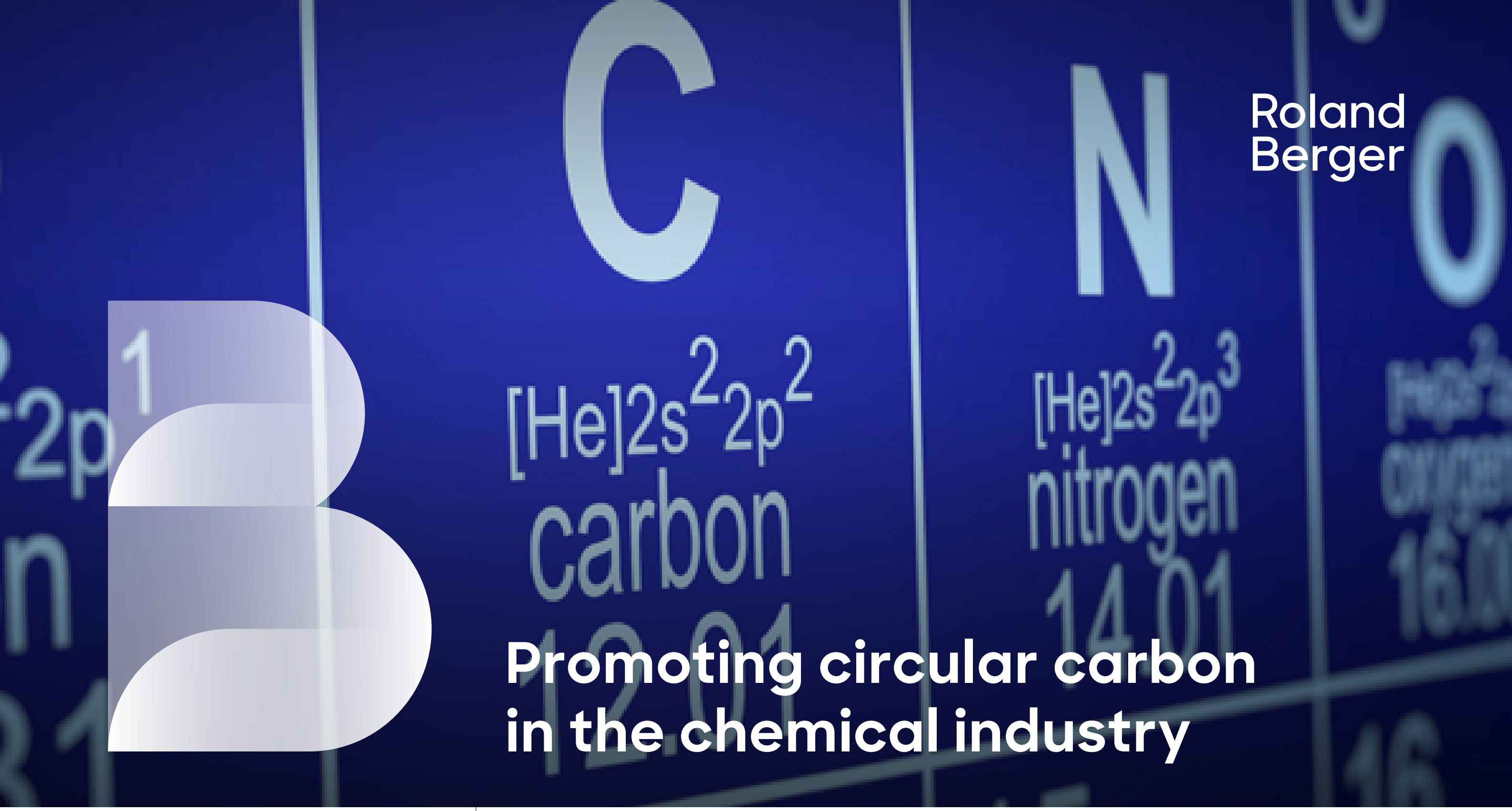

# Promoting circular carbon in the chemical industry

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## Circular carbon is vital for a more sustainable chemical industry

**The chemical industry is the world's largest industrial consumer of energy and is heavily reliant on oil, gas and coal. In terms of direct $CO_2$ emissions, however, it ranks third, largely because around half of the sector's energy input serves as feedstock for hydrogen and carbon, with the other half used as process energy. While emissions from process energy go directly into the atmosphere, carbon from fossil feedstock is embedded into the chemical industry's final products. Decarbonizing chemical processes is, of course, a vital step on the road to sustainability: renewable energy sources, increased electrification, and carbon capture and storage, among others, will be crucial. But to become more environmentally sustainable, the chemical industry must also drastically address the origin of its embedded carbon by creating a more circular value chain. This will require new solutions to major technological, economic and infrastructural hurdles. Roland Berger combines longstanding expertise in both business and technology to help market players manage their transition while maintaining a competitive advantage.**

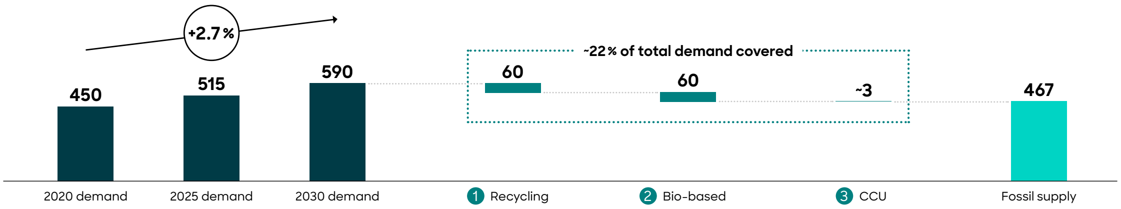
The chemical sector embeds approximately 450 megatons of fossil carbon feedstock into its products each year. With demand for many chemical products growing, including plastic, this is expected to reach 590 megatons by 2030. While the industry is beginning to address the issue of sustainability, based on current trajectories, only 22 % of the 590 megatons will be covered by sustainable sources of carbon. The picture is clear – progress needs to accelerate.

In this report, we examine the three most promising drop-in solutions for creating circular chemical feedstock, each of which has its own advantages and limitations: recycling, biomass materials, and carbon capture and utilization (CCU).

## Carbon feedstock demand in the chemical industry is set to reach ~590 Mt by 2030

Only ~22 % covered by sustainable carbon sources based on current trajectory

Chemical industry's feedstock carbon demand & supply [Mt carbon]



**Key hypotheses**

① Recycling

- Recycling has the **highest technological readiness**
- Significant **shortcomings** in **global waste supply and quality** are key limiting factors

② Bio-based

- **Direct competition for food and feed** in **1st generation** processes
- **2nd generation** (cellulosic) **for commodities**, as bioethanol is **commercialized**
- **Low technological readiness** and high cost of **3rd generation** (algae) **processes**

③ CCU

- **Carbon capture and utilization** is **technologically** the **least advanced** drop-in technology
- For **many products**, this is **still 10-20 years from large-scale commercialization**
- **While direct air capture** is the **least economical**, many **high** concentration **$CO_2$ emitters exist**

■ Total demand ■ Sustainable supply
■ Fossil supply

**Source** nova-Institute, desk research, Roland Berger

## Recycling

Recycling currently has the highest technological readiness of the three options covered in this report. Industrial and municipal solid waste account for a massive 87 % of the approximately 1,500 megatons of available carbon in waste streams. The problem is, nearly two thirds of this is lost by being dumped, scattered or burned, with 23 % of solid waste burned for energy recovery and just 13 % recycled.

The vast majority of the materials recycled are plastics: technologies to extract carbon from sources other than polymer are currently scarce. Some of the processes are well established, with mechanical recycling currently the dominant method. Its lower process temperatures (150–300°C) make it more energy efficient than alternatives, the majority of which are less commercially developed.

> "Intensifying cooperation with waste management companies can help secure more high-quality, sorted waste."

**FRANK STEFFEN**
Partner

These include pyrolysis (heating in the absence of oxygen), gasification (partial oxidation at high temperatures) and de-polymerization (decomposition into monomers), which require temperatures ranging from 500°C up to 1,200°C.

If recycling is to make a bigger contribution to circular carbon in the chemical industry, there is one main challenge to overcome: Both mechanical and chemical recycling processes are very sensitive to feedstock quality, requiring clean, well sorted waste input. And that's not easy to source. Despite improvements to collection and sorting systems, waste management infrastructure remains limited, especially outside Europe. If the chemicals sector is to become less reliant on fossil feedstock, demand for plastic waste as a sustainable feedstock will hit approximately 210 megatons a year by 2030. But based on current projections, recyclers will only be able to supply about half of this – a serious bottleneck.

Economics are a limiting factor: transporting waste between collecting locations and recycling facilities is expensive, and margins in the waste management sector are traditionally low. As such, small companies and startups dominate the market, which lack the ability to scale up operations.

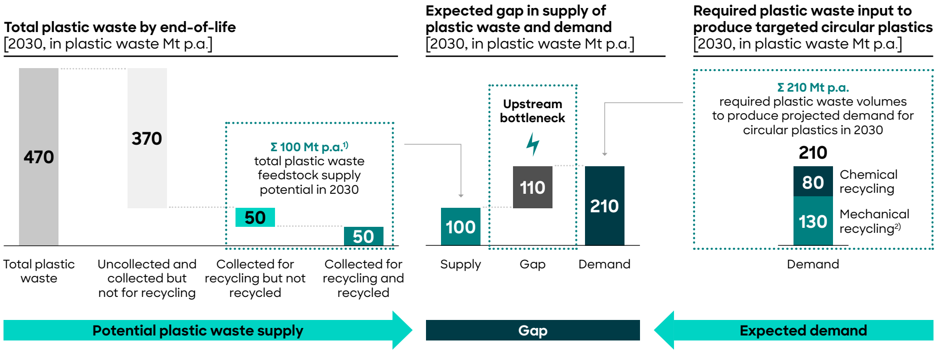
A further point to consider is that recycling equipment is susceptible to damage from low-quality feedstock. Lastly, mechanical recycling downgrades the quality of raw materials it produces, whereas less established chemical processes can lead to virgin-quality plastics without deterioration – a more circular approach.

To improve matters, we recommend major chemical players seek partnerships with waste collectors and sorting companies to meet rising demand for a circular value chain.

## Waste collection and sorting will become a bottleneck and limit feedstock volumes

### At the same time, customer demand is expected to grow substantially

Circular value chain with volume imbalance



**Key issues**

- High expected demand requires large amounts of high-quality sorted plastic feedstock (~210 Mt p.a.)
- Only half of this demand is covered by the forecast amount of collected waste suitable for mechanical and chemical recycling (~100 Mt p.a.)
- Significant supply gap of ~110 Mt p.a. of high-quality sorted plastic waste mainly caused by:
  - Insufficient maturity of waste management, especially outside Europe
  - High cost of transportation between waste collecting locations and recycling facilities
  - Traditionally low margins in waste management sector

Assumptions based on past project experience but only one example with bottom-tier output rates: c. 90% suitable plastic waste extraction rate from mixed plastic waste and >50% pyrolysis liquid extraction rate from sorted plastic waste input and c. 70% circular naphtha extraction rate from pyrolysis liquid after FCC upgrade, c. 80% extraction rate for sorting of mixed plastic waste for mechanical recycling input

1) 100 Mt p.a. represents worst case scenario of available mixed plastic waste; total share of chemical recycling suitable polymers (PE, PP, PS) in total plastic waste is higher, but collection is a problem

2) Ambition for mechanical recycling volume

**Source** OECD, Roland Berger

Roland Berger

**RUIRUI ZONG-RUEHE**
Partner

> "With even relatively basic chemicals like formaldehyde and acetic acid still at TRL 1–3, this highlights that CCU is still in its infancy as a solution for the chemical industry."

## Biomass

Biomass offers an organic, renewable alternative to fossil-based feedstocks and can be produced from a variety of sources, including crops, sewage and agricultural waste. C2 compounds currently make up more than three quarters of embedded bio-based carbon, with bioethanol accounting for 99%. Polylactic acid, or PLA, is a biodegradable polymer made from fermented sugarcane or corn starch, but currently makes up just 1% of bio-based carbon in the chemicals sector.

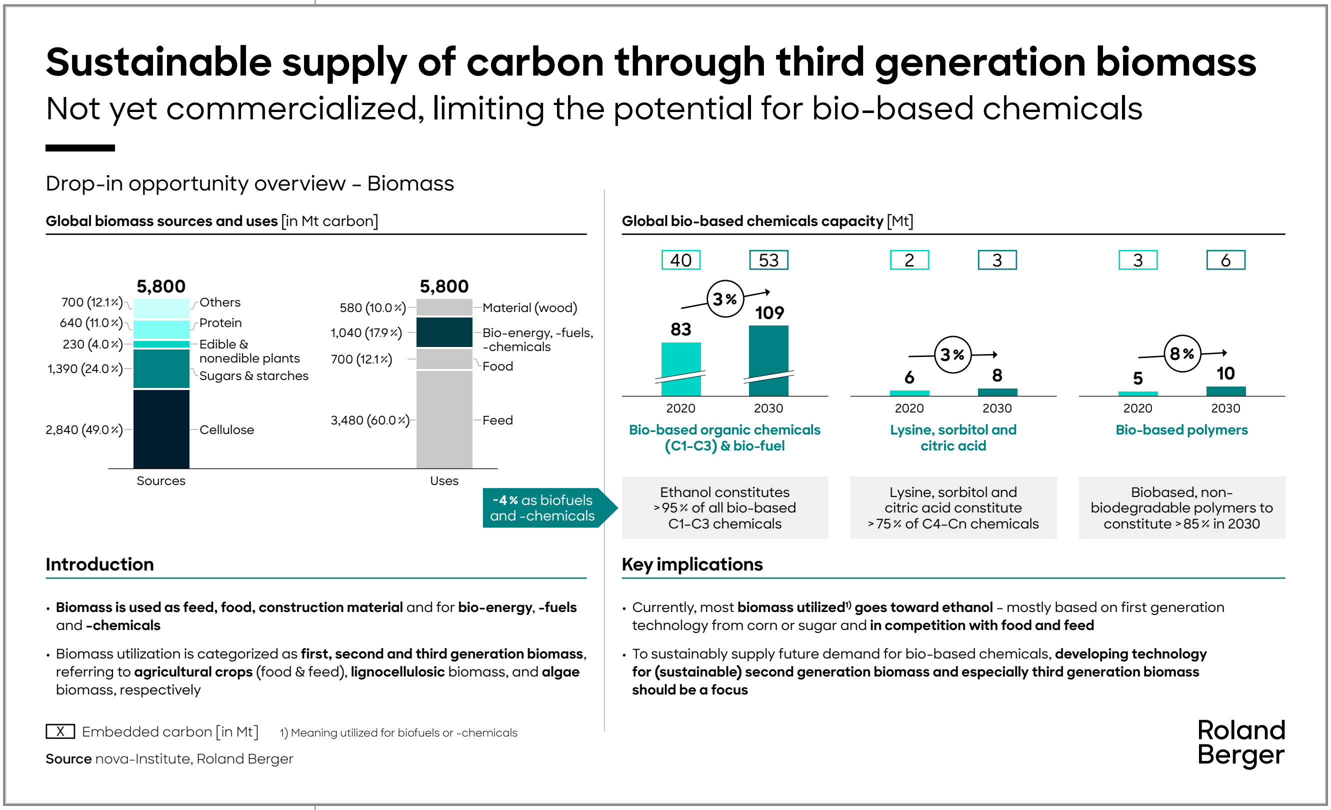
Despite offering a cleaner alternative to fossil-based feedstock, there are currently several limiting factors to bio-based chemicals. Biomass technologies have now been around for several decades and are divided into three generations, each with their own set of pros and cons:

1. ***First generation biomass***
   Is from edible crops such as corn, soybeans and sugarcane. The technologies involved are mature and there is some high-volume commercialization. However, the major drawback is that first generation biomass competes with food production, leading to conflicts of resources and land use. The sheer amount of land needed to generate significant yields is also an issue.

2. ***Second generation biomass***
   Is made from cellulose, typically sourced from non-food crops and waste biomass like agricultural and forest residue. It's not as commercially mature as first-generation biomass, but some technologies for commodity chemicals are available. The key advantages over first generation biomass are that it doesn't compete with food crops, and it also offers lower cost of raw materials. But it does come with major challenges: pretreatment, especially for fermentation, is expensive, and availability of required agricultural residues and land to produce them is limited. It also competes with feed for livestock.

3. ***Third generation biomass***
   Uses algae as a feedstock, meaning it does not compete with food supplies and requires minimal land use. It can also offer a much higher yield potential than the first two generations of biomass. However, the technologies required are still very much in their early stages, with significant research and investment still required to reach commercial maturity.

For biomass to offer a more viable solution in the chemical industry, technological development for second and especially third generation solutions must be accelerated. Green finance guidelines could stimulate private investment, while government incentives are crucial for supporting further research and scaling up solutions.



## Sustainable supply of carbon through third generation biomass

Not yet commercialized, limiting the potential for bio-based chemicals

Drop-in opportunity overview – Biomass

**Global biomass sources and uses** [in Mt carbon]

**~4%** as biofuels and -chemicals

**Global bio-based chemicals capacity** [Mt]

**Bio-based organic chemicals (C1-C3) & bio-fuel**

**Lysine, sorbitol and citric acid**

**Bio-based polymers**

Ethanol constitutes >95% of all bio-based C1-C3 chemicals

Lysine, sorbitol and citric acid constitute >75% of C4-Cn chemicals

Biobased, non-biodegradable polymers to constitute >85% in 2030

**Introduction**

- **Biomass is used as feed, food, construction material** and for **bio-energy, -fuels** and **-chemicals**
- Biomass utilization is categorized as **first, second and third generation biomass,** referring to **agricultural crops** (food & feed), **lignocellulosic** biomass, and **algae** biomass, respectively

**Key implications**

- Currently, most **biomass utilized[1] goes toward ethanol** – mostly based on first generation technology from corn or sugar and **in competition with food and feed**
- To sustainably supply future demand for bio-based chemicals, **developing technology for (sustainable) second generation biomass and especially third generation biomass should be a focus**

X Embedded carbon [in Mt]

[1] Meaning utilized for biofuels or -chemicals

**Source** nova-Institute, Roland Berger

Roland Berger

## Carbon capture and utilization

The sheer abundance of $CO_2$ produced around the world makes it an ideal potential feedstock for the chemical sector. In fact, the $CO_2$ available from emissions is 16 times more than the global chemical industry's expected carbon demand in 2030. Carbon capture and utilization (CCU) technologies can be retrofitted to most industrial and power plants to leverage $CO_2$ from a wide range of sources, including industrial processes used in sectors like power, cement, steel and the chemical industry. Captured $CO_2$ can then be used as feedstock to produce chemicals, building materials (e.g. carbonates) or synthetic fuels.

However, just 0.003% of available $CO_2$ is expected to be utilized by 2030. High costs and immature technologies mean commercialization is still low, with little sign of major growth in the near future. Currently, only a handful of large-scale (more than 100,000 tons of $CO_2$ per year) capture plants using $CO_2$ for the production of fuels and chemicals and yield enhancement are in operation.

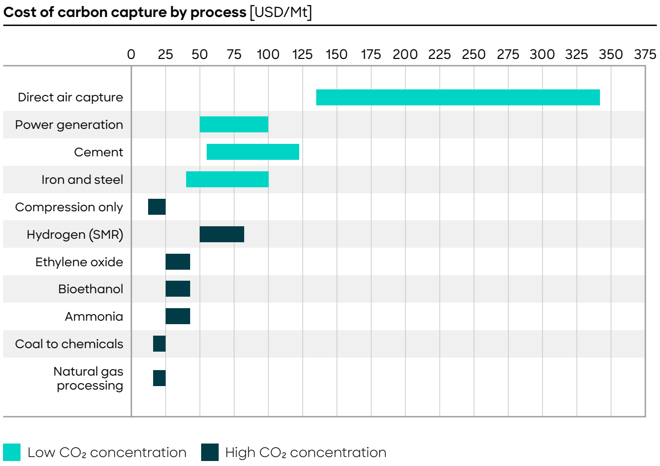
The source of $CO_2$ captured has a major impact on the feedstock cost. Some industrial processes, such as the production of ammonia or hydrogen, emit almost pure $CO_2$, but most have lower concentrations of around 20 %, making the cost of capturing carbon prohibitively high. Direct air capture from the atmosphere has the highest costs, as the average concentration of $CO_2$ is just 0.04 %.

Significant technological and economic improvements are required to make $CO_2$-based products competitive with their fossil-based peers. One ton of CCU-based ethylene, for instance, costs between USD 2,100-2,200, but fossil-based ethylene is valued at USD 500-900, including USD 100-300 of a hypothetical carbon tax.

## Depending on the $CO_2$ purity of different industrial processes, feedstock costs can vary dramatically

### Direct air capture is the most expensive source due to low concentration

$CO_2$ sourcing overview



**Source** IEA, Roland Berger

**Implications**

- The source of the $CO_2$ has a significant impact on the feedstock cost, as some industrial processes (e.g. ammonia, hydrogen production, etc.) emit almost pure $CO_2$; **most industrial processes have lower concentrations of ~20 %**
- Direct air capture has the highest costs overall, as the **global average concentration of $CO_2$ in the atmosphere is ~0.04 %**
- Most **CCU technologies can be retrofitted** to most industrial and power plants and **potentially avoid the additional emission of 8 Gt of $CO_2$ by 2050, thereby offering significant strategic value** for the decarbonization of the chemical industry
- In addition, **affordable sustainable energy sources** as well as **significant volumes of green hydrogen** are required to enable many CCU processes that require catalytic hydrogenation of $CO_2$

Technology readiness levels (TRL) for CCU solutions vary according to the process used and the end product. For instance, CRI's pilot plant for the catalytic hydrogenation of $CO_2$ to methanol is close to commercialization, while other processes are at TRL 1-3, some 15-20 years away from deployment. It's worth noting that catalytic hydrogenation, part of many CCU processes, does require affordable sustainable energy sources as well as significant volumes of green hydrogen.

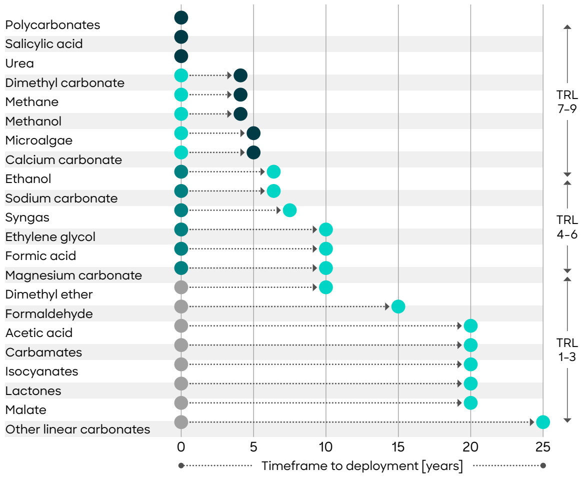
As a rule of thumb, the more complex the end product, the lower the TRL. With even relatively basic chemicals like formaldehyde and acetic acid still at TRL 1-3, this highlights that CCU is still in its infancy as a solution for the chemical industry.

## Technology readiness levels differ depending on the process used

The more complex the product, the lower the TRL

CCU – Technological readiness timeframe

Technological readiness of CCU by product[1]



**Source** Desk research, Elsevier, Roland Berger

**Implications**

- The **technology readiness of chemical products can differ based on the process used**, e.g. the catalytic hydrogenation of $CO_2$ to methanol in the pilot plant operated by CRI[2] is close to commercialization, while other processes are at TRL 1–3
- With **increasing complexity of the desired product, the TRL decreases**, e.g. even basic chemicals such as formaldehyde and acetic acid are still at a **TRL of 1–3** and **are expected to require an additional 15–20 years until pilot stage**
- Considering these major chemical processes, the **overall $CO_2$ uptake potential would be ~500 Mt $CO_2$ p.a.**, which is still small compared to the 36 Gt worldwide $CO_2$ emissions
- **Economically, significant improvements are required in order to make $CO_2$-based products cost competitive to their fossil-based peers**, e.g. one ton of CCU-based ethylene has costs of USD 2,100–2,200, while fossil-based ethylene is valued at USD 500–900, incl. USD 100–300 of a hypothetical carbon tax

■ Commercialized ■ Development stage
■ Pilot stage ■ R&D

[1] Non-exhaustive

[2] CRI = Carbon Recycling International

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> "Based on current trajectories, only 22% of the chemical sector's embedded carbon footprint will be covered by sustainable sources in 2030. During the transition phase and for the remaining fossil-based input, CCS will be a crucial technology for decarbonization. At the same time, captured $CO_2$ can be used as valuable feedstock in the CCU process."

## What's next?

Implementing a more sustainable supply of carbon feedstock is vital for the chemical industry, but the path to circularity will not be easy. Each of the sector's three key solutions faces major challenges: the availability of a suitable waste stream for recycling, and technological and economic hurdles for biomass and CCU.

To accelerate progress, we propose the following steps for companies in the chemicals sector.

In **recycling,** intensifying cooperation with waste management companies can help secure more high-quality, sorted waste to generate circular feedstock. Developing or licensing technologies with higher feedstock tolerance would also simplify waste supply. Higher-quality feedstock, as well as solutions with more stable output quality, can decrease the risk of equipment damage.

For **biomass**, look to utilize second generation biomass to produce chemicals beyond ethanol. And support the development of third generation biomass wherever possible.

For **CCU**, chemicals companies can benefit by helping to develop more efficient technologies and securing access to sources of low-cost sustainable energy and green hydrogen. Work to foster change in the regulatory environment to increase competitiveness with fossil fuel sources.

## *Further reading*

- ➔ *EXTRAORDINARY MEASURES: WAYS TO DECARBONIZE THE CHEMICALS INDUSTRY*
- ➔ *THE SEVENTH DISRUPTION TO THE GLOBAL POLYMER INDUSTRY*
- ➔ *THE PLASTIC BALANCING ACT: DRIVING THE TRANSITION AND SEIZING ITS OPPORTUNITIES*
- ➔ *CHEMICAL WINNERS*

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