind COTC strategies is to maximise the margins resulting from chemicals production compared to transportation fuels [29]. Although the energy transition and the decline of internal combustion engines are possible motivations for the sector to maximise petrochemical yields from the refining of crude oil, there is **no clear evidence that chemicals produced via COTC will provide any benefit in terms of GHG emissions** [31]. Although those processes aim to increase the share of chemicals produced, few are likely to reach 100% chemical yields, at least in the coming years. A key question thus remains regarding the possible uses of the remaining fossil products, and their related climate impacts. Moreover, such pathways would not avoid the end-of-life emissions that occur once chemical products are used and disposed of or incinerated. **For the moment, it seems that no study has thoroughly assessed the life cycle impacts of COTC approaches.**

3. Bio-based chemicals

Using biomass: key processes and challenges

Current production and rationale

Biomass is already used in several chemical processes, mainly to produce detergents, cleaning agents, cosmetics, lubricants, as well as some bio-based plastics. Over the last decades, the transport sector has been a central driver of biomass use at the industrial scale through the development of biofuels and related infrastructures (in particular bio-ethanol, which is also a major chemical commodity).

However, such uses currently represent a negligible share of total demand in each of these sectors – only a few percent of the carbon embedded in chemicals and derived materials [32]. Sourcing carbon from biomass can be key in enabling the manufacturing of carbon-neutral or even carbon-negative chemicals if sustainable biomass management practices are ensured.

Biomass feedstocks

Because biomass is typically composed of a range of organic molecules that contain both hydrogen and carbon atoms, alongside other atoms (predominantly oxygen and nitrogen), any type of biomass can theoretically be used as a feedstock in the production of chemicals.

Biomass feedstocks are often discussed in terms of **“generations”**: first-generation feedstocks refer to food crops (corn, beetroots, sugar cane), while second-generation encompasses all the forms of biomass that are not dedicated to food uses (including woody biomass or waste from food crops, for instance). Third-generation refers to the biomass of microorganisms such as algae or bacteria.

Biomass feedstocks can also be categorised based on their **chemical classes**, which might overlap with the aforementioned classification. To date, **(a) sugars/starch** and **(b) triglycerides/oils** are the main resources used to produce biofuels and bio-derived chemicals, mostly from food crops such as corn (raising questions over possible usage conflicts with other sectors, which will be discussed later).

A shift to **(c) lignocellulosic** forms of biomass may also be possible in the near- to medium-term. Importantly, while lignocellulosic biomass is harder to valorise compared to first-generation biomass, it can be sourced from non-food crops (“energy crops”), such as the often-cited *Miscanthus*, and a range of biomass residues (non-edible parts of food crops, forestry residues, industrial and municipal solid waste). In particular, **lignin**, a key component of lignocellulosic biomass and the world’s second most abundant biopolymer, is composed of around 60% of carbon and is seen as a crucial potential resource for unlocking large-scale industrial production of bio-derived chemicals, especially aromatics [33], [12].

Conversion pathways

Biomass feedstocks are very different from fossil hydrocarbons in terms of their composition, often consisting of complex, highly oxygenated molecules. Several conversion pathways are envisioned to turn raw biomass materials into useful chemicals. Such routes can be broadly classified into:

- **Thermochemical** routes that lead to the production of a syngas, mainly composed of H_2 and CO in varying proportions, depending on the feedstock. Later on, the syngas can be used through various processes (such as Fischer-Tropsch) to produce MeOH or naphtha, similarly to more traditional fossil syngas.

- A variety of **biochemical** routes that rely on processes such as catalysts, solvents or fermentation.

Before converting biomass to chemicals, some pre-treatment steps (milling, pressing, grinding, drying…) are often required to remove impurities due to inherent heterogeneity of feedstock. Those steps may be time-, energy- and cost-intensive.

Appendix 3 contains schematics showing the conversion pathways for: syngas to chemicals (**Figure 15**), bio-based feedstocks to chemicals (**Figure 16**), and CO_2 to chemicals (**Figure 17**).

Biorefineries

A "biorefinery" should not be interpreted as a mere transposition of an oil refinery fitted with biomass feedstocks. Instead, the term designates a large variety of facilities that enable "the sustainable processing of biomass into a spectrum of marketable products (food, feed, materials, chemicals) and energy (fuels, power, heat)" [34].

Several classifications exist [34], [35], which can be based on:

- The **inputs** and **outputs**: phase I biorefineries produce one feedstock from one primary product with fixed capacity, phase II biorefineries yield several products from one input product, and phase III produce several outputs from a variety of feedstocks.

- The **type of biomass feedstocks** (sugar, triglyceride, lignocellulosic).

- The **processes involved** (IEA Bioenergy's classification [34]): mechanical/physical, biochemical, chemical, thermochemical.

Petrochemical plants and refineries, which are among the most materially efficient technological operations, could serve as an example for biorefineries developments over the next decades. Integrated biorefineries would maximise the value retrieved from all extractable fractions of biomass, by targeting the production of both biofuels and bio-derived chemicals for example [34]. Various combinations of the types mentioned above can thus be envisioned [36].

Biomass availability and prioritisation of uses

Although bio-based chemicals have the potential to be carbon-neutral or even carbon-negative in certain cases [37], their overall impacts depend on how sustainably the biomass source can be produced and handled.

Articulating biomass uses is all the more complex considering the **total global sustainable potential**, which is difficult to estimate, and indeed many projections actually shrink due to increased climate impacts over the next decades. While theoretical potential values around 100 EJ/year are often cited [38], some estimates are much more conservative (40–60 EJ/year in 2050 – roughly the same biomass use as in today's energy system, which was around 40 EJ according to latest IEA WEO data) [39], [40].

The possibility of sourcing biomass from **waste streams** is sometimes described as a "no-regret" option [12], providing a solution to the issue of waste handling while encouraging a circular perspective and preventing competition with food uses. However, collecting biowaste that would otherwise return to ecosystems may have further negative impacts that should not be neglected, for instance on soil quality and humus content – Agora Industry [12] estimates that preventing such negative outcomes could reduce potential volumes of available biomass by half (in the specific case of Germany).

In a "bio-economy" approach, limited available biomass must be adequately distributed among a large variety of potential uses, which requires some prioritisation. The concept of **cascading biomass uses** is often used to conceptualise the hierarchy between biomass sources depending on their quality and their final use (as material, as feedstock or as energy), prioritising pathways that maximise circular and efficient biomass uses. In that perspective, using biomass as feedstock to produce chemical intermediates is higher in the hierarchy than energetic uses, but lower than material and feedstock uses, which are most cost-effective and lack alternative mitigation options (see **Figure 6**). Similar concepts or parameters, still being explored, include the **biomass utilisation efficiency** or the **biomass utilisation factor**, a recent concept aiming at combining production efficiency and cascading uses [41].

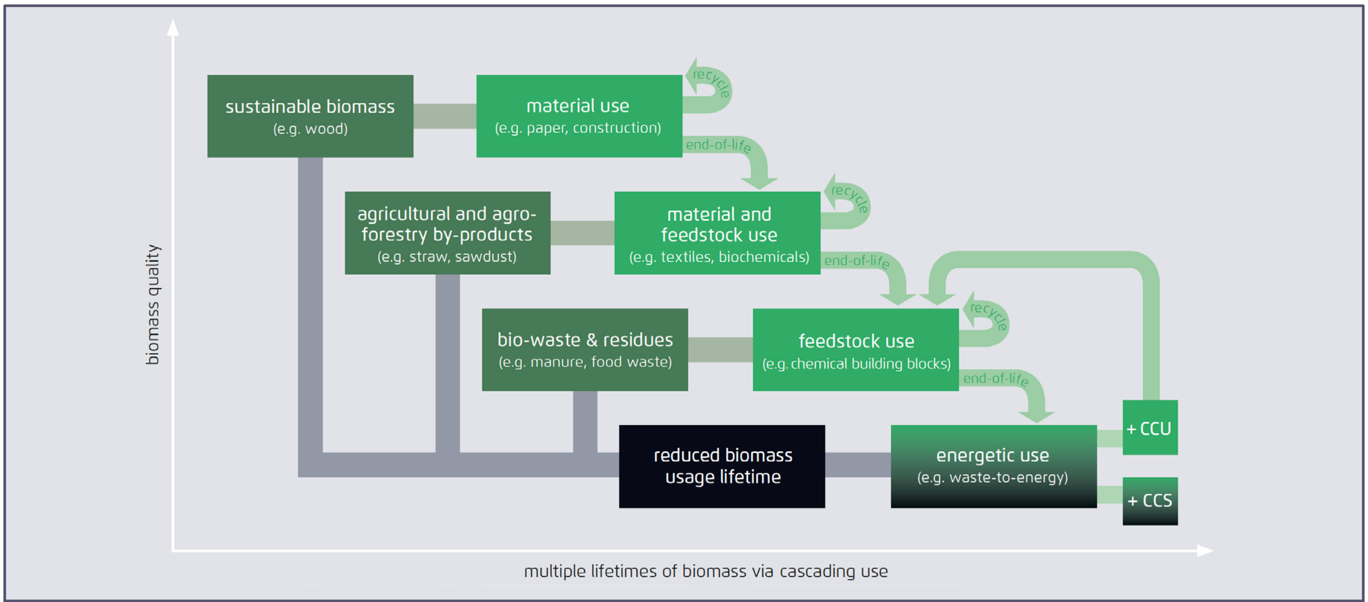


Figure 6. The cascading uses of biomass. Image from Agora Industry [12]. CC BY-NC-SA 4.0.

Bio-based chemicals as a drop-in or disruptive approach?

While the history of the petrochemical industry has been one of converting relatively simple molecules into more complex compounds, a shift towards large-scale bio-based chemistry could represent a switch in the opposite direction [36]. Several approaches can be conceptualised as follows [42]:

- In **"drop-in" pathways**, biomass feedstocks are used to produce base chemicals that have identical properties to their fossil-based counterparts, such as ethene or methanol. This approach asks for minimal adaptation of existing infrastructures and processes, at the expense of lower biomass utilisation efficiency [12].

- Another pathway consists of focusing on producing **novel** or **dedicated chemicals** that more efficiently exploit the intrinsic properties of biomolecules, such as their complex composition and functionality *(see example* ***(a)*** *in* ***Box 1****)*. In addition to displacing the use of fossil carbon, these may be a more sustainable alternative to some damaging (i.e., toxic) chemicals currently used today, and in some cases even show better performances. This more disruptive approach would however rely on innovative processes and require more significant changes to current infrastructures and value chains, as well as shifts in buyer or consumer practices, leading to potentially significant barriers to adoption.

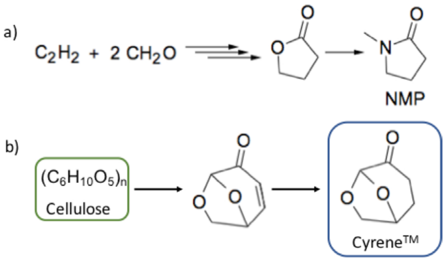
- **Hybrid** approaches, sometimes referred to as "smart drop-in" strategies, combine drop-in chemicals with bio-based compounds used for improving one or several steps of traditional processes *(see example* ***(b)*** *in* ***Box 1****)*.

Drop-in and novel approaches may be **complementary** [43]. From a drop-in perspective, biomass gasification to syngas (an already mature technology) and later conversion to chemicals could provide a relevant near-term opportunity to replace large volumes of fossil carbon with biogenic carbon [12]. As would be expected, novel chemicals, are best deployed in small-scale applications at first [43].

What are dedicated or drop-in bio-based chemicals?

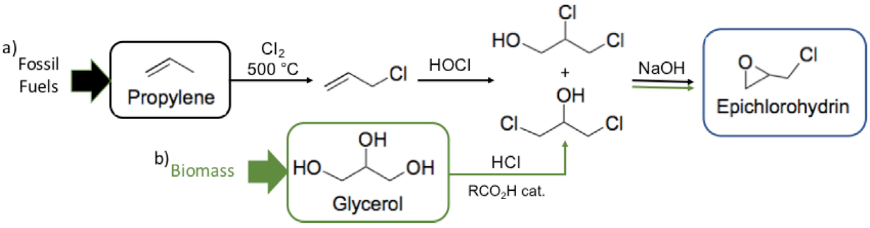
(a) Novel chemical

Cyrene™ can be derived from waste cellulose and replace *N*-methyl-2-pyrrolidone (NMP), a toxic solvent currently used in the production of textiles, resins and plastics.



(b) "Smart drop-in"

Epichlorohydrin, also used to produce resins and plastics, is currently produced in a 3-step fossil pathway from propene. However, it could be produced in 2 steps only using biomass-derived glycerol as an input.



Box 1. Examples of bio-based chemicals. Image from Carus *et al.*, 2017 [42].

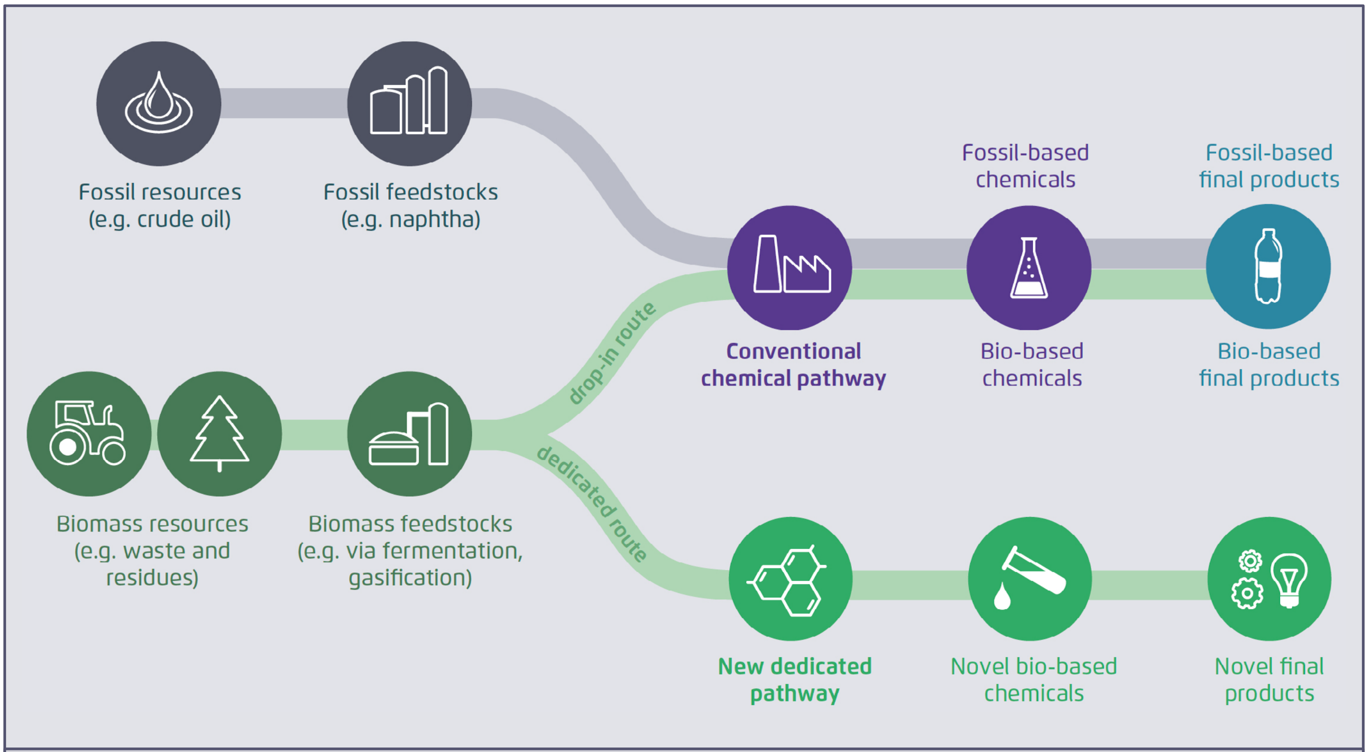


Figure 7. A simple visualisation of drop-in vs dedicated routes for bio-based chemicals. Image from Agora Industry, 2023 [12]. CC BY-NC-SA 4.0.

Value chain transformations

Whether drop-in or disruptive strategies are adopted, replacing fossil feedstocks with biomass will have major consequences on the key operations and skills required by the current petrochemical industry.

For instance, consider the inputs: **collecting** raw biomass has little in common with the extraction and refining of fossil fuels. Biomass collection rates are prone to **seasonal variations** that may lead to mismatches between feedstock supply and demand. **Storage** would only provide a partial solution, for many bio-feedstocks deteriorate rapidly.

The **transport** of biomass raises further questions. Biomass raw materials, most often solid, cannot be transported via pipelines. A possible solution could be to convert biomass into intermediaries (syngas or MeOH) prior to transport. This may have important ramifications for the location and scale of future biochemical plants. For example, rather than relying on the skills and value chains of the current petrochemical industry, a shift toward bio-based feedstocks may benefit from the existing infrastructure of other activities, such as the pulp and paper industry [12].

4. CO_2–based chemicals

Rationale

A much-discussed molecule in the fight against climate change, CO_2 could also provide an interesting source of carbon for producing chemicals. As carbon capture is gaining momentum in the discussion on decarbonising industrial sectors, several players are carefully considering **carbon capture and utilisation (CCU)** technologies to provide a carbon source for chemicals. Note that some types of carbon dioxide removal (CDR) can also provide a stream of CO_2 but the exact source of CO_2 is beyond the scope of this report; we focus here on its conversion to chemicals.

CO_2 sources and climate impacts

The climate benefits of captured CO_2-based chemicals are not to be taken for granted, and depend on several aspects, illustrated in **Figure 8**.

First, the **source of CO_2** is of primary importance: while the use of atmospheric or biogenic CO_2 could theoretically provide a pathway to carbon-neutral (or even net-negative, see SYSTEMIQ 2022 [37]) chemicals, CO_2 from fossil carbon can at best avoid or reduce emissions from incumbent pathways and can never lead to carbon-negative products.

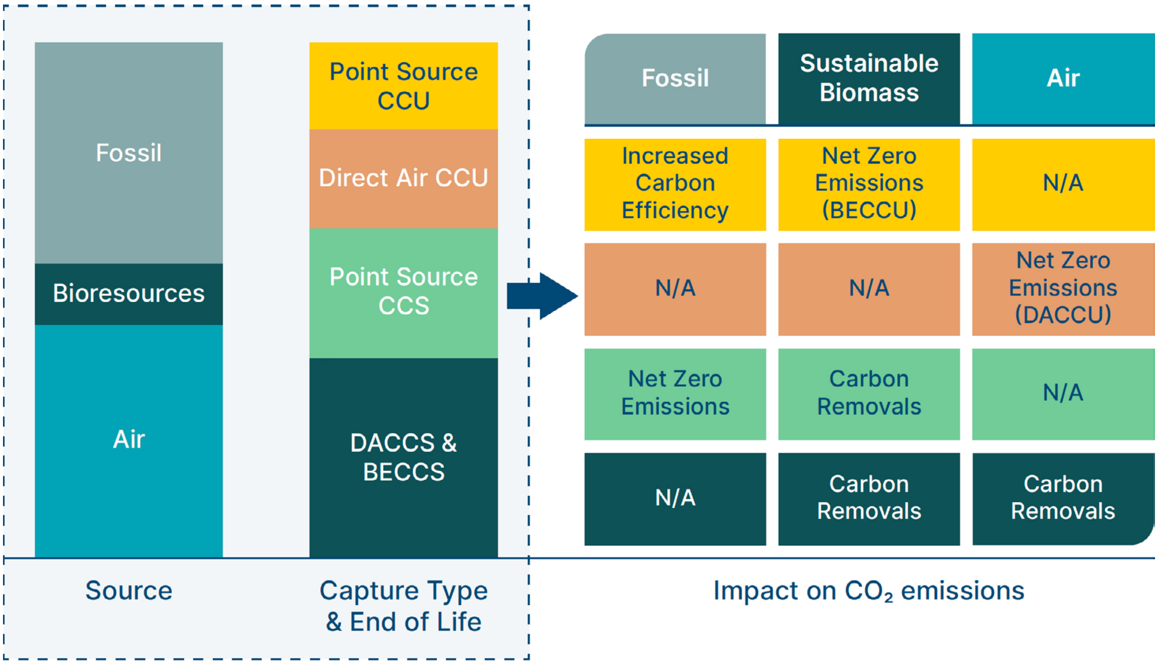


Figure 8. Impacts of on overall CO_2 emissions of CCU-based products (and CCUS) depending on the CO_2 source and capture type. Image from Energy Transitions Commission, 2022 [44].

CCU = carbon capture and utilisation, CCS = carbon capture and storage, DACCS = direct air carbon capture and storage, BECCS = bioenergy with carbon capture and storage, BECCU = bioenergy with carbon capture and utilisation, DACCU = direct air carbon capture and utilisation.

Another essential variable not shown in **Figure 8** is the **lifetime** of the products. Once products reach their end of life, they might release the carbon back to the atmosphere as CO_2 (when they deteriorate or are combusted) or CH_4 (decomposing in landfills). The lifetime of chemicals varies from several weeks to several years, or even longer in the case of some long-lived plastics.

Finally, all **lifecycle emissions**, as well as other non-climate impacts, need to be considered, which can include electricity-related emissions, for example. Life cycle assessment (LCA) is particularly challenging in the case of chemicals because of the large diversity of possible combinations or products and processes combinations, the low maturity of processes, the generally poorly known end-of-life behaviour and the difficulty in incorporating time dynamics, among other reasons.

Conversion pathways and target chemicals

Several pathways are envisioned to turn CO_2 into useful molecules, as described by the IEA [23]:

- **Direct conversion** through CO_2 hydrogenation.
- **Indirect conversion** through syngas production and reverse water-gas shift reaction.

Through these conversion routes, nearly all C-containing chemicals can theoretically be generated from captured CO_2 [45] – see **Figure 17** in Appendix 3. Turning CO_2, a low energy state molecule, into useful products generally requires adding a lot of energy in the processes. For that reason, molecules that already contain C-O bonds, such as MeOH, appear to be interesting target molecules, for they do not require CO_2 to be further reduced [23].

Finding the right sources of CO_2

CO_2 can be captured from **point sources** (fossil plants and other industrial equipment, as well as bioenergy facilities) or removed from the **atmosphere**. Only atmospheric and biogenic CO_2 can be used to manufacture CO_2-negative chemicals. Typical point sources include production plants for steel and iron, cement or ammonia. The chemical industry generally requires **high-purity CO_2** compared to CO_2-derived concrete production, which tends to require more concentrated CO_2 sources or extra purifying steps, both of which are likely to add to costs.

Resource and impacts at scale

In a "what-if" scenario, the IEA explored what it would take to produce the current amounts of chemicals entirely from CCU technologies [23]. Theoretically, while the supply of CO_2 would not be a limiting factor with 1.4 $GtCO_2$ required, the energy demand would be more challenging at 11,700 TWh (representing around half of the world's electricity production in 2018). More nuanced prospective results from various scenarios are further described in **Section 5. Scenarios**.

Electricity is a cornerstone of CO_2-based production pathways. A first challenge is to ensure the electricity used is low carbon. Depending on the end products, a threshold ranging from 260 to 74 gCO_2e/kWh (for MeOH and xylenes respectively) has been shown to be necessary for ensuring CCU-based chemicals make sense from a climate perspective [45]. Such **carbon intensities** of energy generation are about two to six times lower than the global average in 2022 [46]. Therefore, in many regions, using the grid to power CCU-based processes will not provide a climate solution in the near-to medium-term, at least before the grid is decarbonised. Alternatively, shifting production to more suitable locations (with cleaner energy sources) and importing the resulting products, or relying on dedicated off-grid low-carbon production, may be the appropriate route to net-negative CO_2-based chemical production.

Another challenge lies in the quantities of low-carbon electricity that CCU-based pathways may require (see **Section 5. Scenarios**), and which may have several unintended impacts. Refineries powered entirely by wind and solar could require more than 150 times as much land as current refineries [47]. Furthermore, such electricity demand might come at the expense of other sectors that also require low-carbon power: using 1 kWh_{el} for decarbonising mobility is often more efficient in terms of emissions reductions than using it for producing CCU-based chemicals [45].

The same logic also applies to **low-carbon hydrogen** and **captured CO_2** itself. Chemicals are only one of many possible applications of captured CO_2, next to construction materials and synthetic fuels. As for biomass, **prioritising uses** may be necessary, and may be done based on several criteria such as the scale-up potential, mitigation potential, energy requirements, etc. As an example, using direct air capture with the intention of providing CO_2 for chemical production might compete with using the technology coupled with geological carbon storage for carbon dioxide removal (CDR) purposes [13].

Towards a methanol economy?

Already fundamental in the chemical industry, there may yet be an even bigger role for **methanol (MeOH)** as a platform chemical, in particular through **methanol-to-X (MTX) routes** to produce olefins (MTO) and aromatics (MTA). This would be part of what some have called a large-scale **methanol economy** [48]. **Electricity-based MeOH (e-MeOH)** can be produced either via CO_2 hydrogenation or catalytic conversion. Provided that the electricity, CO_2 and H_2 used are all low-carbon, the whole process could be a gamechanger for low-carbon MeOH production. Such technologies are gaining momentum and have now reached a high technological readiness level (TRL) of approximately seven (prototype stage).

While the direct synthesis of olefins from CO_2 is at a low technological maturity level (TRL 3–4), some **MTO** processes are already running at large commercial scales in China, generating about a fifth of the country's domestic HVC production, although unfortunately they currently run on coal-derived MeOH. Adapting those processes to e-MeOH is doable and may represent an interesting low-carbon pathway for producing olefins in the medium-term. **MTA** is currently a less developed pathway (TRL 7), partially because it involves more process steps to produce more complex molecules. While olefins and aromatics are generally co-produced in refineries, MTA is one of the only ways aromatics can be produced independently from olefins in a net zero future [37].

Controlling the **individual shares** of the olefins and aromatics that are physically produced via MTX processes is complex. Meeting ethene demand through large-scale MTO might lead to an oversupply of propene, while MTA may result in benzene or xylene oversupply [37]. The shift to large-scale chemical production via MTO and MTA may thus require some flexibility in production.

Using or storing CO_2?

The implementation of CCU pathways shares common challenges with large-scale deployment of CCUS, described earlier. A remaining question is that of the **balance between CCU and CCUS** in the portfolio of climate solutions. While by 2050, CCUS largely dominates in terms of volumes in net zero scenarios, interesting synergies could be observed between both approaches. By establishing an easily identifiable use case for captured CO_2, CCU-based chemicals could spur investment in capture facilities and act as a catalyst, potentially solving the CCUS “chicken-and-egg” conundrum [49]. The chemical industry could thus act as a system service provider to other industries willing to rely on CCUS [37]. CCU applications, generally small-scale, might in return benefit from mutualising transport infrastructure built for larger-scale CCUS facilities, for instance in CCUS hubs [50].

5. Scenarios

A large number of studies and scenarios focus on possible trajectories that would allow the chemical industry to reduce its emissions or reach carbon neutrality. Such analyses comprise scenarios focusing on the chemical industry alone, on industry in general (e.g. Gailani *et al.* 2024 [51]), or more broadly on energy systems (IEA 2023 [52]). Scenarios can widely differ in terms of their technical scope (i.e., the chemicals, technologies and processes that are considered and modelled), timescale (from 2030 to 2100), geographical scopes (global, European level, single country), goals (emissions reductions, net zero of the chemical industry, defossilisation) and level of detail and granularity.

For the purpose of this assessment, scenarios that focus solely on the transition of the chemical industry at the global scale and that present a strong emphasis on alternative feedstocks were compiled and assessed.

Table 1. Compiled scenarios and key results. Indicative values are given to put scenario ranges in perspective, both for 2022 and 2050 (projections from IEA 2023 [52] and ETC 2023 [1]).

Reference	Rationale and key hypotheses	Scenario	Feedstock shares (non-NH_3)			
			fossil	recycl.	bio	CCU
Lopez *et al.* 2023 [14]	Develops several scenarios reaching net zero by 2040, 2050 and 2060, based on MeOH as a key platform chemical (both bio-MeOH and e-MeOH). Variants with high (H) and low (L) biomass availability are considered.	NZE 2050H	**0%**	–	**21%**	**79%**
		NZE 2050L	**0%**	–	**6%**	**94%**
Renewable Carbon Initiative (RCI) 2023 [32]	Aiming at providing a pathway towards fossil-free chemical industry by 2050, RCI proposes an explorative scenario focusing on embedded carbon and renewable carbon sources.	–	**0%**	**55%**	**20%**	**25%**
Saygin & Gielen 2021 [53]	Decarbonisation scenario for the global chemical industry, assessing the techno-economic potential of 20 decarbonisation options, with a strong focus on feedstock and embedded carbon.	–	**36%**	-	**25%**	**39%**
Kätelhön *et al.* 2019 [45]	Focuses on the technical potential of CCU for mitigating climate change in the chemical industry by 2030. Two scenarios are developed: a *high-TRL scenario* where most chemicals are derived from e-MeOH, and a *low-TRL scenario* where chemicals are directly produced from CO_2 after significant progress in catalysts.	–	-	-	–	**100%**
SYSTEMIQ 2022 [37]	In their "Planet Positive Chemicals" report, SYSTEMIQ explores the possible transformations of the chemical industry towards net zero with high granularity. The *LC-ME* explores a "most economic" pathway towards net zero, while *LC-NFAX* focuses on the fastest possible abatement trajectory (no fossil capacity installed after 2030).	LC-ME	**74%**	-	**15%**	**8%**
		LC-NFAX	**18%**	-	**43%**	**36%**

	Electricity (TWh)	**Biomass (EJ)**	**H_2 (Mt)**	**CO_2 for CCU ($MtCO_2$)**	**CO_2 for CCUS ($MtCO_2$)**
Range in scenarios for chemicals industry	4,800–32,000	9–35	136–590	up to 3,700	0–940
Global totals in 2022 for all sectors	28,000–29,000		90	40	
Global totals in 2050 for all sectors	77,000 [52] 61,000–73,000 [1]	50–60 [1]	420 [52] 360–590 [1]	3,736 [52] 4,000–4,800 [1] (point-source capture only)	

Key conclusions from scenarios

- **Technologies:** Most scenarios focus on technologies that are already mature or still need to be proven at scale (TRL ≥ 7). Apart from Kätelhön *et al.*'s *low-TRL* scenario [45], less mature processes are often excluded from models and considered only in qualitative terms.

- **Biomass:** Bio-based chemicals play a role in most scenarios. The type of biomass considered is not always specified. Lopez *et al.* [14] rule out the use of generation 1 biomass, while RCI [32] has a more flexible approach considering a wider variety of feedstocks. The maximum sustainable biomass potential considered also varies. Lopez *et al.* [14] use Creutzig *et al.*'s [38] upper estimation of 100 EJ, and define two scenario subvariants, one optimistic (35 EJ) and the other more pessimistic (9 EJ) on biomass availability. In RCI's scenario [32], part of the biomass demand (about one quarter) is met through resources previously used for biofuels but freed up thanks to the development of alternatives for decarbonising transport (such as electric vehicles).

- **CO_2 utilisation:** Kätelhön *et al.* [45] provide a technical potential of 2.77–3.72 $GtCO_2$ by 2030 for CCU technologies, which they present as a maximum estimate that does not consider detailed constraints on deployment. CCU plays a more balanced role in the other scenarios.

- **Electricity and H_2 demand:** Unsurprisingly, the highest values for electricity demand occur in scenarios with high shares of CCU, and may represent up to 50% of the power generation capacity projected by 2050. This is mainly due to demand for H_2 production, a very solicited resource; volumes required for CO_2-based chemicals sometimes exceed H_2 production capacities projected by the IEA for 2050. Demand for electricity is reduced by almost 50% in Kätelhön *et al.*'s *low-TRL* scenario compared to the *high-TRL* variant [45], highlighting the disruptive potential of new CCU catalysts with respect to energy efficiency.

- **Remaining share of fossil fuels:** Some scenarios explicitly rule out the continued use of fossil fuels, even when abated with carbon capture [32]. The highest fossil-derived chemical share is found in SYSTEMIQ's *LC-ME* [37], a scenario prioritising the most economic pathways where abated fossil fuels represent 74% of feedstock by 2050, 361 $MtCO_2$ to be captured and stored (excluding ammonia).

Further resources

Other scenarios or roadmaps provide further insights at country or regional levels:

Kloo *et al.* 2023 [18] provides an exhaustive meta-analysis of decarbonisation and defossilisation scenarios and roadmaps with a main focus on Germany and neighbouring countries.

Agora Industry 2023 [12] explores decarbonisation strategies for the German chemical industry based on three pillars: direct electrification, circular carbon economy and renewable feedstocks.

DECHEMA 2017 [54] provides a detailed review of possible technological pathways for decarbonising the European chemical industry, with a key focus on maturity, costs and mitigation potentials.

World Resources Institute 2024 [9] explores what a shift to renewable carbon feedstocks would imply for the production of chemicals in the US, with a detailed geographical analysis and high granularity down to the facility level.

Meys *et al.* 2021 [55] provides a circular carbon pathway for plastics.

6. Sketching the impact of a switch to renewable feedstocks on the chemical industry

Diversifying the feedstock portfolio

There is "no technological silver bullet based on renewable carbon to make the chemical industry fully sustainable", which calls for a deployment of a **"portfolio of alternatives"** [56]. The need for such a portfolio is quite clear when surveying the different scenarios presented in **Section 5. Scenarios**.

Synergistic opportunities appear between the different routes. This paper has already described such opportunities between CCU and CCUS technology. In polyurethane production, a combination of bio-based and CCU-based production leads to higher emissions mitigation while reducing the impact on resources [57]. Encouraging such synergies is all the more important given that pathways based on renewable feedstocks generally tend to require both more energy and land use when compared to the current fossil fuel-based system [58].

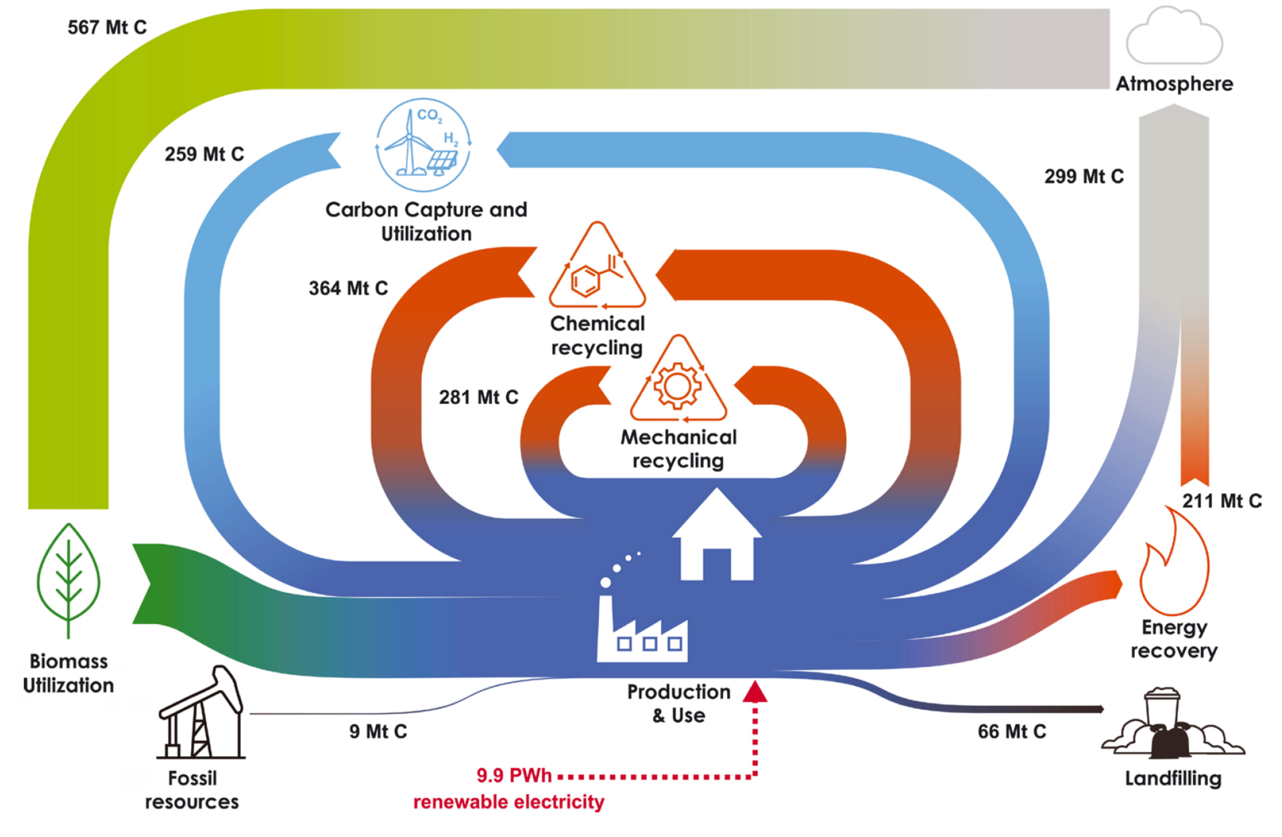


Figure 9. An illustrative pathway for low-carbon plastics, articulating increased recycling and novel feedstocks. Image from IPCC 2022 [59].

Coordinating the different solutions in time

The different technological levers for the defossilisation of the chemicals industry may become market-ready at different times. And so it will be necessary to coordinate the timing of solutions' entry on the market.

Some research proposes a transition that first maintains fossil facilities equipped with CCUS to reduce their emissions, and gradually switches to biomass feedstocks, starting with first generation biomass sources and later focusing on lignocellulosic feedstocks as technologies mature. Captured carbon/CO_2 (and DAC) play a role later in time, when (if) the technology becomes developed enough to compete with biomass [15].

According to some authors, CCU infrastructures could first develop using CO_2 from point sources, gradually substituted by DAC-captured CO_2 once (and if) the technology is able to develop at scale in the longer term [56].

Focusing first on specific products may also help in launching a more diversified market later. In the IEA's report on CO_2 utilisation for instance, polyurethane is identified as the most relevant chemical application for CCU in the short- to medium-term, and envisioned as a possible way for CCU value chains to mature and eventually be extended to further chemicals [23].

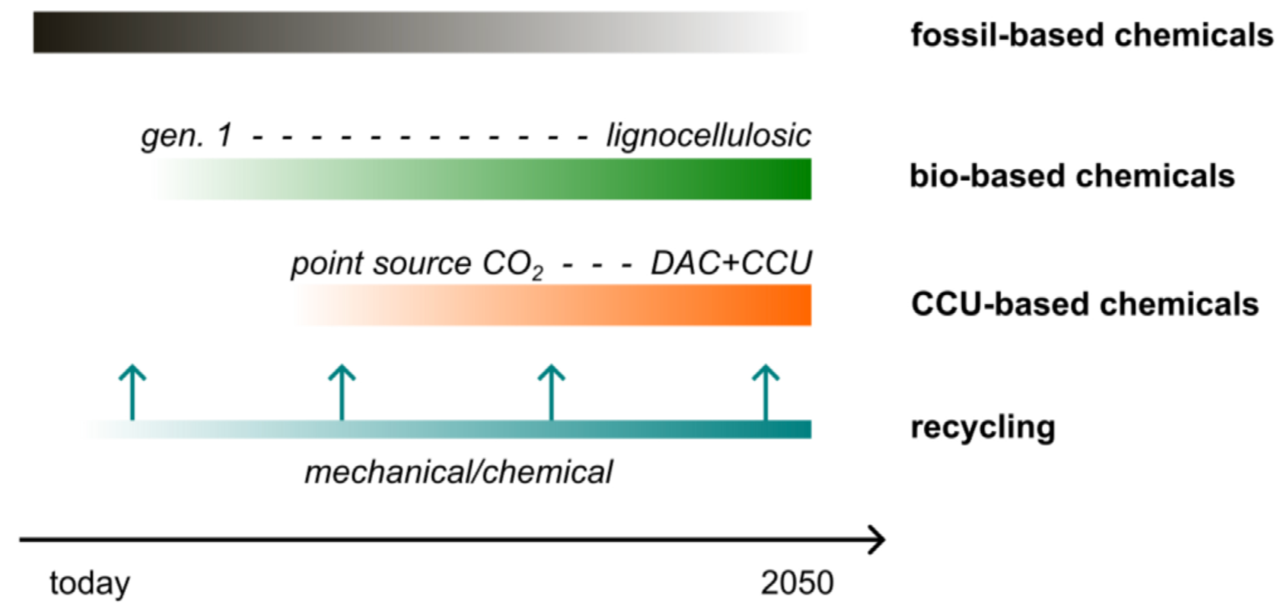


Figure 10. A possible, illustrative pathway towards the uptake of alternative feedstocks in the chemical industry. Visual by François de Rochette. DAC = direct air capture, CCU = carbon capture and utilisation.

Allocating carbon uses

Determining which source of carbon may be most relevant for chemical production will heavily depend on aspects such as:

- The **local context** and the availability of certain resources (biomass, CO_2, low-carbon and cheap electricity), which may considerably reshape the geographical production dynamics (as detailed later)
- The overall **lifecycle impacts**, which requires clear, comparable LCAs
- The **type of chemicals**. CCU may be a more interesting option for producing bulk chemicals, at least in the short-term, while biomass compounds, with their inherent complexity could be more relevant for producing complex or higher value molecules, such as aromatics (that share certain similarities with lignin).

In the likely first phase of chemical defossilisation, in which non-fossil feedstocks will progressively enter existing value chains, for instance as inputs in conventional refineries, it may be challenging to account for the overall climate impact of feedstock substitution and allocate it to the final products. Tools such as **mass balance** and **free attribution** have been developed by certification frameworks (ISCC PLUS, RSB, REDcert) and are already used in working environments, for instance when substituting fossil inputs with biomass [60]. Such concepts are fostered and further challenged by independent and academic players such as the Renewable Carbon Initiative [61], advocating for transparency and harmonisation of methods.

Interplay of chemical defossilisation strategies with other climate technologies/solutions

Certain synergies can be found between chemical defossilisation and other decarbonisation levers, such as energy efficiency gains and CCUS [62]. Overall, the **reduction of primary demand** through increased circularity ("eliminate, reduce, substitute, recycle") helps to lower the scale at which novel feedstocks and resulting infrastructure need to be deployed – by 20% [37], 35% [12] and up to 55% [32]. Circular economy approaches also have the key advantage of limiting the negative impacts of resource exploitation [13]. It is therefore a key adjustment parameter in any decarbonisation or defossilisation strategy.

Allocating resources such as captured CO_2, H_2 or biomass to the chemical industry should be considered through a broader lens that accounts for the decarbonisation needs of other sectors (as mentioned earlier).

Production costs and cost structure

Absent of economic incentives, technologies based on novel feedstocks will compete with incumbent processes that have been optimised for decades and that benefit greatly from economies of scale and low fossil fuels prices (often subsidised).

Fossil-based production is currently significantly cheaper than alternative low-carbon routes. In some cases, primary chemicals produced in a low-carbon process are more expensive than their fossil equivalents by at least one order of magnitude (**Figure 11**).

Costs for raw biomass materials can represent a large share of overall production costs of bio-derived chemicals, up to about 60–70% [54]. The type of feedstock is thus a key determinant of the economic viability of the product and/or process. For CO_2-based pathways, CO_2, H_2 and electricity costs are the main economic drivers – techno-economic assumptions taken on the electricity mix, the capacity factor, etc. are thus crucial. Some sources find that very low H_2 costs (sometimes down to 0.45 $/kg, compared to 3–6 $/kg today) would be necessary to make CCU-based pathways competitive [56]. Reaching such low costs for green H_2 could take several decades, according to recent projections [63].

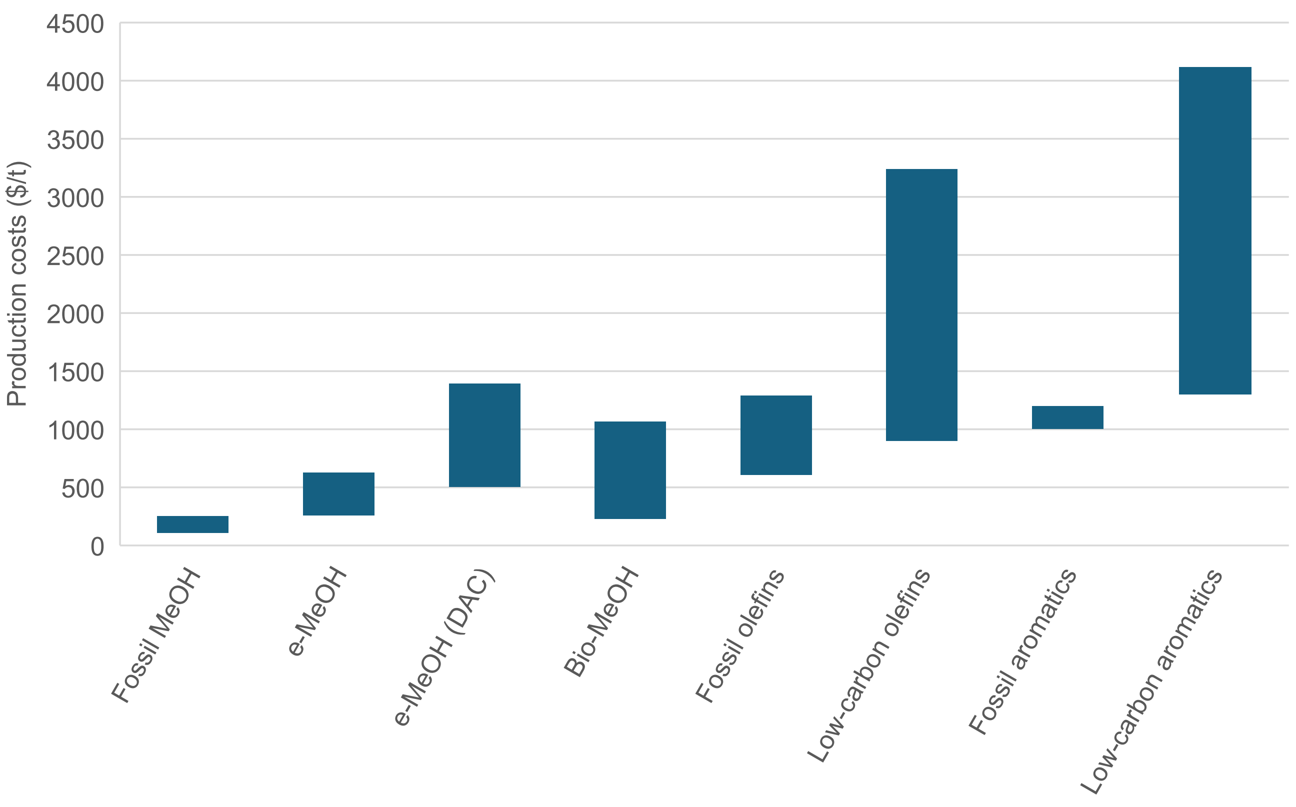


Figure 11. Cost comparison of production pathways for primary chemicals. 'Low-carbon olefins' and 'low-carbon aromatics' encompass a range of possible technologies (MTX, bio-oils, bioethanol dehydration etc.). Data: SYSTEMIQ 2022 [37], IRENA 2021 [64], DECHEMA 2017 [54], De Luna *et al.* 2019 [65].

MeOH

Fossil MeOH costs typically run between 100–250 $/t, with regional variations. Such low costs represent the main barrier preventing the adoption of the more expensive low-carbon pathways [64].

According to the IRENA, costs for bio-MeOH range between 320 and 770 $/t [64]. DECHEMA gives a wider range (160–940 €/t), mainly due to variability in raw biomass materials costs [54]. Using waste streams as raw materials could lower those production costs down to 220–560 $/t and 200–500 €/t respectively. High capital expenditure (CAPEX) drives the high production cost of bio-MeOH, which is approximately three times higher than fossil-derived MeOH [54].

CAPEX for e-MeOH is dominated by the costs of electrolysers, which may represent up to 75% of total installed costs [54]. Production costs depend strongly on H_2 costs, that need to drop below 1 $/kg for e-MeOH to be economically viable [37]. Using DAC-sourced CO_2 leads to more expensive MeOH compared to CO_2 from point sources, although there is high uncertainty on DAC costs at scale [37], [64].

Olefins and aromatics

Since MeOH is a primary chemical, MeOH costs are, unsurprisingly, the key determinant of olefins and aromatics production costs following MTX processes. According to SYSTEMIQ, MTO could be the cheapest means to produce olefins (1220 $/t), compared to naphtha-based (1500 $/t) or bio-based (2000–2600 $/t) pathways [37]. All routes are more expensive than incumbent fossil pathways (propene around 800 $/t, ethene around 1000 $/t). Because of the lower yield of MTA compared to MTO, this difference is even more important for aromatics which can cost up to four times more than their fossil-based counterparts.

Making low-carbon chemicals competitive

Providing detailed pathways to decrease the costs of chemicals is out of the scope of this study, however some important possibilities are worth mentioning. **Gradual integration** into fossil-based processes by increasing the shares of bio- or e-MeOH may be an opportunity for the value chains to mature progressively [64], and possibly observe economies of scale [54]. Mapping and **prioritising regions** with the most cost-effective resources (biomass, H_2, CO_2, electricity) will also be crucial. **Carbon prices** and **subsidies** would increase the competitiveness of bio- and CO_2-based chemicals compared to fossil ones, although the economic impacts of such incentives may vary depending on the chemicals, processes and locations [37]. Finally, the deployment of **related technologies** (H_2, DAC, etc.) that have a major influence on the economics of chemicals is also likely to bring production costs down – although this aspect is hard to quantify.

Decommissioning, retrofitting, new-built facilities

While **retrofitting** existing long-lived assets such as industrial plants is usually less capital-intensive than **decommissioning** and/or **building new facilities** [65], it is far from being a straight-forward solution, especially in the case of the chemical industry. Refineries and chemical plants are purpose-built facilities that involve highly integrated and optimised processes, within which changing even one piece of equipment can have consequences that cascade down the value chain [9], ultimately influencing the overall energy and economic efficiency. Retrofitting thus asks for careful **"re-engineering"** [37].

The optimisation of chemical plant retrofitting, re-designing and retiring still needs to be explored. Few studies examine these precise needs in detail. **However, SYSTEMIQ 2022 identifies steam crackers as a key piece of equipment to be retrofitted**, while electric crackers for olefins would be economical only if newly commissioned [37]. In this analysis, coal-based facilities must be completely retired, as well as most naphtha equipment and catalytic reformers for aromatics. In this scenario, MeOH constitutes the largest part of new-build infrastructures, mainly because of its role as a key platform chemical – requiring more than 1000 MTA and 100–150 MTO plants by 2050 [37].

Net zero refinery concepts

As C-THRU 2022 highlights [66], the **practicality** of novel chemical facilities designs still remains a seldom addressed topic. In addition to the different possible biorefinery configurations described earlier, some concepts of climate-aligned refineries (for now largely theoretical) have emerged. Concawe's EU 2050 Refinery explores the combination of renewable electricity and low-carbon hydrogen with a switch to alternative feedstocks [67]. Vogt & Weckhuysen's "refinery of the future" is an integrated facility that produces both fuels and chemicals solely from plastic waste, biomass and CO_2 [47]. The World Resources Institute proposes a conceptual "semi-circular refinery" [19] that also includes a diversity of feedstocks and focuses heavily on Fischer-Tropsch synthesis and hydrocracking. Further approaches can also be mentioned, such as e-refineries that would rely entirely on DAC and CCU.

Appendix 4 shows Vogt & Weckhuysen's "refinery of the future" concept.

Fitting production to the variability of renewable sources

Current chemical facilities are designed to run on a 24/7 basis, both for safety reasons and as a means to stay economically viable [65]. Switching to biomass feedstocks, which may be characterised by large seasonal variability, or to CO_2 and H_2 produced from intermittent renewable electricity may considerably change the operation dynamics of chemical plants. Possible adaptations to smooth supply may include [15]:

- **Combining variable power sources**, for instance wind and solar, which have been shown to be complementary in a number of contexts [68], and can be complemented with **controllable backup capacities** (nuclear, hydro);
- **Oversizing** production capacities;
- Relying on **buffers** or **storage**.

Options to smooth demand have not been thoroughly investigated yet in the literature. Business models may well need to adapt, as we go on to discuss.

Towards new production geography and geopolitics?

Although historically, Europe and the United States have been major producing countries, their chemical output has begun to stagnate over the last few years, while China has emerged as a major producer [69].

Novel chemical production pathways and the resulting value chain transformations are likely to further change **geographical dynamics**. Regions such as South America, Southeast Asia and Africa are generally expected to play a bigger role in future chemical production, mainly because they show the most advantageous conditions for abundant and low-cost renewable energy, H_2 and biomass production [14]. Some regions, such as the Middle East, may lose industrial leadership due to limited available resources, and players in those locations may be forced to find new business models (such as focusing on smaller-scale, higher value production to make best use of the scarce resources available) [70]. Next, relocation dynamics, such as the "renewables pull" (as highlighted in Verpoort *et al*. 2024 [71]), need to be better understood to inform which products should be manufactured where.

Because current oil refineries and petrochemical plants are large facilities that have benefitted from economies of scale, adapting the industry to novel feedstocks and their requirements (transport, storage) may result in a very different industrial landscape: decentralised production in **smaller-scale** facilities that are integrated with **local resources** (biomass, H_2, CO_2, electricity) could become standard [31], [72]).

Transforming the chemicals business

Novel business models might emerge, putting a stronger focus on the end uses of chemicals: molecule leasing, take-back schemes and chemicals-as-a-service are some examples of pathways that could develop in the coming years [37]. These concepts remain very theoretical due to complex logistical requirements and lack of political or financial incentives towards a circular chemicals economy.

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Appendix

Appendix 1 – Definitions and key figures

Table 2 – Primary chemicals: key facts and figures. Sources: IEA 2018 [2], SYSTEMIQ 2020 [37].

	Chemical	Main uses	Current production pathways	Production (Mt 2020)
	Methanol ($MeOH$ or CH_3OH)	Production of formaldehyde (25%), olefins (25%), methyl tert-butyl ether (11%), and gasoline blending (14%).	Currently produced from syngas derived from natural gas (55-65% of global production) and coal gasification in China (30-35%).	102
Olefins	**Ethylene (C_2H_4)**	Polymers (polyethylene and polypropylene) and precursors to polymer production (ethylene oxide and propylene oxide, acrylonitrile).	Steam cracking, refinery by-products, coal-based methanol-to-olefins (MTO) in China.	162
	Propylene (C_3H_6)			113
BTX aromatics	**Benzene (C_6H_6)**	Building blocks for polymer applications – 45% of benzene is used to produce polystyrene, 82% of xylenes go to produce polyethylene terephthalate (PET) production. Key applications in the food, health and hygiene sectors.	Mainly as refinery by-product (FCC and catalytic reforming). Toluene can also be used to further produce benzene and xylenes.	42
	Xylene			27
	Toluene			46

Process definitions

Cracking The process in which large molecules are broken down (thermally decomposed) into smaller molecules. Several types of cracking exist, such as:

- **Catalytic cracking**, involving a catalyst which may be used in a fixed bed or fluid bed (**fluid catalytic cracking**, FCC).
- **Hydrocracking**, which occurs at high-pressure and high-temperature in the presence of fresh and recycled hydrogen.
- **Steam cracking**, in which the feedstock is treated with superheated steam.

Reforming The conversion of hydrocarbons with low octane numbers into hydrocarbons having higher octane numbers. Can either occur through a catalyst (**catalytic reforming**) or using heat (**thermal reforming**).

Definitions adapted from Speight J., Handbook of Petrochemical Processes. [73]

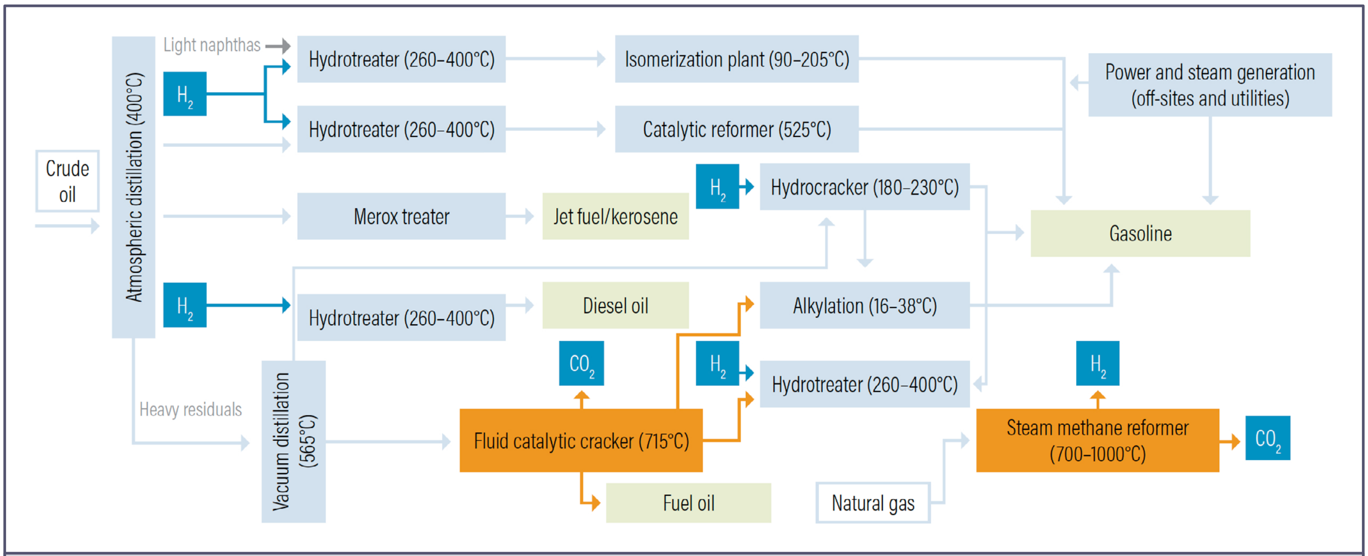


Figure 12 – A representative flow diagram of a "typical" refinery. Image from World Resources Institute, 2021 [19] CC BY 4.0.

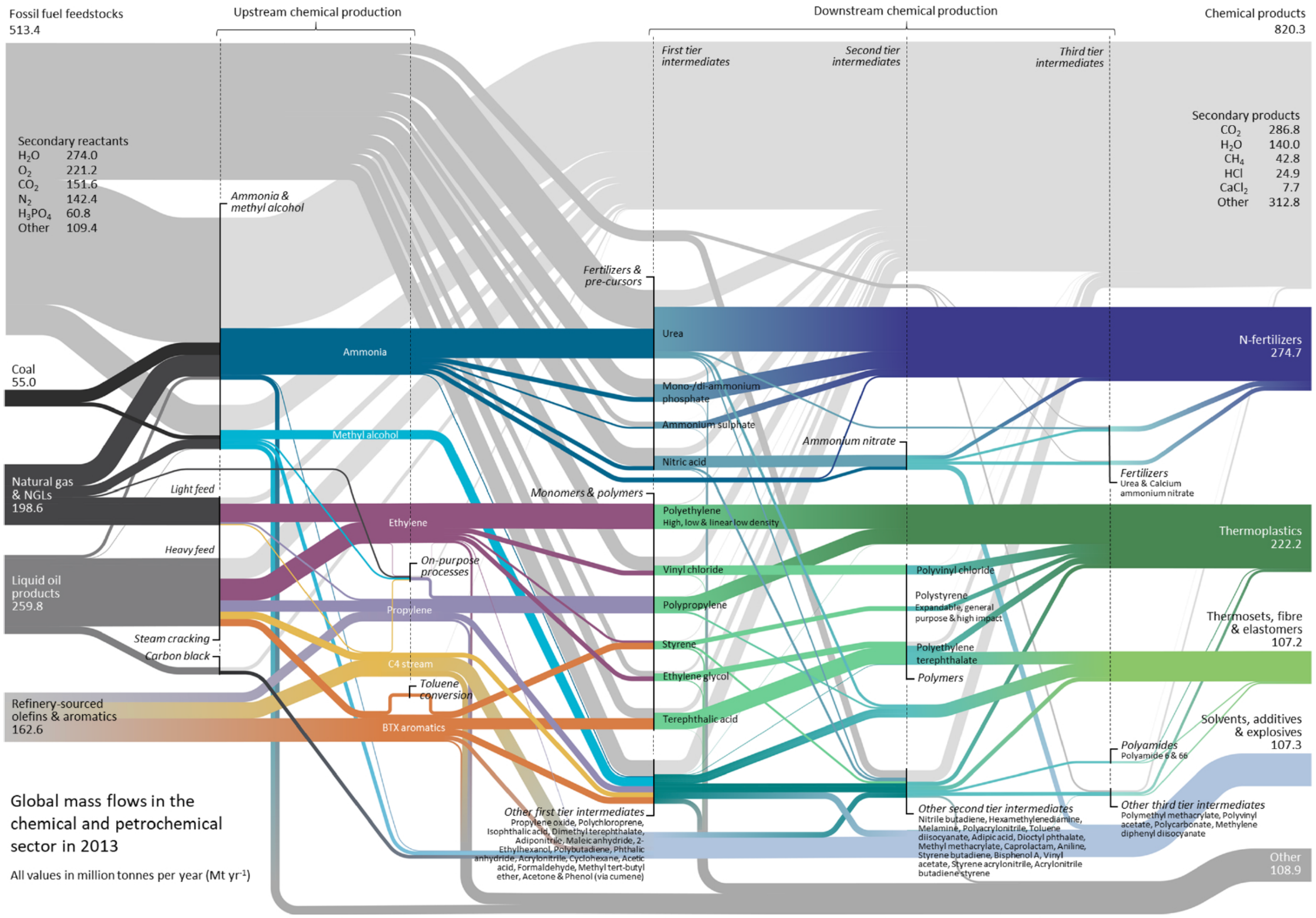
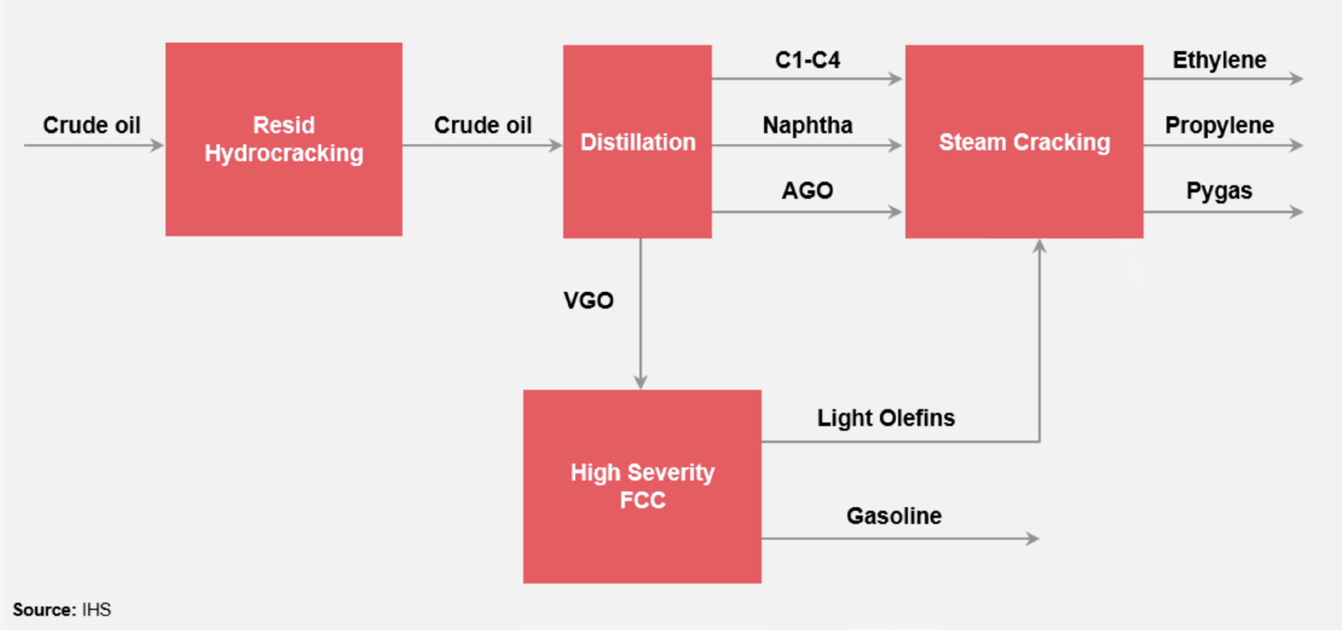


Figure 13 – Global mass flows in the petrochemical sector in 2013. Image from Levi & Cullen, 2018 [74]. ACS AuthorChoice Licence

Appendix 2 – Crude oil to chemical projects

Project	Refinery capacity (MMTPA)	P-Xyline capacity (MMTPA)	Olefin capacity (MMTPA)	Estimated chemical conversion/ bbl of oil (%)	Investment ($ billion)	Start trial operation
Hengli Petrochemical	20	4.3	1.5	42	11.4	2018
Zhejiang Petroleum and Chemical (ZPC) Phase 1	20	4	1.4	45	12	Est. Q2 2019
Hengyi (Brunei) PMB Refinery-Petrochem	8	1.5	0.5	>40	3.45	2019
Zhejiang Petroleum and Chemical (ZPC) Phase 2	20	4.8	1.2	50	12	2021
Shenghong refinery and Integrated Petrochem	16	2.8	1.1	60	11	2021
Aramco/SABIC JV	20	–	3	45	20	2025

Table 3 – Selected COTC plants. Data from FutureBridge 2019 [75].



Source: IHS

Figure 14 – An example of a COTC plant: Saudi Aramco's configuration. Data from FutureBridge 2019 [75].

Appendix 3 – Bio- and CO_2-based production pathways

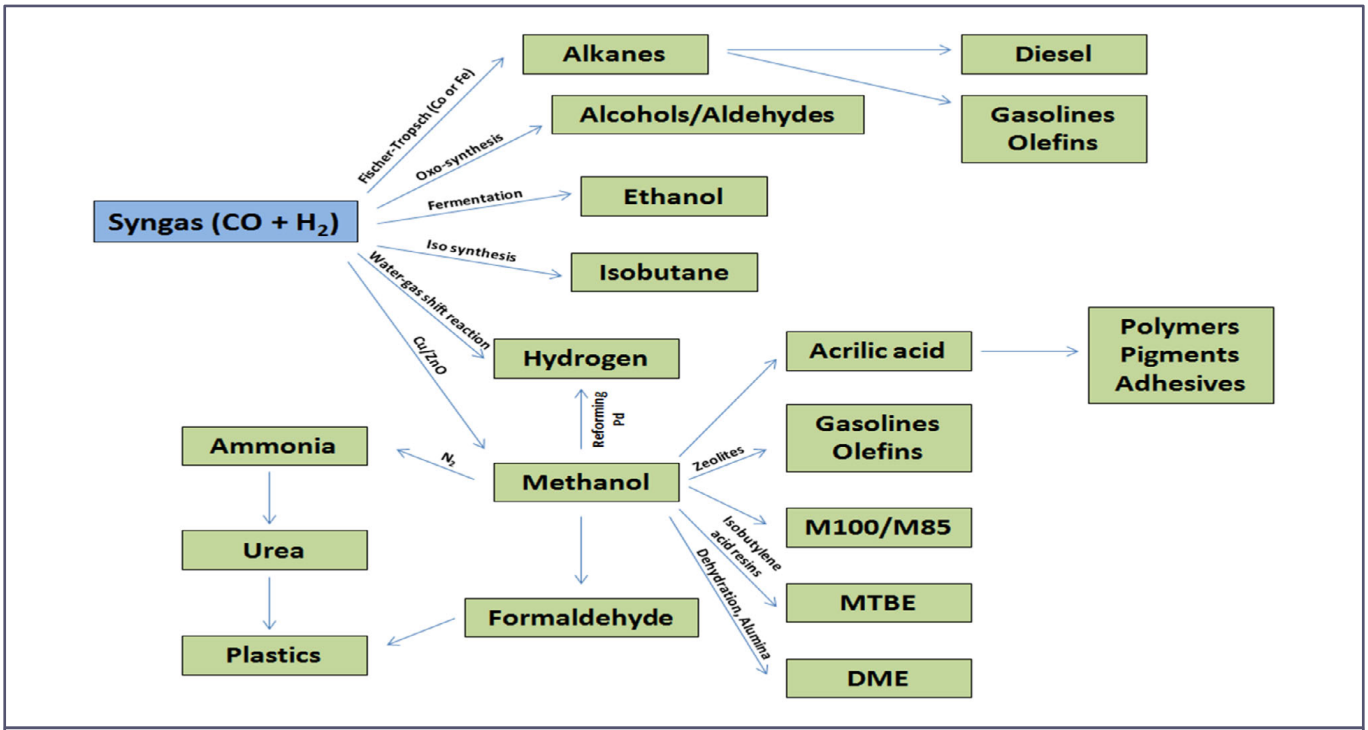


Figure 15 – Syngas to chemicals pathways. Image from IEA Bioenergy 2020 [33].

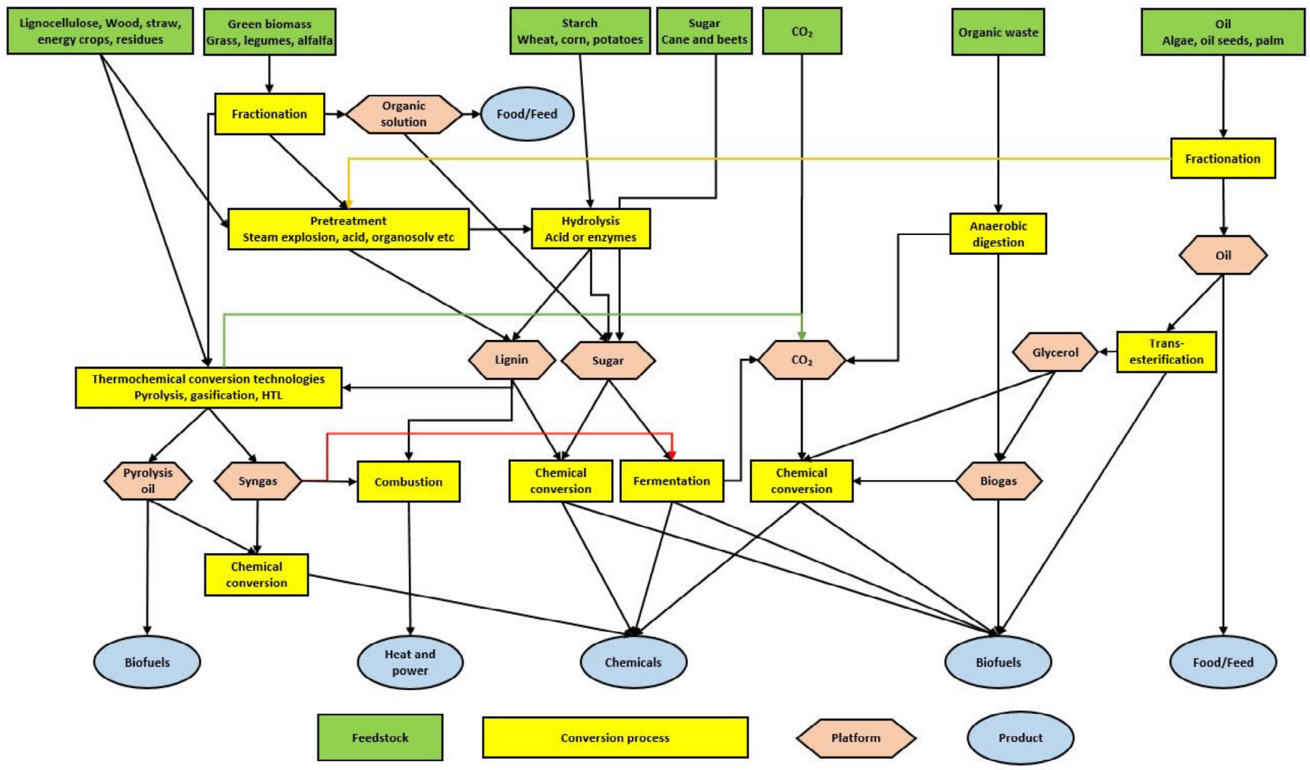


Figure 16 – Conversion technologies for bio-based chemicals. Image from IEA Bioenergy 2020 [33]

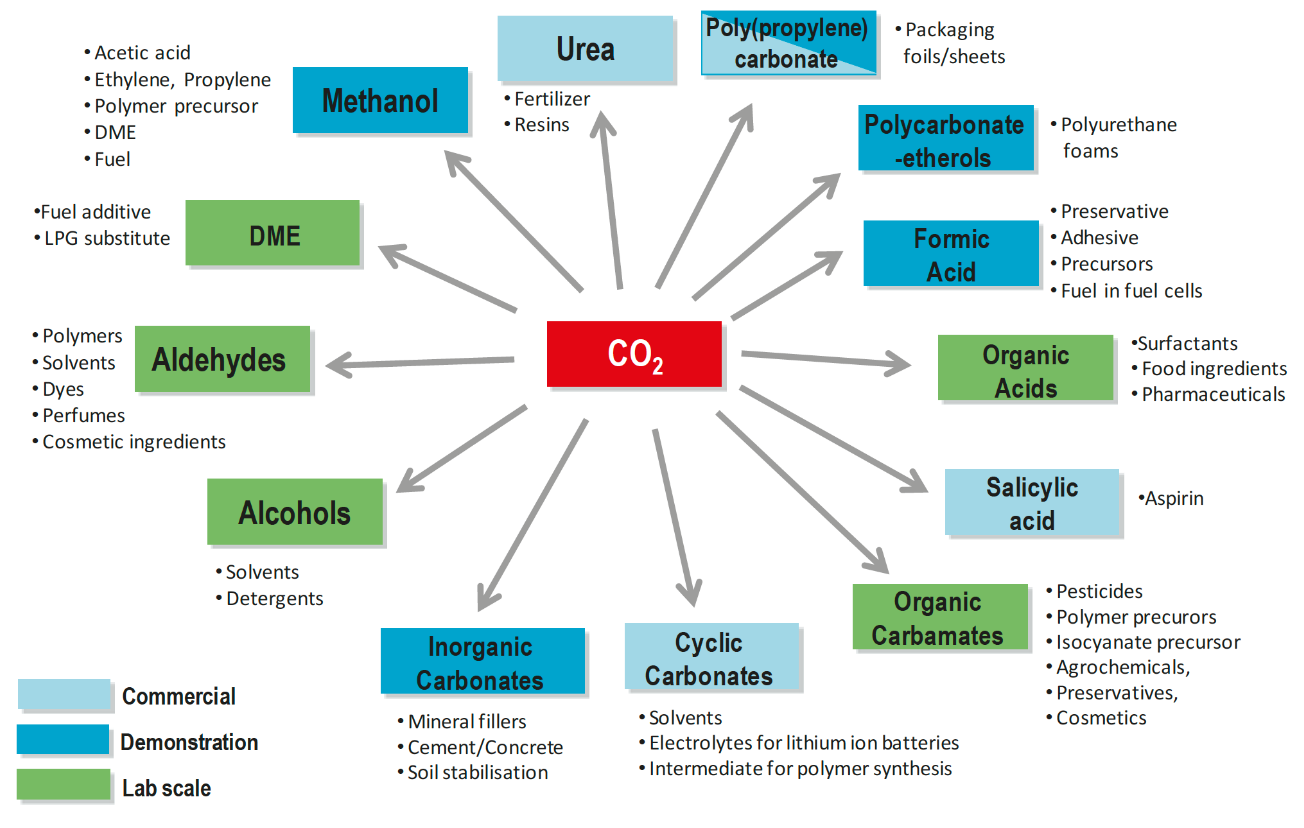


Figure 17 – Conversion technologies for CO_2-based chemicals and their respective maturity levels. Image from DECHEMA 2017 [54].

Appendix 4 – The refinery of the future

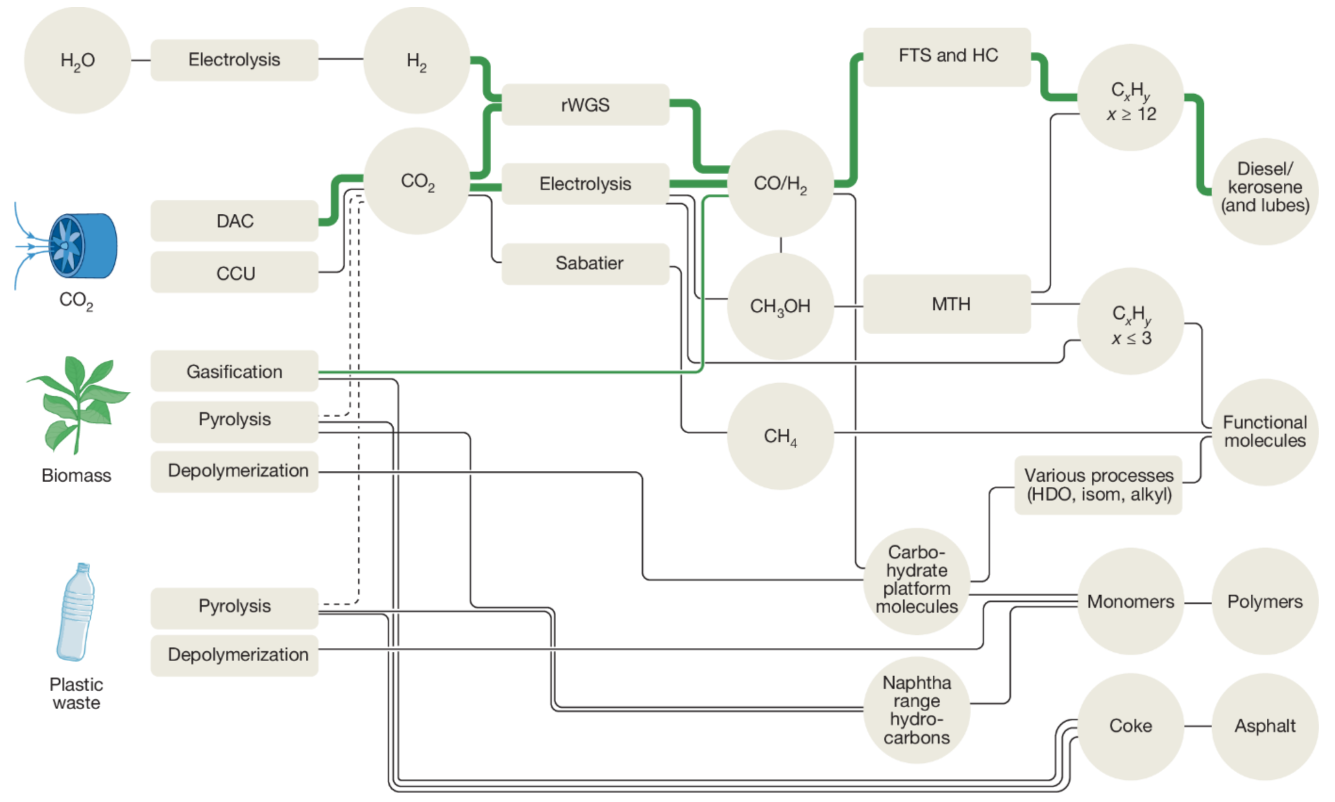


Figure 18 – An illustrative flow diagram for a (theoretical) refinery running solely on non-fossil feedstocks. Image from Vogt & Weckhuysen, 2024 [47].

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