Carbon Stewardship

A new guiding principle for the plastic and chemical industry

May 2024

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Executive summary

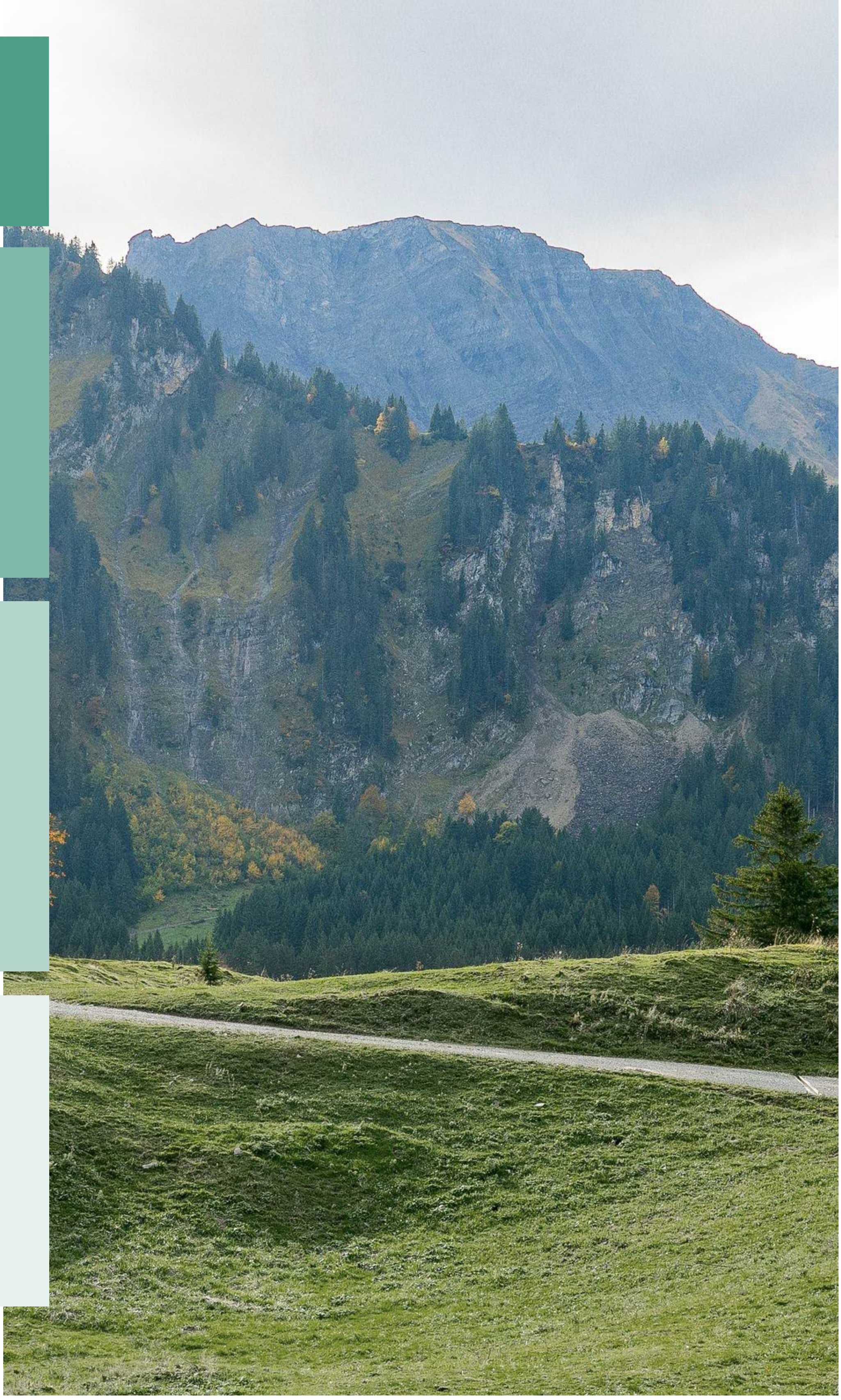
This white paper serves as a starting point for a more comprehensive dialogue and action-driven approach on carbon stewardship among industry, feedstock providers, policymakers, science, and society. Carbon stewardship means that the chemical industry:

Takes a larger responsibility for handling carbon along the entire life cycle, from extraction to the end-of-life.

Respects the safe operating space of all planetary boundaries and considers impacts on the broader climate and carbon environment, such as efforts to protect and enhance standing carbon pools (e.g., forests and peatlands), eliminate pollution, and promote biodiversity.

Implements science-based strategies and targets to minimize emissions and look for efficient ways to remove or sequester carbon from the atmosphere in the value chain. With this in place, the chemical industry can move from being a contributor to climate change to become a contributor in combating it.

Develops a joint vision and agenda for transforming the plastic and chemical industry, for example by engaging customers and policymakers with the benefits which a sustainable chemical industry will bring to nature and society.



What can the industry, industry associations and policymakers do to pave the way to enable carbon stewardship and what hurdles need to be overcome? We have identified five key challenges and enablers:

The chemical and plastic industry is a key enabler of the circular economy by keeping carbon in the loop and providing circular materials for various applications. However, a circular industry will never be perfect, losses are inevitable. That means that a certain need for virgin feedstock will always remain. As of today, fossil-based virgin feedstock is predominantly used mainly due to lower prices. However, fossil feedstock prices are artificially low as the costs of their negative impacts are not fully taken into account. Thus, there is a need for policy encouraging the switch to renewable feedstocks in line with overall climate targets. Policy mechanisms such as renewable feedstock mandates, pricing externalities, removing fossil extraction subsidies or tax breaks, may incentivize the creation of low-emission product markets.

Biomass is one of the most important virgin feedstock alternatives for a more sustainable chemical and plastic industry. But, a lack of understanding and alignment regarding the availability of sustainably sourced biomass, coupled with possible trade-offs between various land uses, is impeding the transition to more bio-based solutions. Biomass production for the chemicals and plastics industry must be balanced across the wider food, industry, energy, and natural systems' land uses to meet biodiversity and climate targets. To this end, sourcing sustainable biomass requires effective and comprehensive assessments, ensuring that certain sustainability criteria (e.g., biodiversity and land use change) are met.

In Europe, incineration is currently the dominant end-of-life pathway releasing embedded carbon to the atmosphere and generating significant emissions. Reducing end-of-life emissions needs credible planning to transform the waste management system, maximizing recycling and to enable a net-zero chemical and plastic system. For the remaining carbon released, CCU and CCS may bring the carbon back into the system or store it.

Carbon accounting is a crucial tool to describe the environmental impact of products. The calculated carbon footprints still depend on the applied accounting method. Eliminating their variance is key in providing a consistent basis for decision making. Currently, mainly cradle-to-gate carbon accounting is used. Complementing cradle-to-gate with cradle-to-grave product-level carbon accounting would allow for transparent purchasing activities aiming to minimize life-cycle emissions. A cradle-to-grave perspective is needed to evaluate the life cycle impact of products and highlight the importance of end-of-life treatment.

Establishing a common terminology will help communicate the benefits of a transformed chemical industry and to prevent any accusation of greenwashing. The industry, including the entire value chain, policymakers, and cross-sectoral initiatives such as GHG protocol and SBTi should come together to align on common terminology related to renewable plastics, carbon removal/sequestration/storage, and net carbon negative plastics.

If all these elements come together, net carbon negative plastic and chemical value chains are achievable. In fact, net carbon negative plastic products may already be possible for long-lifetime applications today if renewable feedstocks are used and end-of-life emissions are reduced or eliminated. Net carbon negative products could be an additional competitive value proposition. However, on a system level, prioritizing the available renewable feedstock for long-lifetime applications is not more beneficial as prioritizing it for short-lifetime application as the total amount of carbon sequestered and emitted by the system stays the same. Ultimately, transitioning to renewable feedstocks and extending product lifetimes are two separate requirements for a net-zero transition. Hence, policies should support both of these in parallel.

> The vision of a world where renewable feedstocks is the norm, not the exception, and where chemicals and plastics are part of the solution is achievable. It will require unprecedented levels of collaboration between industry, policymakers, and civil society to ensure that necessary changes are made on time to reach a global net-zero economy by 2050.

Setting the stage for carbon stewardship

Chemicals and plastics are very pervasive in our lives. In Europe, 96% of all manufactured goods rely on input from the chemical industry. Compared to many other materials – such as metals – chemicals and plastics are unique because they are carbon-based molecules. Today, some 90% of chemicals and plastics are made from virgin fossil feedstocks (oil, coal, or natural gas)[1]. Thus, production and end-of-life disposal of chemicals and plastics accounts for more than 4% of global greenhouse gas (GHG) emissions, making the industry the third largest contributor[2] of carbon emissions in the industrial sector. Due to an increasing demand for plastics and chemicals, this contribution will rise if appropriate measures are not undertaken[3]. Around 36% of GHG emissions across the lifecycle of chemicals and plastics arise from manufacturing (the energy and process emissions), and the remaining majority of 64% from the extraction of fossil resources and the release of embedded fossil carbon at the end of life[4].

Thus, a new guiding principle is needed to transform the chemical and plastic value chain from being an emitter to carbon neutrality or even beyond. We call it carbon stewardship. This white paper presents our vision of the plastics and chemicals industry as a carbon steward driven by circularity and non-fossil feedstocks. Furthermore, we outline the environmental and social benefits, as well as business opportunities related to the responsible handling of carbon. Bringing this vision into place takes work. Thus, we address key aspects for the industry and policymakers to make this vision a reality.

The facts

96%	of all manufactured goods rely on input from the chemical industry In Europe.
90%	of chemicals and plastics are made from virgin fossil feedstocks (oil, coal, or natural gas).
4%	of global greenhouse gas (GHG) emissions, making the industry the third largest contributor of carbon emissions in the industrial sector.
36%	of GHG emissions across the lifecycle of chemicals and plastics arise
64%	from the extraction of fossil resources and the release of embedded fossil carbon at the end of life.

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[1] Renewable Carbon Initiative analysis (2023)
[2] PNAS (2022), Planet-compatible pathways for transitioning the chemical industry
[3] IEA (2023), Net Zero Roadmap a Global Pathway to Keep the 1.5 °C Goal in Reach
[4] Systemiq (2022), Planet Positive Chemicals

Scope of the work

This work focuses on aspects for European industry players and the European policy landscape. Nevertheless, some of the learnings may be applied to other regions. Furthermore, the transformation of the chemical and plastic industry requires various innovative raw materials, such as biomass, carbon dioxide, and circular (recycled) feedstock. Here, we particularly emphasize bio-based feedstock due to their higher short-term availability and potential impact on standing carbon pools.

Carbon stewardship in a defossilized chemical and plastic industry

When it comes to transformation of an industry, many sectors focus on decarbonization.
As most chemicals and plastics are inherently carbon-based, decarbonizing this industry is impossible. Therefore, the term ‘defossilization’ is more accurate when describing the needed transformation. Instead of replacing carbon, we need to manage it: where it comes from and where it ends up. With that, the embedded carbon becomes a limited and thus valuable resource that needs someone to take care of.
As a carbon steward, the chemical and plastics industry will need to take a leading role in cooperation with other actors.

What is carbon stewardship?

We envision the plastic and chemical industry as a carbon steward.

Carbon stewardship involves taking **greater and more proactive responsibility in carbon management across the entire lifecycle**, from feedstock supply to consumption and end-of-life. This includes scaling reuse, recycling, and carbon circularity in the form of carbon capture and utilization.

Carbon stewards implement **science-based strategies** and targets to minimize emissions and actively seek efficient ways to remove or sequester carbon from the atmosphere across the value chain.

Carbon stewardship **requires respecting the safe operating space of all planetary boundaries** and balancing overall societal needs with resource availability. This also includes considering impacts on the wider climate and carbon environment, such as **efforts to protect and enhance standing carbon pools** (e.g., forests and peatlands), eliminate pollution, and promote biodiversity.

Finally, carbon stewardship also means **developing a joint agenda for transforming the plastic and chemical industry.** This also means engaging customers with the benefits a sustainable chemical industry brings to society.

In our vision for the chemical industry, shifting to a circular economy will reduce resource consumption and increase resource efficiency. In combination with developing other renewable feedstocks to replace fossil alternatives and minimizing production and end-of-life emissions, this brings the transition in line with a 1.5°C scenario and the goals of the Paris Agreement. In fact, the chemical and plastics value chains have the potential to do even more and shift from being a carbon emitter to becoming net carbon negative. This can, for example, be achieved by:

- sequestering carbon during feedstock supply,
- carbon capture and storage of production emissions,
- realization of emission-free end-of-life.

We will see later that, subject to sustainably sourced biomass as raw material for the chemical and plastic industry, the usage of renewable energy in the production and improved end-of-life treatment combined with CCSU, long-lifetime applications may even offer net carbon negative products today.

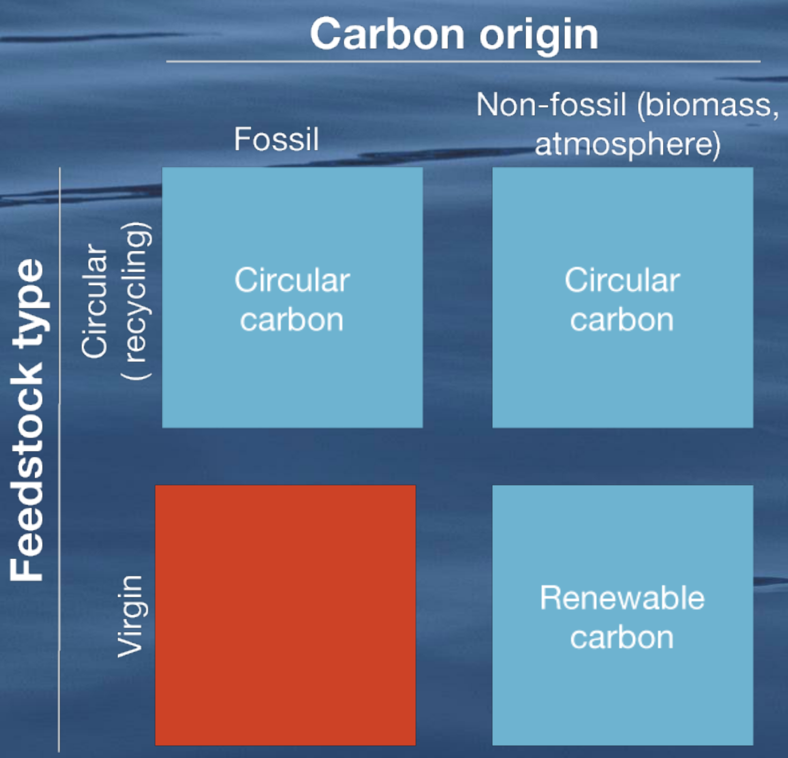
What is "renewable" and "circular" carbon?

For a chemical industry based on fossil resources, the origin of carbon did not matter as long as it was cheap and abundant. With the transformation of the chemical industry, the origin and type of carbon are key differentiators: in this paper, we divide the origin of the carbon source into fossil vs. non-fossil and the type of feedstock into virgin vs. recycled. The term circular carbon refers to recycled feedstock coming from plastics or chemicals. The origin of circular carbon can be either fossil or renewable, i.e., bio-based or atmospheric.

Renewable carbon is exclusively used for virgin carbon from biomass (including waste and residues such as used cooking oils) or atmospheric CO_2. During the transition, circular carbon will still be partly fossil- based, due to the majority of plastic waste being fossil-based but replaced over several recycling loops by renewable carbon.

Non-fossil carbon entails carbon that was sequestered from the atmosphere via natural or technological processes.

Therefore, it can potentially provide net-negative emissions, as will be discussed in more detail later. This is impossible for fossil carbon, even if recycling is involved.



Feedstock type	Carbon origin: Fossil	Carbon origin: Non-fossil (biomass, atmosphere)
Circular (recycling)	Circular carbon	Circular carbon
Virgin	🟥	Renewable carbon

Figure 1: Overview of renewable and circular carbon used in this white paper. Point source CO_2 can be purely fossil origin (e.g. coal-based steel blast furnace) but can also be purely biogenic (e.g. CO_2 biogas plants) or mixed (e.g. Carbon Capture and Utilization from waste incinerators with mixed bio/fossil plastic waste). Plastic waste can similarly contain carbon from fossil or non-fossil origin.

The benefits of carbon stewardship

Transitioning to circular or renewable carbon is inevitable to set the plastic and chemical industry on a path toward net-zero GHG emissions.

> **"By implementing carbon stewardship, the chemical industry can make its contribution to combating climate change."**

Providing a purpose for the industry and setting guiding principles will unlock new ambitions and innovations. However, besides less tangible benefits, implementing carbon stewardship will have purely economic motivations. Companies can translate this into a business opportunity, as early movers can capture new value pools and retain market shares in a rapidly changing environment. Taking more proactive responsibility in carbon management across the entire lifecycle enables a closer relationship with value chain partners, which is much more difficult in a commodity-like, fossil-based industry. For example, the industry players can tighten customer relationships and increase customer attachment via a shared value narrative. Additionally, first-movers can develop and secure future feedstock channels by creating partnerships with other operators in the value chain.

Furthermore, the pressure from financial institutions, markets, and regulation is growing on the oil & gas industry as well as the plastic users to accelerate the transition. For example, the European Commission has set a target of 20% non-fossil carbon for plastics and chemicals by 2030. Recently, an increasing number of court cases against both oil & gas producers and companies using plastic were filed, which also impacts the chemical and plastics industry itself. Furthermore, financial sector ESG initiatives (e.g., Glasgow Financial Alliance for Net Zero (GFANZ), Task Force on Climate-related Financial Disclosures (TCFD)) alongside shareholder activism (e.g., ShareAction, ClientEarth) increases the pressure to set and fulfill ambitious sustainability targets.

Leading companies can turn this pressure into an advantage: Studies have shown that environmentally friendly companies are valued significantly higher compared to companies that are less ESG-conscious[5]. Thus, deploying a sustainability strategy is an attractive opportunity to increase the company's value.

Finally, the downstream industry increases pressure to include and improve tracking and reporting of full life cycle emissions, including resource extraction and end-of-life (e.g., WBCSD PACT, Carbon Disclosure Project). Implementing science-based climate targets and strategies ensures that enterprises are future-proof and reduces the potential pressure of regulatory changes, markets, and downstream partners. Broader initiatives like the Science-Based Targets Initiative (SBTi) and Carbon Disclosure Project (CDP) can serve as guiding principles to develop climate strategies and targets.

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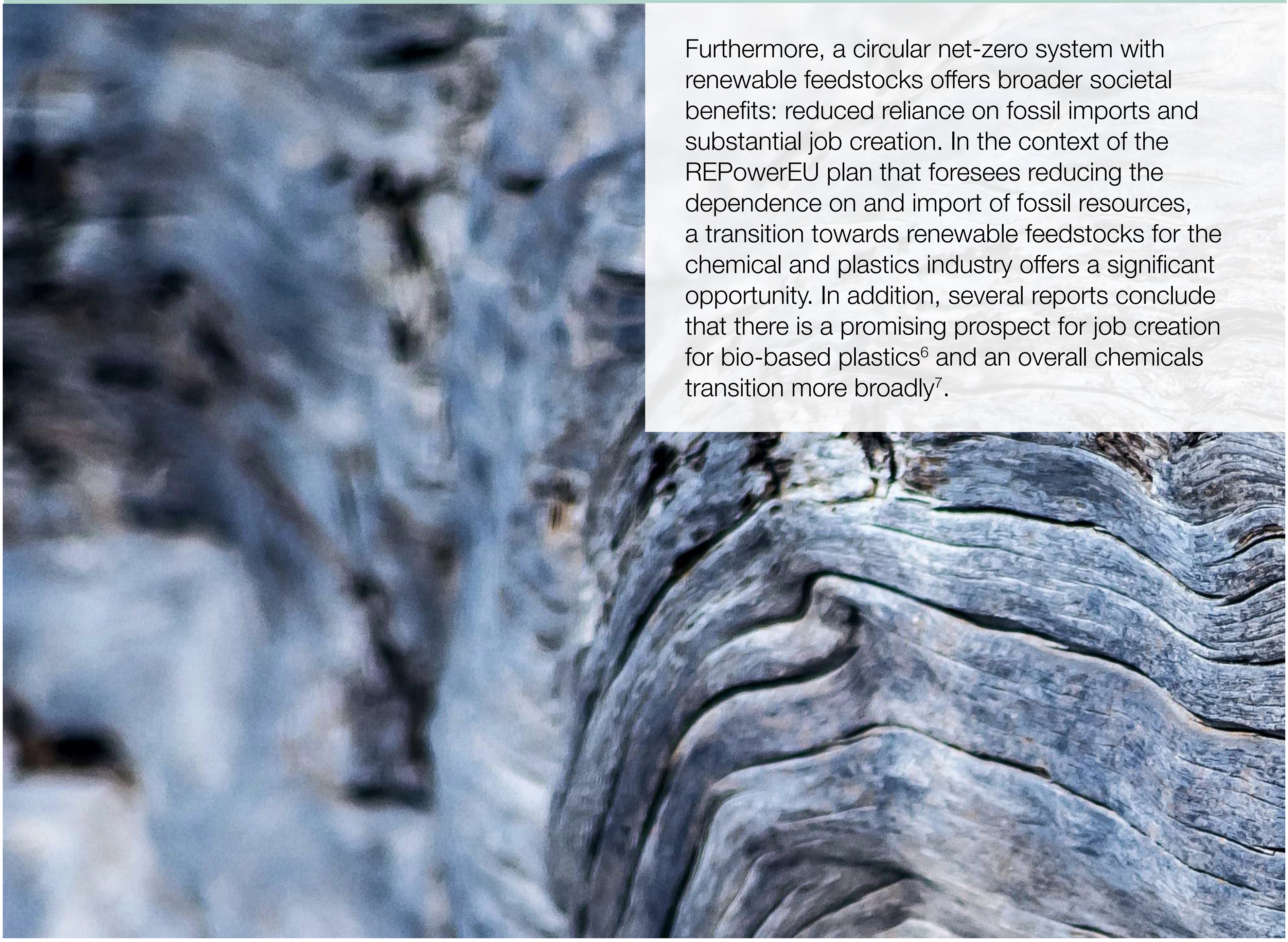
[5] Schroder (2019), SustainEx

To capture these opportunities, leading companies should act in concert to embrace this evolving landscape and accelerate the formation of a low-emission product market. This requires alignment on a shared vision for carbon stewardship and a roadmap for the net-zero transition of the sector.

"In fact, the plastic industry can lead in achieving climate goals by developing net carbon negative plastics value chains."

Thus, becoming a carbon steward is an industry play rather than a single organization strategy. At times of talent shortage, a joint vision of the chemical industry at the forefront of climate change mitigation helps the industry to be attractive for current and future employees and to increase the support of residents near production facilities.



Furthermore, a circular net-zero system with renewable feedstocks offers broader societal benefits: reduced reliance on fossil imports and substantial job creation. In the context of the REPowerEU plan that foresees reducing the dependence on and import of fossil resources, a transition towards renewable feedstocks for the chemical and plastics industry offers a significant opportunity. In addition, several reports conclude that there is a promising prospect for job creation for bio-based plastics[6] and an overall chemicals transition more broadly[7].

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[6] European Commission, DG Environment (2022), Biobased plastic sustainable sourcing and content

[7] Systemiq (2022), Planet Positive Chemicals

Challenges and enablers for the chemical industry as a carbon steward

Implementing carbon stewardship for the chemical and plastic industry brings various benefits for both the players in the market and the broader societal system. The industry can provide proof points for cost-efficient, scalable, and reliable technologies. Advocating for supporting legislation can speed up the path for bringing more sustainable technologies into reality. However, there are several aspects to consider when it comes to the transformation. In the following, we describe the key elements of our vision, hurdles, and potential intervention points for industry players, industry associations, and policymakers:

(1) Both circular and renewable carbon are needed to unlock the transition of the chemical industry to a net-zero system. If external costs are taken into account, renewable feedstocks will be cost-competitive

A shift to a circular economy for plastics and chemicals will reduce fossil resource consumption and increase resource efficiency. Plastic consumption, and subsequently, plastic waste generation can decrease by 30-50% through reduction and reuse[8]. In addition, recycling can keep resources in the value chain as long as possible. However, shifting to a circular economy does not fully close the carbon loop, as a circular economy operates within technical limitations and carries inherent system inefficiencies (see Figure 2 on page 14).

However, losses along the value chain (e.g., use phase, leakage, collection, sorting, recycling, processing) mean that not all products, materials,

> **“Recycling (both mechanical and chemical) will contribute anywhere between 10% and 70% to the chemicals and plastics industry feedstocks in the future, according to various studies[9/10].”**

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[8] Systemiq (2022), Planet Positive Chemicals

[9] Wuppertal Institute (2023), Towards a Net-Zero Chemical Industry

[10] Laboratory for Circular Process Engineering (LCPE) (2023), How much can chemical recycling contribute to plastic waste recycling in Europe? An assessment using material flow analysis modeling

and, therefore, carbon can be fully recirculated. Hence, transitioning to a circular economy does not entirely remove the need for virgin carbon inputs. Non-fossil carbon sources that are renewable by design include renewable biomass sources and CO_2 from air (direct air capture, DAC). Other renewable feedstocks are point source (PSC) CO_2 from different sectors (e.g., CO_2 from cement kilns) (see Figure 1). In line with the strategy of the industry to become a carbon steward, the industry should advocate for a supportive policy framework, leveraging, for example, the following ideas:

- policies encouraging the switch to renewable and circular carbon feedstocks, in line with overall climate targets, by setting mandatory targets for their use,
- pricing in externalities of fossil fuels, the prices of which are artificially low as the costs for their negative impacts are not taken into account.

Carbon flow diagram in the plastics and chemicals industry

(Illustrative 2050 outlook)

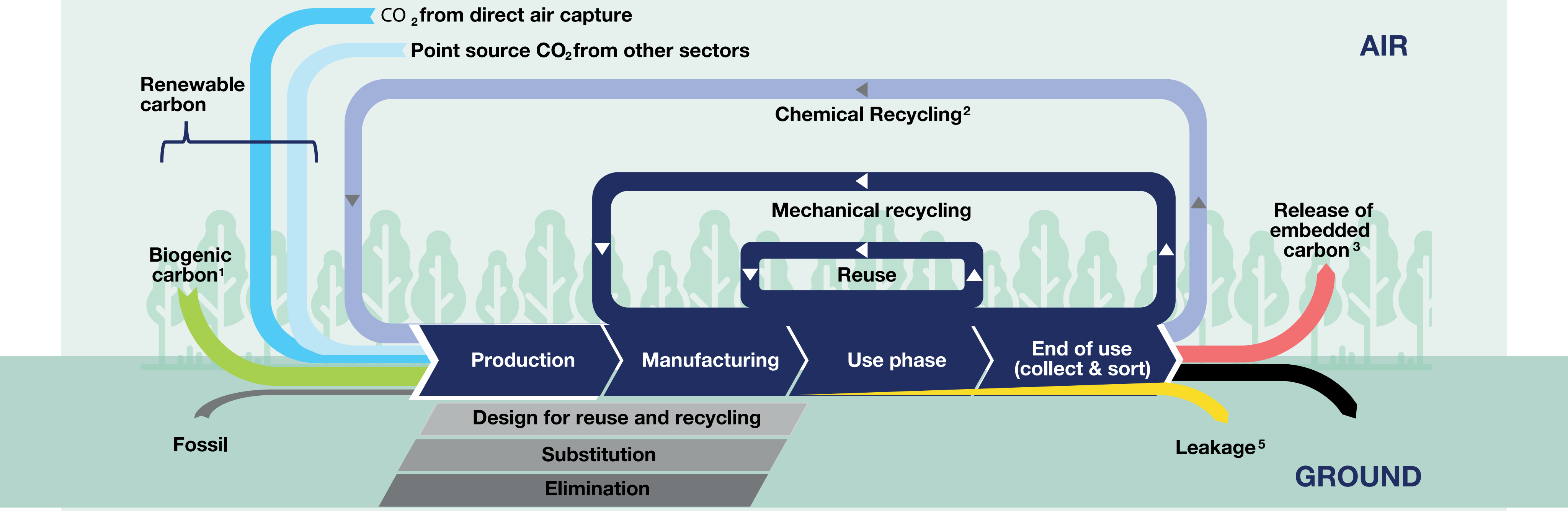

Figure 2. Outlook of a future carbon flow in the plastics and chemicals industry with limited amounts of residual fossil feedstock, plastics leaking out of the system, and CO_2 being released into the atmosphere. The relative sizes of feedstocks are purely illustrative and do not aim to give preference to specific solutions over others.

(1) Biogenic carbon refers to carbon flowing from biomass and Direct Air Capture (DAC)
(2) This includes technologies such as waste polymers to Gasification Pyrolysis and Depolymerisation
(3) Release of embedded carbon to the atmosphere takes place when carbon contained in waste materials is incinerated without CCS as well as openly burned. Emissions during production and manufacturing are not explicitly shown in the figure
(4) Safe Carbon Storage occurs when carbon from waste materials is geologically stored via controlled landfilling (free from organic contamination and thereby methane emissions) or through incineration of waste with CCS.
(5) Leakage can occur terrestrial and water-bound in mismanaged waste systems, e.g. improper collection or waste handling, littering. Carbon contained in leaked waste is also considered as locked above or below ground, without being liberated into the atmosphere

Currently, the regulatory framework of the EU plastic system is being adapted to create a more circular system with measures to promote sustainable production, consumption, and greater recycling at the end of life. As summarized in Figure 3, current policies aim at expanding recycling for sectors with the highest consumption of plastics (e.g., packaging, automotive, and textile sectors). Furthermore, policy mechanisms curbing the production of plastics by reducing demand are more recently being integrated. A growing number of policies aim at a system transformation that includes guidelines to eliminate unnecessary plastic applications, shift towards reuse models, and substitute plastics with more sustainable materials (if a positive sustainability impact can be proven). While this is a significant cornerstone of the transition, it is insufficient, as there will always be losses of materials of the circular economy (e.g. due to degradation) and some virgin carbon feedstock will always be required. Hence, on top of the existing aspects, policy focus needs to be given to the origin of the carbon.

Chemical and plastic legislation thus needs to incorporate renewable carbon feedstocks (e.g., bio-based, CO_2-based) to supplement circular feedstock to reach overarching climate targets. Luckily, renewable biobased feedstocks are readily and commercially available. Setting binding targets to also use renewable feedstocks in the chemical industry and its final products would be one of the most impactful options for policy intervention. Other options include for example emission intensity targets for products or intermediates and direct financial support for low-emissions plant investments.

The EU policy framework on biobased, biodegradable, and compostable plastics Communication (BBBDCP)[11] as well as the Sustainable Carbon Cycles Communication (SCC) mark the first acknowledgment by the European Commission of the contribution of these feedstocks (e.g., bio-based, CO_2-based) to the system and sets the first guidelines for the creation of a detailed regulatory framework. SCC sets out a visionary goal in which “sustainable, non-fossil carbon sources”, i.e. both renewable and circular carbon, should account for 20% of the supply of virgin raw material used by the chemical industry by 2030. Luckily, more and more initiatives are in the pipeline. For example, adding biobased plastic feedstock targets is discussed within the development of Packaging and Packaging Waste Regulation (PPWR) as well as End-of-life Vehicles Regulation (ELVR). The Ecodesign for Sustainable Products Regulation (ESPR) considers renewable materials a key parameter to assess the mandatory sustainability requirements set in the regulation. These requirements include, among others, resource efficiency and carbon and environmental footprint.

> **“In the next few years, market segment regulations could set mandatory sustainability requirements for different products, promoting the use of renewable and circular raw materials among other aspects.”**

Moreover, new ideas for incentivizing or mandating renewable and recycled carbon feedstock use are brought up, for example, the Dutch proposal for a new EU instrument regulating “Industrial Sustainable Carbon.” However, none of the aspirational guidelines and targets contained in these documents can be considered legally binding yet. Despite the recent positive signs of moving away from fossil feedstocks, there needs to be more clarity on how renewable feedstocks regulations will proceed.

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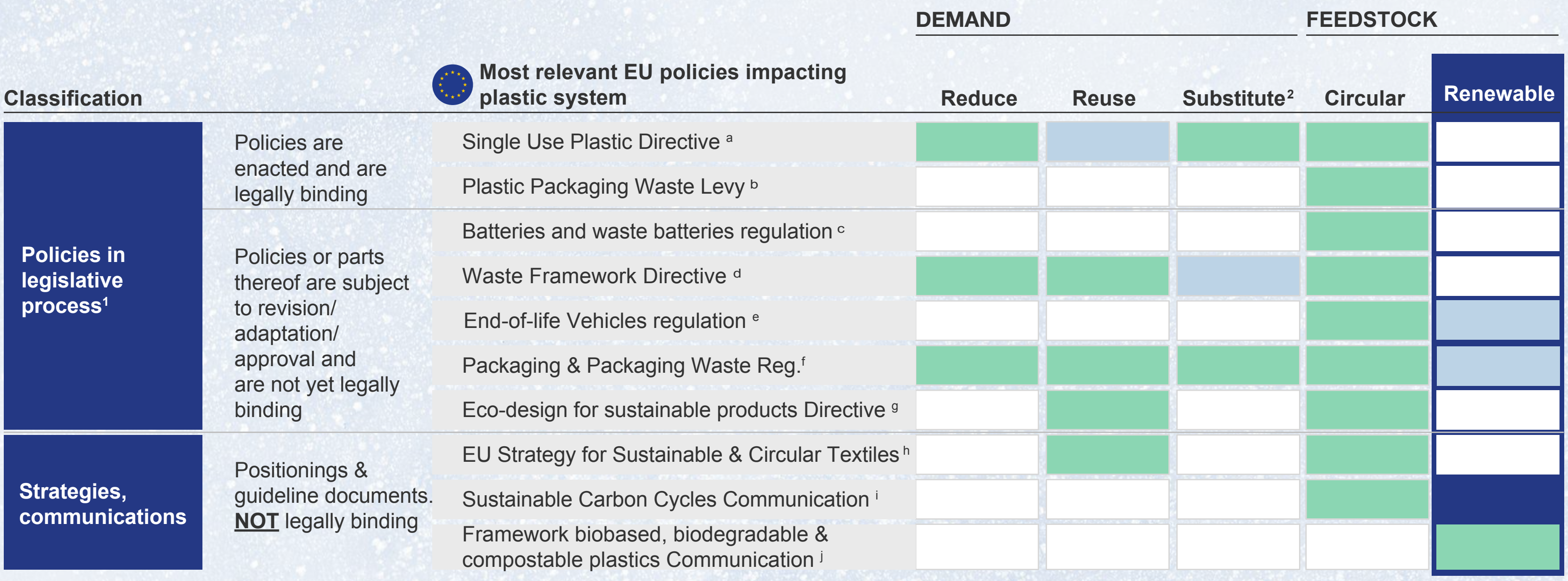
[11] European Commission (2022), Communication: EU policy framework on biobased, biodegradable, and compostable plastics

In the current market environment, where externalities of fossil feedstocks are neither priced in nor communicated effectively, plastics and chemicals based on renewable carbon appear to be more expensive than fossil-based products. Inherent chemical properties of renewable carbon sources (as primary biomass has lower energy and higher oxygen content than primary fossil feedstocks) make them more costly and energy-intensive to transport and process. Furthermore, some technologies that transform renewable carbon sources are also at lower TRL (e.g., CO_2 capture and utilization, biomass/waste gasification to chemicals) and require significant scale-up. Nevertheless, the playing field vs. fossil feedstocks is not appropriately leveled today, causing substantial distortions in the cost comparison. This distortion becomes even larger, if the social cost of using fossil carbon would be considered[12]. The combination of unpriced externalities and the lack of clear communication about the environmental impacts of fossil feedstocks presents a challenge for replacing fossil with renewable carbon sources. Figure 4 on page 17 shows that pricing externalities and removing

Overview of the gap in the regulation of renewable feedstock (EU regulation)



Classification		Most relevant EU policies impacting plastic system	DEMAND Reduce	 Reuse	 Substitute[2]	FEEDSTOCK Circular	 Renewable
Policies in legislative process[1]	Policies are enacted and are legally binding	Single Use Plastic Directive [a]	🟩	🟦	🟩	🟩	
		Plastic Packaging Waste Levy [b]				🟩	
	Policies or parts thereof are subject to revision/ adaptation/ approval and are not yet legally binding	Batteries and waste batteries regulation [c]				🟩	
		Waste Framework Directive [d]	🟩	🟩	🟦	🟩	
		End-of-life Vehicles regulation [e]				🟩	🟦
		Packaging & Packaging Waste Reg.[f]	🟩	🟩	🟩	🟩	🟦
		Eco-design for sustainable products Directive [g]		🟩		🟩	
Strategies, communications	Positionings & guideline documents. **NOT** legally binding	EU Strategy for Sustainable & Circular Textiles [h]		🟩		🟩	
		Sustainable Carbon Cycles Communication [i]				🟩	■
		Framework biobased, biodegradable & compostable plastics Communication [j]					🟩

Figure 3. Overview of the gap in the regulation of renewable feedstock (EU regulation).

(1) Includes enacted, proposal, revisions, and drafts
(2) no formal mandate but includes mentions and guidelines for substitution. Systemiq analysis based on (a) Directive (EU) 2019/904 of the European Parliament and of the Council of 5 June 2019 on the reduction of the impact of certain plastic products on the environment; (b) Council Decision (EU, Euratom) 2020/2053 of 14 December 2020 on the system of own resources of the European Union and repealing Decision 2014/335/EU; (c) Directive 2006/66/EC of the European Parliament and of the Council of 6 September 2006 on batteries and accumulators and waste batteries and accumulators; (d) Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste; (e) Directive 2000/53/EC of the European Parliament and of the Council of 18 September 2000 on end-of life vehicles; (f) EC (2022), Proposal for a Regulation on packaging and packaging waste; (g) EC (2022) Proposal and Annexes for a Regulation establishing a framework for setting ecodesign requirements for sustainable products and repealing Directive 2009/125/EC (h) EC (2022), Communication - EU Strategy for Sustainable and Circular Textiles (i) (EC (2021), Communication From The Commission To The European Parliament And The Council (j) EC (2022), Communication – EU policy framework on biobased, biodegradable and compostable plastics.

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[12] Tol (2023), Nature Climate Change, Social cost of carbon estimates have increased over time

subsidies or tax breaks for oil extraction could close the price gap between renewable plastic and fossil plastic (please not this is just an exemplary calculation, actual product prices may vary significantly e.g. over time, by location and with sustainability criteria):

Plastics production cost including externalities

($ / tonne polypropylene)

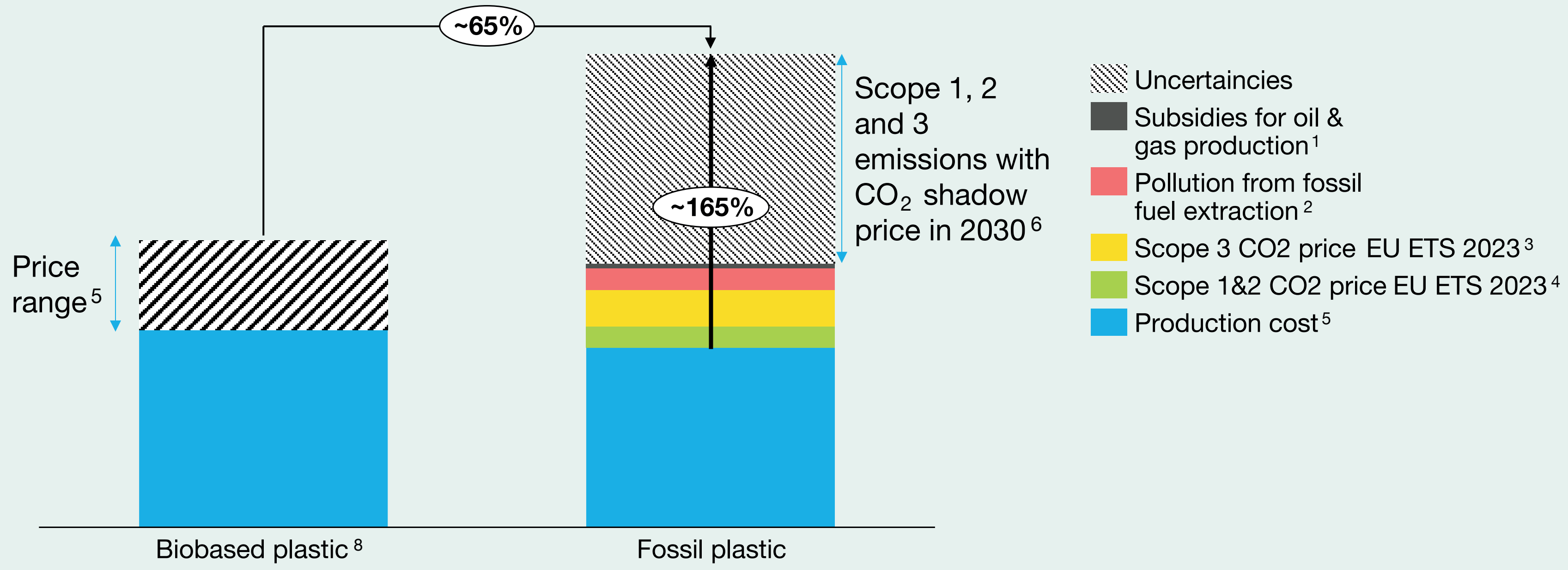

Figure 4. Comparison of production cost including externalities for bio-based and for fossil-based plastics ($ / tonne polypropylene).

Note: this is just an exemplary calculation, actual product prices may vary significantly over time, by location and with sustainability criteria. Here we assumed the following: (1) Based on global oil production subsidy reported by IMF (2021), Still Not Getting Energy Prices Right: A Global and Country Update of Fossil Fuel Subsidies, (2) Pollution costs were estimated based on costs per tonne of oil leaked faced by BP after the deepwater horizon accident combined with oil leakage data reported by Louisiana state as global proxy, (3&4) Based on average EU Emissions Trading System (EU ETS) CO_2 price in 2023 (90 €/tonne) and LCA emissions reported in Journal of Cleaner Production 379 (2022) 134645, (5) The cost difference for bio-based plastics production was assumed to be 10-60% based on Nova Institute (2020), Bio-based products: Green premium prices and consumer perception of different biomass feedstocks. (6) The UK government assumes a CO_2 shadow price (medium scenario) of 280 GBP/tonne CO_2 in 2030. https://www.gov.uk/government/publications/valuing-greenhouse-gas-emissions-in-policy-appraisal/valuation-of-greenhouse-gas-emissions-for-policy-appraisal-and-evaluation. (7) No externalities were factored in for biobased plastic as sustainable biomass was defined to have no associated land use change emissions and emissions during production and end of life are assumed as carbon neutral (i.e., no carbon price) including scope 2 emissions which are 0 if green electricity is used.
Plastic pollution costs upon leakage into the environment are not factored in as they would occur for both equally. Health-related impacts of airborne fossil fuel emissions are not accounted for as they almost exclusively occur during fossil fuel combustion.
Source: Systemiq analysis

Price externalities via carbon pricing (e.g., EU ETS for chemicals and plastics industry) and stronger regulation around the pricing of pollution. Carbon border adjustment mechanism (CBAM) or related schemes are vital in ensuring such newly introduced policy instruments do not lead to emissions leakage and industry production shifting to other regions of the globe. Existing extended producer responsibility schemes (EPR) could also play a role by incorporating eco-modulated fees that reward renewable feedstock.

Current EU ETS prices for production emissions would increase the costs by 12%. However, to generate an even playing field between fossil and all renewable feedstocks, taking only scope 1 and scope 2 emissions into account is not sufficient. The chemical and plastics industry receives free allocation of CO$_2$eq certificates until 2030 to prevent the risk of carbon leakage. With the implementation of carbon border adjustment mechanisms and tracking materials and products along the value chain, this may change in the near future.

Carbon pricing of end-of-life emissions would make the most significant difference. Carbon prices of ~90 $/t CO$_2$eq, as observed on average in 2023 in the EU emissions trading system, would lead to ~220 €/t cost (~20% cost increase) for fossil carbon at the end-of-life, assuming all carbon content is combusted in a waste incinerator.

Considering a price for CO$_2$eq that is in line with net-zero scenarios, biobased plastics would cost significantly less than fossil plastics. A 2030 CO$_2$eq shadow price, as used by the UK government, of ~300 €/tonne CO$_2$eq applied to the current full lifecycle emissions would more than double the price of fossil plastics.

The oil and gas industry benefits from long-standing production subsidies and, in some instances, tax breaks. These resulted from a complex mix of historical measures and government incentives to encourage economic development and growth[13]. In addition, there is no comprehensive global monitoring of oil leakage[14], but large accidents and regular smaller oil spills create ecological damages associated with clean-up costs[15]. While the exact pricing of each remains an area of research, the order of magnitude is significant and requires more attention.

> In summary, pricing externalities (i.e., CO$_2$eq price, pollution) and removing subsidies would at least close the price gap between renewable and fossil-based plastic and chemicals. In fact, climate change mitigation is the most economical path once all negative impacts are internalized[16]. The negative consequences of using fossil feedstock on the environment beyond carbon emissions are often ignored in public debates. This includes, but is not limited to, direct and indirect land-use changes, spillage, and biodiversity impacts. In comparison, only renewable carbon has the burden to prove its positive environmental impacts. In the following, we describe which criteria must be fulfilled to minimize potential negative impacts of biobased carbon and how the chemical industry can unlock new volume streams.

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[13] IMF (2021), Still Not Getting Energy Prices Right: A Global and Country Update of Fossil Fuel Subsidies

[14] Hannah Ritchie, Veronika Samborska and Max Roser (2022) - “Oil Spills”. Published online at OurWorldInData.org. Retrieved from: ‘https://ourworldindata.org/oil-spills’ [Online Resource]

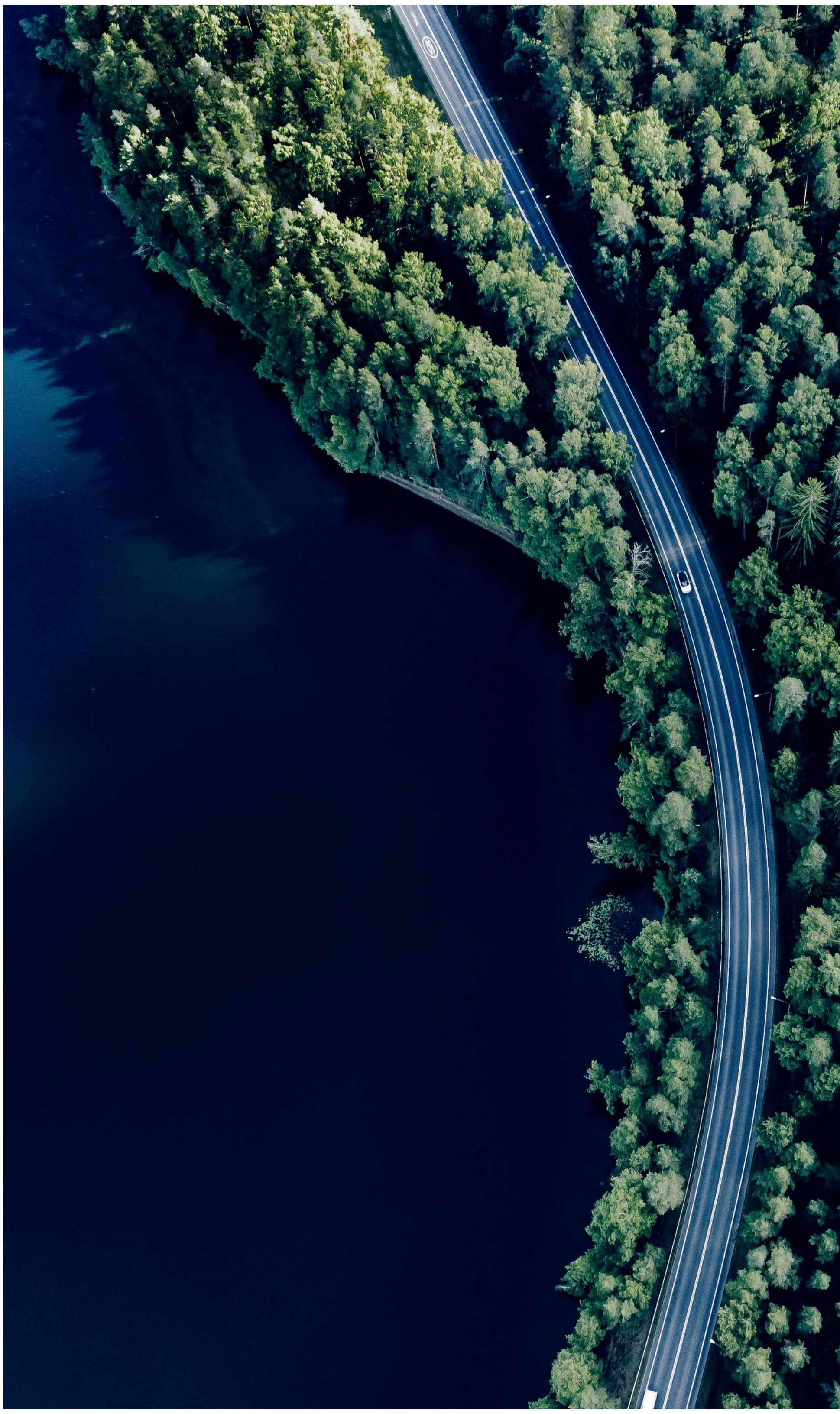
[15] Washington Post (2018), “A 14-year-long oil spill in the Gulf of Mexico verges on becoming one of the worst in U.S. history”

[16] Glanemann, N., Willner, S.N. & Levermann, A. Paris Climate Agreement passes the cost-benefit test. Nat Commun 11, 110 (2020). https://doi.org/10.1038/s41467-019-13961-1

(2) Collaboration with biomass producers and ensuring sourcing criteria will improve the sustainability performance of biobased polymers and chemicals

When replacing fossil feedstock by renewable and circular feedstock, sustainable sourcing becomes much more important. Terrestrial ecosystems like forests, peatlands, or grasslands play a vital role in regulating climate, hosting biodiversity, or providing livelihoods[17/18]. To meet closely interlinked biodiversity and climate objectives, around 10% of agricultural land globally must be taken out of production and returned to nature[19]. Without safeguards, additional biomass cultivation for the chemical and plastic industry could create a risk of undesired effects, e.g., deforestation. Therefore, sourcing sustainable biomass needs to be aligned with the broader food, industry, and energy systems. Scenarios that avoid displacement effects (aligned with Science Based Targets Network (SBTN)) conclude that total bio-resources that can be used in non-food applications are restricted to 40-60 EJ/annum in 2050 (Energy Transitions Commission), while other organizations have estimated it can conservatively go up to 110 EJ/annum[20].

There are several sustainable biomass sources that the chemicals and plastics industry could unlock to increase the availability of sustainable biomass, for example waste, residues, and biomass from novel agricultural systems such as intermediate cropping.



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[17] SBTN (2023), Science Based Targets for Land Version 0.3 – Supplementary Material
[18] The Food and Land Use Coalition (2022), Assessing the G7's international deforestation footprint and measures to tackle it
[19] The reduction refers to crop- and pastureland by 2050 and is based on scenario SSP1 in IPCC (2018), Summary for Policymakers of IPCC Special Report on Global Warming of 1.5°C approved by governments. SSP1 is aligned with the Sustainable Development Goals (SDGs) and balances human needs with goals for nature and climate.
[20] ETC 2021: Bioresources within a Net-Zero Emissions Economy

To make waste and residues accessible, the industry needs to further advance sorting, pre-treatment, and conversion processes. Improving the economics of smaller streams and unlocking synergies between supply chains of different end-use segments will provide additional feedstock volumes. Finally, the chemical industry can establish collaboration with agriculture, forestry, and food production for supply of innovative feedstocks:

Collaborating in developing optimal crop rotations to serve all industries and to avoid monoculture production.

Combine the restoration of degraded land with biomass production through regenerative agriculture, agroforestry, and reforestation.

Optimizing land use efficiencies by advanced agricultural systems including more efficient fertilizer use.

To fully leverage the synergies between different end-use segments and to enable a level playing field between biomass used for plastics and energy, the minimum regulatory sustainability criteria in the EU should build on the sustainability criteria developed for bioenergy, i.e., Renewable Energy Directive (RED). These sustainability criteria ensure mitigation of risks for climate change, biodiversity, and soil health and should be accompanied by strict traceability and transparency requirements (see Figure 5).

In particular, sustainability criteria for biomass should cover:

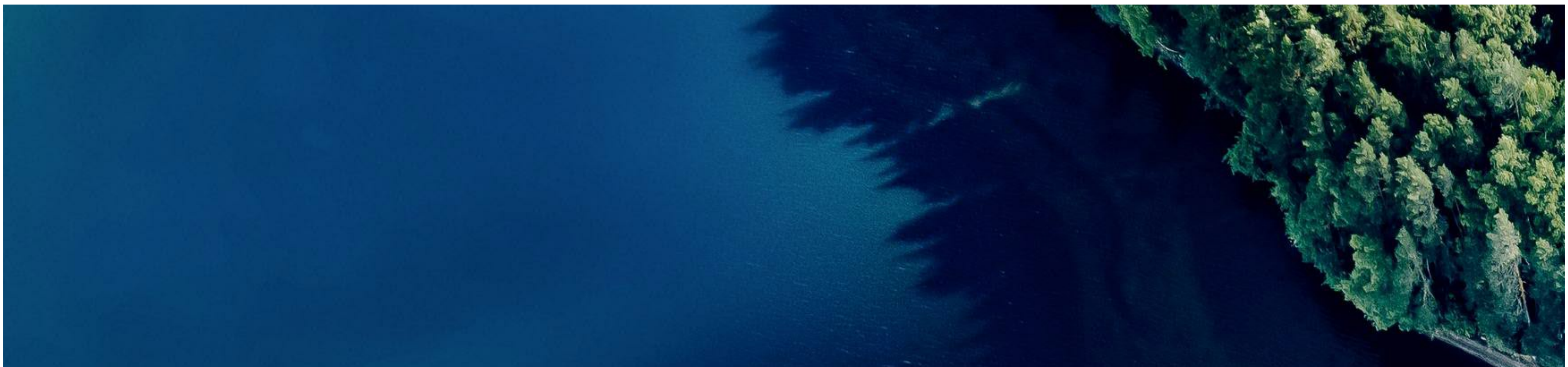
The protection of land with high biodiversity or high carbon stock.

Protection of peatlands.

Ensuring sustainable forest management.

Maintaining or improving soil quality and soil carbon.

Greenhouse gas emission savings compared to using fossil feedstocks.



While the land use related sustainability criteria of RED can be applicable for other end use segments as such, further and harmonized methodological developments are needed before setting detailed quantitative criteria for the GHG reductions when using biomass in the chemical sector. For example, today's quantitative LCA methodologies typically do not capture emissions from or improvements of soil carbon stocks, mainly due to the complexity of accurately capturing these impacts. To address this issue, various qualitative certification schemes and labels have emerged in the last decade and should be further developed. On top of setting minimum regulatory sustainability criteria, stakeholders need to continue to improve the sustainability of their value chains. For example, by aligning with SBTN targets to minimize the risks of unintended negative consequences.

Critical sustainability factors of biomass based value chains

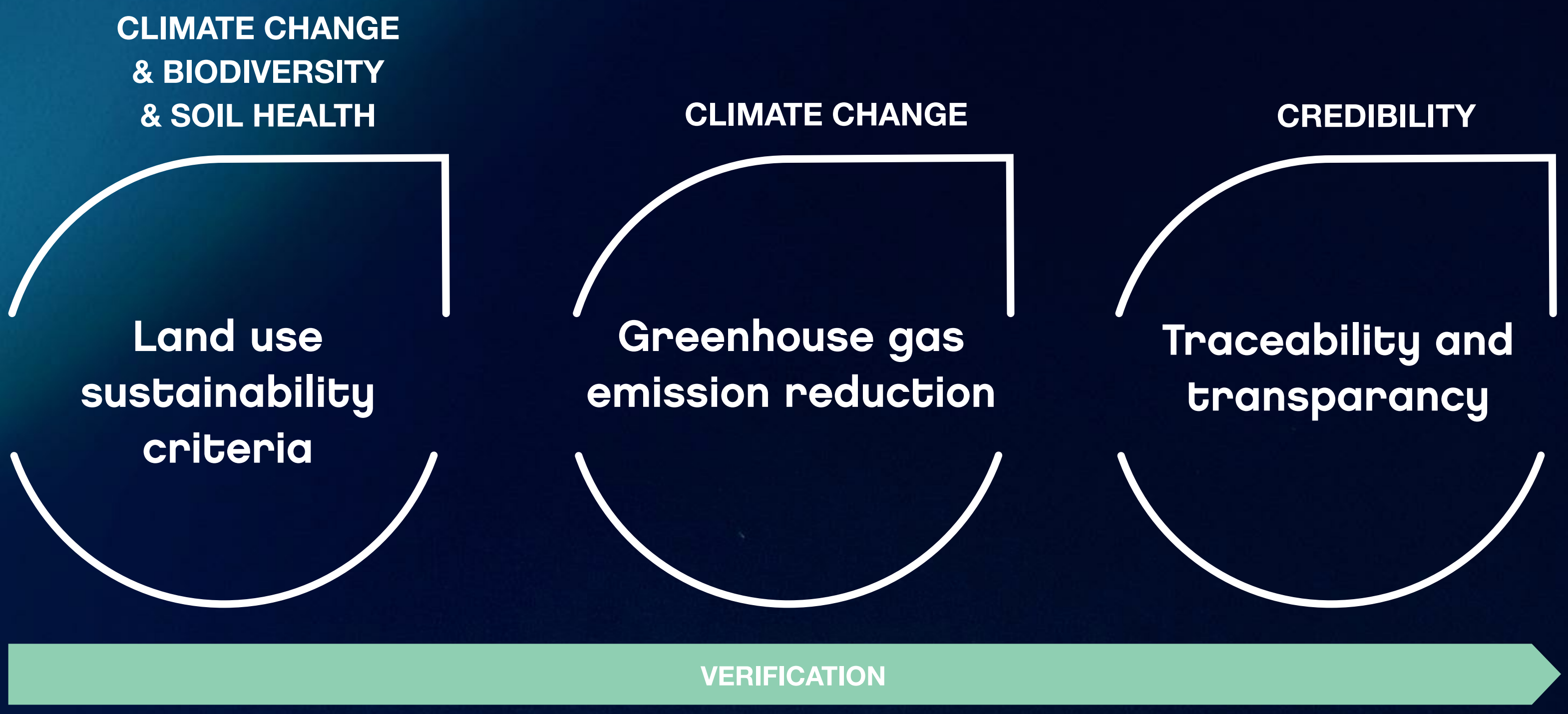


Figure 5: Criteria and verification for sustainable biomass supply.

(3) Reducing end-of-life emissions is an underestimated pillar of a carbon neutral chemical industry

So far, we have been looking at the beginning of the chemicals and plastics' lives. Let's now have a look at what happens when products reach their end. Today's European plastics system is primarily linear, producing significant end-of-life emissions by releasing the embedded carbon. Circularity levers, including reuse and recycling, are vital in abating end-of-life emissions. Recycling can tackle somewhere between 50%-80% of plastic waste by 2050, reducing end-of-life emissions by 27%. But not all plastic can be avoided, reused, or recycled. In Europe, the enforcement of the landfill directive means that incineration with energy recovery is the dominant pathway for plastics over landfill[21/22]. As a result, **"incineration with energy recovery is likely to grow for plastic waste that cannot be eliminated, reused, or recycled"**

The related emissions can be avoided by abating incinerator emissions using carbon capture utilization or storage (CCUS, see Figure 6).

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[21] Council Directive 1999/31/EC of 26 April 1999 on the landfill of waste limits the share of municipal waste that is landfilled to 10% by 2035.

[22] The waste framework directive puts incineration with energy recovery above landfilling in the waste hierarchy. Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste.

However, a credible plan of net-zero compatible incinerators needs to be developed for the remaining waste that cannot be recycled. To address the issue, the European Commission recently decided to include the waste management industry, specifically incinerators, in the ETS system. However, implementation will only take effect in a few years[23] and, as of today, it needs to be proven that the costs of ETS are sufficient to encourage the development of CCUS. Incinerators are typically small units and distributed across the region, leading to high capture and transport costs[24]. CCU typically requires significant amounts of green hydrogen and therefore depends on local energy prices and hydrogen availability. Currently, CCUS still relies on large infrastructure projects. Thus, ensuring cost competitiveness at scale usually goes beyond the development of a single incinerator[25]. Some countries are leading the way, although success is still to be confirmed. Norway was, until recently, developing a large-scale CCS pilot at its Oslo incinerator, but halted due to prohibitive costs[26]. Germany has passed a tax on incinerator emissions which started in 2024[27] as a lever to close the financial gaps, yet no CCS projects have been announced so far.

European end-of-life mix and associated emission factors

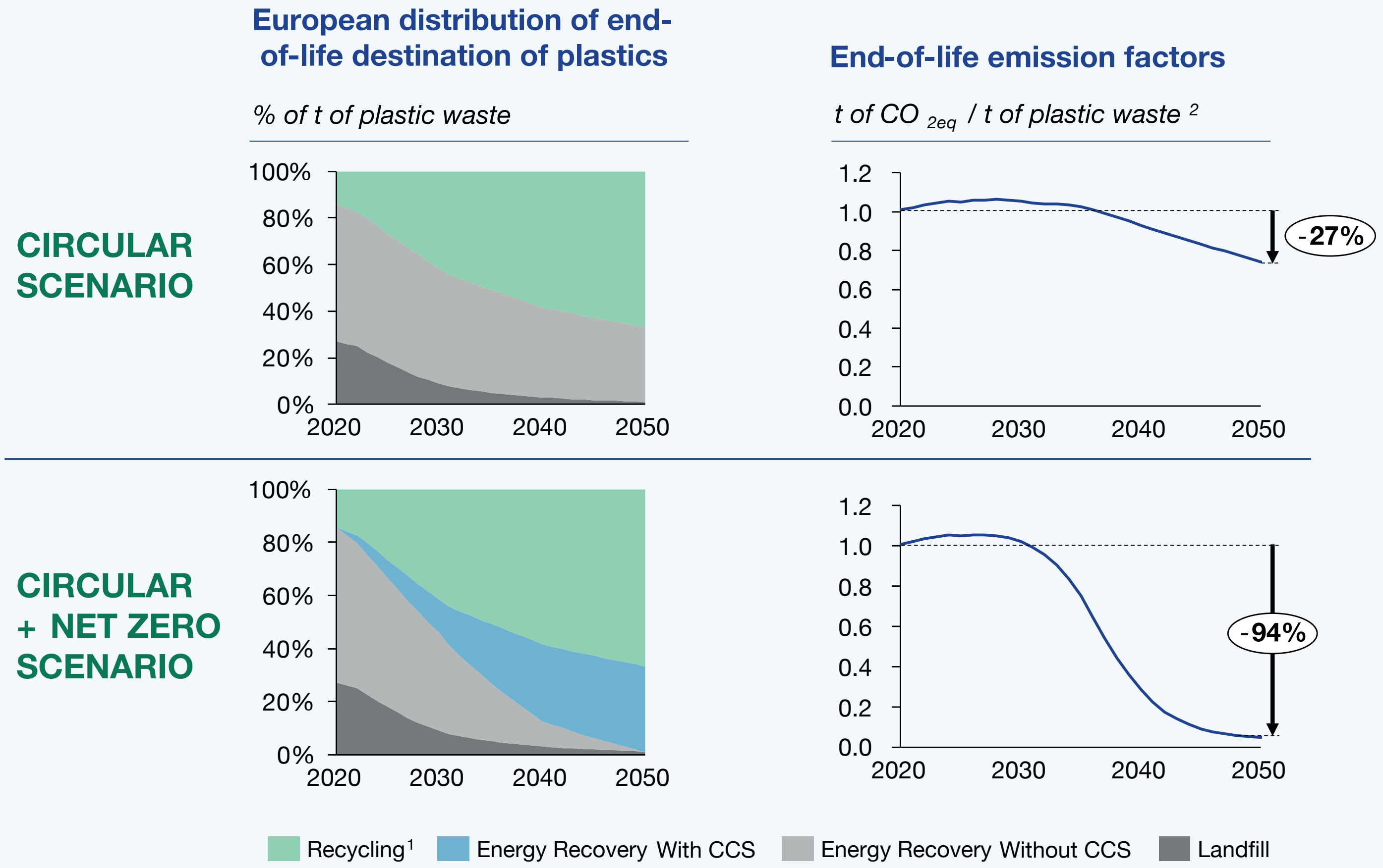

Figure 6. European end-of-life mix and associated emission factors.

Note: (1) Recycling includes all forms of recycling (i.e., mechanical and chemical recycling) (2) blended average (2) Average end-of-life emission factors are increasing in the first years as incinerators will get less carbon credits from energy recovery due to progressing electricity grid abatement. (3) The emissions are captured and then utilised or stored. In both cases the end of life emissions are physically abated, but, depending on CO2 accounting rules, in the utilisation case, the emissions factor from the incinerator needs to be accounted for in the CO2 use case.
Source: ReShaping Plastics, Systemiq, 2021

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[23] European Commission Press Release (Dec. 2022). "EU countries must measure, report, and verify emissions from municipal waste incineration installations from 2024. By 31 January 2026, the Commission shall present a report to include such installations in the EU ETS from 2028 with a possible opt-out until 2030 at the latest."
[24] https://www.cewep.eu/interactive-map/
[25] ETC (2022), Carbon Capture, Utilisation and Storage in the Energy Transition: Vital but Limited
[26] https://www.reuters.com/world/europe/carbon-capture-project-norway-temporarily-halted-by-high-costs-2023-04-26/ (consulted in July 2023)
[27] https://www.bundesregierung.de/breg-de/suche/co2-preis-kohle-abfallbrennstoffe-2061622

Further incentives for abating incineration and developing technological innovations, such as on-site CO_2 utilization, may be required to accelerate a net-zero waste management system.

> **“To unlock net carbon negative plastics, the waste management industry, in collaboration with wider industry and policymakers, will have to align with a net-zero trajectory and develop a strategy for implementation.”**

For example, if the ETS pricing is insufficient as a mechanism to price end-of-life emissions and finance incinerator retrofit, the Commission could explore using extended producer responsibility and chain of custody. To ensure such transformative changes, alignment on a trajectory for future end-of-life emissions improvements would be a helpful policy framework. Overall, enabling the abatement of incinerator emissions via CCUS at the site requires a combination of the following:

Storage site development: Accelerated planning and permitting of CCS storage sites is needed to ramp up the number of available sites for long-term safe underground storage of CO_2[28].

Transport infrastructure development: Incinerators are scattered across the continent, with many of them not located close to, e.g., an offshore CO_2 storage site. Beyond multiplying the number of available storage sites, transport pipelines will be needed to connect incinerators and emitters from other sectors (e.g., cement) to CO_2 storage sites.

Point source carbon utilization: Recognize point source CO_2 utilization as a relevant technology for the transition (e.g., on-site CO_2 carbonation or utilization). Particularly, waste incinerators that are close to low-cost hydrogen sources and are not able to connect to a CO_2 storage site should be incentivized to deploy either novel storage technologies like on-site CO_2 mineralization[29] or carbon capture and utilization. The latter can be performed in collaboration with upstream chemicals players who want to close the carbon cycle by using CO_2 from incinerators as feedstock. Equivalently to circular and bio-based mandates, targets for CO_2 as a feedstock for the chemical industry would incentivize waste incinerators and chemical industry players to develop and scale corresponding technologies, which would help to further close the carbon cycle. The critical role of industrial carbon management by carbon capture, utilization, and storage in achieving carbon neutrality in the EU by 2050 has recently been acknowledged by the EU Commission[30].

Here, the industry can provide proof points for reliable and scalable technologies.

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[28] CCS is considered safe and has a high long-term (thousands of years) storage capacity. Source: ETC (2022), CCS: Vital but limited

[29] For example, developed by the start-up CarbonFree together with BP: https://www.bp.com/en_us/united-states/home/news/press-releases/carbonfree-and-bp-collaborate-to-help-bring-carbon-capture-and-utilization-technology-to-industrial-sites-around-the-world.html

[30] European Commission: Industrial carbon management – carbon capture, utilization, and storage deployment

(4) A full cradle-to-grave life cycle analysis highlights the favorable climate impact of chemicals and plastics based on renewable carbon

As described in the previous section, reducing end-of-life emissions is a key lever to improve climate performance of the chemical value chain. However, the chemical and plastic industry still commonly refers to cradle-to-gate emissions, neglecting emissions at the end of life. This is partly due to a lack of knowledge on material flows of products during use-phase and end-of-life[31]. However, in the EU, incineration of plastic is the most common end-of-life treatment and leads to the release of embedded fossil carbon into the atmosphere. In comparison, plastics and chemicals based on non-fossil feedstocks benefit from upstream carbon removal (e.g., via photosynthesis). This carbon uptake results in significantly lower cradle-to-grave emissions of renewable products compared to fossil-based products.

Even if a plastic product from biogenic or atmospheric carbon may be net negative from a cradle-to-gate standpoint, emissions due to embedded carbon release must be accounted for in the cradle-to-grave perspective (see Figure 7 on page 30). The attainment of net negative emissions for the entire lifecycle of the product relies both on the choice on feedstocks and on the appropriate treatment of end-of-life processes. This claim will only be feasible by implementing carbon capture and storage technologies to mitigate emissions effectively, as described above.

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[31] Note that as part of the European Commission's Environmental Footprint (EF) initiative, a consortium of organizations, is developing EF 4.0, a secondary lifecycle inventory database. This will improve the availability and quality of end-of-life industry average emission data.

However, current methodologies of carbon accounting[32] still need further development to measure progress towards net-zero. The vision of a net-zero chemicals and plastics industry is set on a system level (e.g., EU policy, industry coalitions). Using corporate carbon footprints, plastics companies set corporate emission reduction targets that are aligned with the system vision (e.g., Science-Based Target initiative). However, by minimizing and communicating products' carbon footprints (PCF), companies ultimately drive the net-zero transition – especially since this enables customers throughout the value chain to make conscious choices for products with lower carbon footprints. Thus, accurate PCFs are essential to enable the transition on system-, corporate-, and (intermediate) product-level.

PCFs build on different standards and methodologies. Standards like ISO 14067 and the GHG Protocol Product are well established

Emissions comparative per feedstock/technology

(Average tonnes of CO_2eq per tonne of plastic output considering average plastic composition in Europe, 2020 using the -1/+1 carbon accounting approach)

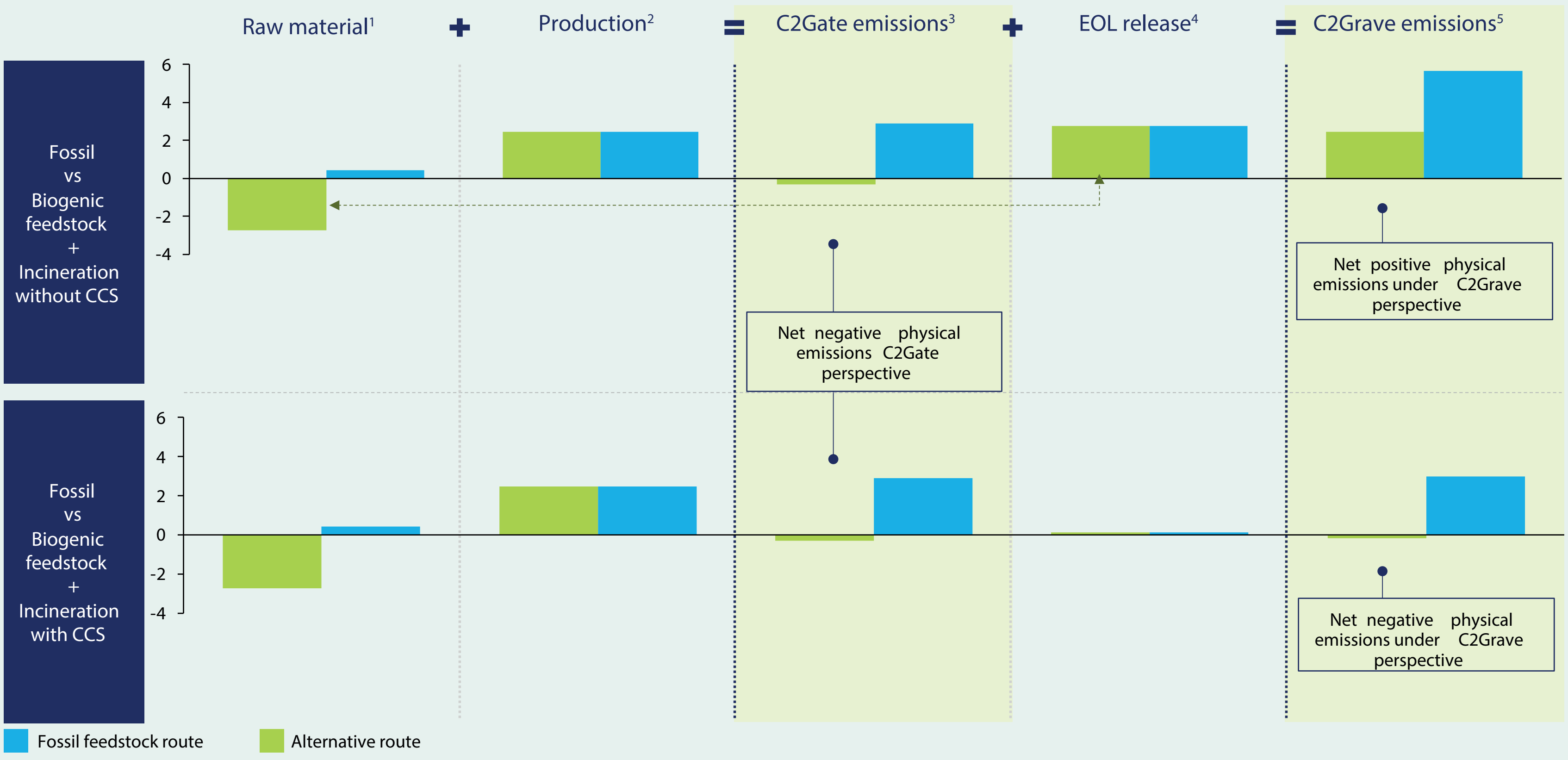

Figure 7 | Emissions comparative per feedstock/technology (Average tonnes of CO_2eq per tonne of plastic output considering average plastic composition in Europe, 2020 using the -1/+1 carbon accounting approach).

(1) Raw material phase contemplates extraction of fossil resources in conventional route and production of biogenic feedstock in alternative route (assumes no emissions in the latter in line with guidelines on the production of sustainably sourced biomass; (2) Production stage contemplates refining, steam cracking, polymerization and conversion stages; (3)Cradle to Gate – Considers total emissions from extraction and production of raw materials up to production of plastic end-products; (4) EOL considers the complete release of carbon from waste (as if in 100% incineration); In CCS scenario, positive emissions from EOL release correspond to residual emissions from CCS; (5) Cradle to Grave – Considers total emissions from extraction and production of raw materials to end-of-life of waste materials
Source: Systemiq analysis, 2023

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[32] Carbon accounting refers to measuring and tracking the carbon or greenhouse gas emissions produced by a product, company, or sector. It involves quantifying the amount of carbon dioxide (CO_2) or other greenhouse gases released into the atmosphere as a result of various activities (e.g., energy use, transportation, manufacturing processes, release of embedded carbon, carbon offsets)

but leave methodological choices, such that PCFs can vary significantly depending on the choices made by the practitioner. Hence, more prescriptive and sector- or even product-specific guidance and methodologies like Together for Sustainability's (TfS) PCF Guidance, WBCSD's Pathfinder Framework, or the EU's PEF methodology and the closely linked JRC Plastics LCA aim to harmonize PCF data exchange, calculation, and reporting[33]. However, product-level carbon accounting still needs to improve variance in methodology and thus resulting carbon footprint to increase clarity in the market and its significance for decision-making. The PCF ecosystem is evolving quickly, but as outlined in Figure 8, today's standards and methodologies still do not fully capture the benefits of non-fossil feedstock and, thus, hinder the transition towards net zero. For example, the current PEF accounting methodology does not allow claiming carbon uptake of biogenic feedstock[34]. Mechanisms that allow for capturing carbon uptake in PCFs (e.g., as in TfS) incentivize the use of sustainable biomass (or DAC-CO_2) and enable cradle-to-grave net negative emissions[35]. While this methodological choice (i.e., allowing capturing the carbon uptake in PCFs) does not impact physical emissions, it is essential for creating marketable net carbon negative products, which may function as a differentiator in the market. Therefore, methodological consensus is required – especially between industry players and regulatory bodies – to decrease variance in PCF approaches and to incentivize the use of non-fossil feedstocks.

We identify key levers that enable the proper use of PCFs in decision-making and foster markets for plastics based on non-fossil feedstock:

(a)
Enable decisions that minimize emissions on a system level by complementing cradle-to-gate (C-to-Gate) with cradle-to-grave (C-to-grave) perspectives.

(b)
Reflect biogenic uptake at the beginning of the value chain (i.e., CO_2 removal due to photosynthesis) in PCF, particularly in the EU regulatory frameworks, such as EU PEF.

(c)
Incentivize the reduction of end-of-life emissions and extension of the lifetime independent of carbon origin.

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[33] Note that sector- or product-specific rules are often not directly comparable and can lead to difficulties for policymakers when prioritizing between these sectors or products.
[34] PEF and the JRC Plastics LCA set the characterization factor of biogenic carbon to 0, meaning that biogenic carbon uptake (and emissions) cannot be considered in PCF values based on both methodologies. However, PEF and JRC Plastics LCA demand separate modeling and reporting of biogenic uptake and emissions (i.e., not in the PCF).
[35] The PEF standard is often referred to as the 0/0 mechanism, whereas standards allowing for carbon uptake are called +1/-1.

Complementing cradle-to-gate by cradle-to-grave perspective would improve the informative value of lifecycle assessments (LCAs). Cradle-to-grave carbon accounting allows downstream partners to select feedstocks with the lowest PCF values. In addition, cradle-to-grave perspectives provide a basis for end-customers to make profound decisions for more sustainable products, taking end-of-life into account. To avoid misleading claims, the methodology applicants need to report cradle-to-grave emissions - under different downstream scenarios - alongside partial cradle-to-gate PCFs. For example, some companies claim carbon negative products but just consider cradle-to-gate emission. However, the entire life cycle still results in overall emissions, e.g. if the value chain is not fully defossilized. Thus, product-specific lifecycle assessment considering each step of the value chain is required to credibly document the emissions of the product. Collaboration along the value chain is essential, as a single player cannot provide a full lifecycle for each product. This will also strengthen the relationship between the players in the market.

Relevant technicalities		TfS[1]	Pathfinder[2]	PEF & JRC[3]	Existing bottlenecks of some or all methodologies	Implications
Scope	Cradle- to-grave (vs. gate)	✗	✗	✓	Industry (TfS, BASF, and Pathfinder) focus is on cradle-to-gate (C2Gate) emissions today as this within their control. Only EU PEF demands cradle-to-grave (C2Grave)[4]	C2Gate does not enable truly carbon negative claims as it does not capture the full life cycle. Moving to C2Grave requires value chain cooperation and accurate secondary data
	Broader impacts (vs. GHG only)	✗	✗	✓	Industry focus is on greenhouse gas (GHG) emissions only, while PEF demands a broader set of impact categories (16 in total)	By only assessing a product's GHG emissions, other significant impacts might be ignored ("carbon tunnel"), risking misleading claims
Accounting of land-use change emissions	dLUC	✓	✓	✓	While broadly accepted methodologies for quantifying direct land use change (dLUC) emissions exists, there is need of internally agreed-upon an accurate to calculate LUC (iLUC emissions)	To avoid unfair advantages for less sustainable biomass and missing significant impacts, qualitative assessment (e.g. certifications) can provide an effective alternative to assessing land use change emissions and especially iLUC
	iLUC	(✓)	(✓)	(✓)		
Accounting of feedstock	Bio- based	✓	✓	(✓)	PEF does not allow for including biogenic uptake in PCF values[5] and, therefore, does not fully incentivise the use and scaling of bio-based feedstock in plastic applications	PCFs based on PEF cannot become carbon negative using bio-based feedstock
	CO_2-based	✓	-	(✓)	Only TfS & JRC provide preliminary and partial guidance on accounting for CO_2-based feedstock	Insufficient allocation guidance increases variance of PCF results and makes it more challenging to capture life cycle carbon negative plastics based on CO_2-based feedstock
	Waste and residues	✓	✓	✓	Economic value as the determining factor which raw materials carry upstream burdens	Inappropriate burdening of waste and residues
Accounting of carbon storage	Temporary	(✓)	-	✗	Definitions of temporary and permanent storage are not consistent, and methodologies do not allow for considering carbon storage in PCFs	Lack of consensus and excluding temporary and permanent storage in PCFs makes it challenging to capture the benefits of carbon storage
	Permanent	-	-	✗		
Accounting of future EoL improvements		(✓)	-	-	Methodologies do not provide tools for reflecting future end-of-life emissions improvements that are imperative in the system's net zero transition	Due to the lack of auditable tools, long-lifetime plastics struggle to benefit from future end-of-life improvements that will lower their life cycle emissions

✓: required/possible | (✓): separate reporting (not in PCF) allowed | ✗: not allowed / prescribed | -: not mentioned

Figure 8. Major gaps in carbon accounting methodologies.

Source: Based on TfS PCF Guidance Version 2.0, BASF SCOTT Version of 20.07.2022, WBCSD Pathfinder Framework Version 2.0, EU PEF Annexes (1&2) 12/2021, JRC Plastics LCA 20211: Together for Sustainability PCF Guidance (is more extensive but in general aligned with BASF SCOTT) | (2) WBCSD Pathfinder Framework | (3) EU PEF & JRC Plastics LCA | (4) cradle-to-grave demanded by default, while cradle-to-gate required intermediate products | (5) EU PEF requires the separate modelling and reporting of biogenic carbon emissions and removals, but sets the characterisation factors for biogenic uptake and emissions to zero.

Streamlining product carbon footprint (PCF) methodologies is the fastest way for the industry to accelerate the formation of a low-emissions product market already today. Ideally, this translates into the availability of harmonized tools and methodologies to capture products' cradle-to-grave impacts (as opposed to cradle-to-gate methodologies most commonly used today). These products can then compete in the market and earn a premium vs. conventional fossil products (until externality costs are fully incorporated). Even though they are less established, prospective, or dynamic LCA tools that allow for future improvements of end-of-life emissions for long-lifetime plastics applications could further incentivize the formation of a low-emissions product market.

(5) A common terminology will help to communicate the benefits of a transformed chemical industry

One other key element is to establish a common terminology to recognize the use of all renewable feedstocks in a shared agenda with all stakeholders to address climate change, pollution, and biodiversity impacts. The industry, including the entire value chain, policymakers, and cross-sectoral initiatives such as GHG protocol and SBTi should come together to align on common terminology related to renewable plastics, carbon removal/sequestration/storage, and net carbon negative plastics (we provide a deep dive on relevant terminology used in this paper in the technical appendix). Aligning on terminology can avoid misunderstanding and misleading language to the market and enable adequate regulations. Such dialogue can take place through existing coalitions and standardization bodies. Examples of promising contributions to this are the upcoming GHG Protocol – Land Sector & Removal Guidance, EU Carbon Removal Certification Framework and EU Green Claims Directive, which will set common sources of terminology and criteria for its utilization. There may also be a need to create new and/or strengthen existing standards.

A net carbon negative chemical and plastic value chain is achievable

In the previous section, we have described the bottlenecks and enablers of a defossilized and carbon-neutral chemical industry. This will be a major transition. However, we think that the chemical industry and its associated value chain can do even more: become carbon negative. Four elements are making this possible:

1. Increasing existing carbon pools, such as soil carbon content during feedstock supply
2. Capturing biogenic (or atmospheric) CO_2, which is produced during production processes
3. Capturing CO_2 at the end of life instead of releasing back into the atmosphere
4. Storing carbon in long-lifetime products

> **"Due to the conversion of land to croplands or pastures, worldwide soils have lost around 50%-70% of the carbon they once held. "**

Regenerative agriculture system can bring back the carbon and sequester CO_2. Regenerative agricultural systems can thus provide both feedstock for the chemical industry, combat climate change, and improve overall soil health. Actually, increasing soil carbon content is one of the most scalable and cheapest methods for negative carbon removal[36]. Additionally, CO_2 that is produced and captured during production processes can be stored or utilized. If this CO_2 is of biogenic or atmospheric origin, it can contribute to an overall negative carbon balance, i.e., carbon removal.

As described above,

> **"reducing end-of-life emissions is one of the largest leverages to improve the overall climate performance of the chemical and plastic value chains"**

Both recycling and CCUS of waste incinerators can mainly reduce end-of-life emissions. Products with a long lifetime may benefit from reduced future end-of-life emissions and might already today be carbon negative from a cradle-to-grave perspective. According to our models, a lifetime of ~25 years (e.g., construction materials) for biogenic or atmospheric base products might be sufficient (see Figure 9), assuming these end-of-life improvements are applied by the time these products become waste. With further production and end-of-life emissions improvements, even more short-lifetime bio-based (or DAC-CO_2) products could become cradle-to-grave net carbon negative. Additionally, if a value chain can prove it has control over the entire lifecycle including the after-use phase (e.g., return schemes), some products can be net carbon neutral or negative already today. However, claiming future end-of-life improvements is not compliant with current carbon accounting standards, as credible references for a set of agreed future trajectories for end-of-life emissions do not exist.
Policies could further help to reduce the uncertainty related to using these trajectories. When asserting such claims, it's also important

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[36] Fuss (2018), Environmental Research Letters, Negative emissions—Part 2: Costs, potentials and side effects

to bear in mind that the terms ‘carbon-neutral’ or ‘negative’ specifically address carbon emissions, not wider factors such as an unintended impact on nature (e.g., biodiversity). Consequently, additional sustainability metrics are necessary to capture such challenges for both fossil and renewable carbon feedstocks.

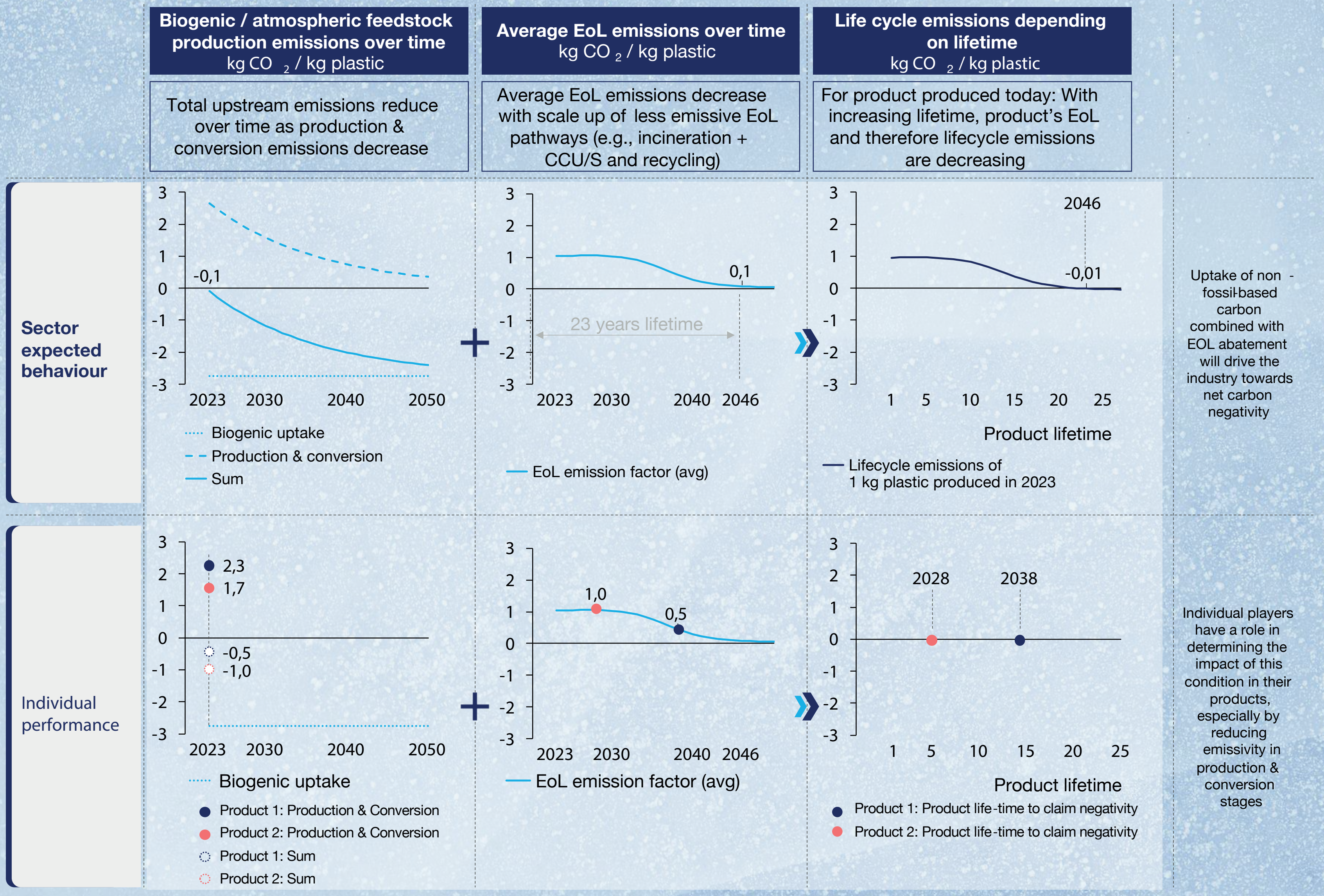

Figure 9. Bio- and Direct-Air-Capture-based long-lifetime plastics applications produced in 2024 could already be considered carbon negative given that significant future EoL emissions reductions materialize. A lifetime of approximately 25 years is probably sufficient to benefit from sufficient EoL improvements and claim carbon negative plastics already today.

1: Use-phase emissions are not considered

With the potential of carbon negative products, the question arises if the chemical value chain should prioritize renewable feedstock for either short-lifetime or long-lifetime applications? Provided that the industry has developed proper carbon accounting methods, guidelines for labeling and green claim as well as associated regulation, long-lifetime applications (e.g., construction) could already be considered net carbon negative today when biogenic or atmospheric carbon sources are used, and the strict reduction of end-of-life emissions is implemented. At the product level, this could provide a comparative advantage and generate pull in markets where sustainable products still have significant price premiums against fossil products.

However, only around one-third of plastics produced in 2020 have a lifetime of over ten years. This limited volume of long-lifetime plastics applications and the current timeframes to reach negative end-of-life emissions limit the impact on net physical emissions abatement. It should therefore not simply lead to the prioritization of renewable carbon for long-lifetime applications in comparison to short-lifetime application as hinted in some reports and discussions[37]; rather, all applications need to be defossilized. In fact,

“there is no difference on a system level for annual or cumulative emissions whether the renewable feedstock is used in long-lifetime or short-lifetime applications, as long as the total amount of substituted fossil carbon remains the same.”

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[37] UK Committee for Climate Change (2018), Biomass in a low-carbon economy

Hence, prioritization of renewable feedstocks for long-lifetime or short-lifetime applications has no benefits from a system perspective. Instead, product development from the industry and policy design from regulators must concentrate on system level changes: expanding the production and uptake of renewable feedstocks in general, accelerating end-of-life emissions abatement, and incentivizing extending product lifetimes by reuse schemes across all plastic applications and sectors.

The total net negative emissions needed by 2050 to stay below 1.5°C warming are still uncertain, but scenarios reach from ~1.5-7 Gt CO_2eq/year[38]. Bio- and CO_2-derived plastics and chemicals with abated end-of-life emissions, could effectively contribute maximally 1 Gt CO_2eq/year of negative emissions. Recent modeling suggests ~0.5 Gt/year by 2050 as an ambitious but feasible goal[39] for the chemical industry. The exact number will depend on the feedstock portfolio, degree of circularity, as well as reduction and reuse initiatives.

The cost for negative emissions for a full lifecycle of biobased plastic value chain could be as low as 200 €/tonne CO_2eq considering a fully abated waste incineration facility and very low remaining production emissions[40] (this does not include negative emission associated with feedstock supply). At this cost range, bio-based plastics compete with other means of generating negative emissions, with the added benefit of providing a utility to society (see Figure 10).

In addition, when renewable and circular carbon is used for plastic production, atmospheric carbon accumulates in the plastics system. Thus, chemical products could be considered as carbon storage, in particular if used for long-lifetime applications. However, at least today, these net negative emissions are difficult to claim as they require holistic value chain collaboration and tracing of the product over its lifetime.

Also, it should be emphasized that this negative emissions potential should not be used as an excuse to expand production, but rather to highlight that circularity in addition to non-fossil feedstocks and end-of-life abatement together achieve the best overall system outcome.

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[38] The forecasts for negative emissions in 2050 vary significantly: IEA 1.5 C scenario (WEO NZE 2022) scenario reaches 1.5 Gt/year, the Energy Transitions Commission suggests 3-5 Gt/year, IRENA 1.5 C scenario (World Energy Transitions Outlook 2023) 4.9 Gt/year and the IPCC SSP2-19 scenario suggests 7.2 Gt/year as a few examples.

[39] Systemiq (2022), Planet Positive Chemicals

[40] The costs to reach cradle-to-grave net negative carbon emissions are difficult to assess for bioplastics as they strongly depend on the specific production technology and associated investments. In this illustrative example, a 25% cost premium for bio-based plastic was assumed. If investments into new assets are required (beyond CCUS at the waste incinerator), the cost of negative emissions would likely increase.

Process	Description	TRL[1]	Indicative estimated maximum CO2 removal potential per annum in 2050 [Gt CO_2/Yr]	Cost [€ / t CO_2][2]	Key Co-Benefits[3]	Resource Constraints
Bio-based plastic with incineration + CCS at EoL	Biogenic carbon is used to produce plastics and upon end-of-life (if not recycled) incinerated. CO2 is captured at the incinerator and stored via CCS.	Medium	● <1	~200[1]	Plastics utility to society	Biomass CCS
Natural climate solutions (NCS)[4]	CO_2 is sequestered via photosynthesis and stored in biomass and soils through natural processes.	High	● >15	<50	Ecosystem restoration and use of wood to displace cement & steel as construction material	Land Water
Biochar	Biomass is pyrolyzed and used to stabilise organic matter.	Medium	● ~2	<120	Soil health	Biomass
BECCS	CO_2 is sequestered via photosynthesis, the biomass used for bioenergy, and most of the CO_2 is then captured and geologically stored (CCS).	Medium	● ~5	<200	Heat and power	Land Water CCS
DACCS	CO_2 is captured from ambient air and stored via CCS.	Medium	● ~5	<300	-	Power Water CCS
Mineral Absorption	Adding mineral materials to accelerate biogeochemical processes on land ("enhanced weathering") and in oceans ("ocean alkalinisation") that sequester CO_2.	Low	● ~5	<200	Habitat restoration (ocean) and soil health (on land)	Power Minerals

Figure 10. Relative comparison of carbon negative plastics vs. some of the most well-known other net negative emissions.

Note: NCS: Natural climate solutions. DACCS: Direct air carbon capture and storage. BECCS: Bioenergy with carbon capture and storage. TRL = Technological readiness level. CCS: Carbon capture and storage.
(1) TRL level: low <4, medium: 5-7, high: >8-9. (2) The cost for 1 tonne of negative emissions is calculated via the sum of a 25% cost premium during production between bio-based and fossil plastic and CO_2 capture, transport and storage cost for CCS on a waste incinerator (~100€/tonne CO_2). A negative emissions potential of -2.35 t CO_2/t biobased plastic was assumed in a full lifecycle perspective. This relays to minimal remaining production and end of life emissions. Other costs were taken from Fuss et al. (Environ. Res. Lett. 13 (2018) 063002). (3) List of co-benefits not exhaustive. (4) Not all NCS options have a land use requirement. Source: SYSTEMIQ analysis adapted from ETC (2022) Mind the Gap Report - Limiting Global Warming To 1.5°C

Summary

This white paper presents our vision of the chemical industry as a carbon steward. This means taking larger responsibility for carbon resources and managing the entire lifecycle of chemicals and products. In the vision, the chemical industry can transform from being a GHG emitter to being part of the solution, i.e., generating a net carbon negative value chain. In this work, we have presented the opportunity, hurdles, and action points for this transformation:

1. Substitute virgin fossil feedstocks by renewable feedstocks to reduce GHG emissions
2. Implement incentives for renewable feedstocks to reduce GHG emissions
3. Apply third party verified criteria for sourcing sustainable biomass
4. Reduce end-of-life emissions to eliminate the release of the embedded carbon into the atmosphere
5. Aligning carbon accounting methods to describe the cradle-to-grave footprint

In addition, the industry needs to call for policy support for their action. When this is in place, creating a net negative chemical and plastics system might be possible. However, this transformation is not a single-player game but needs the communication and collaboration of an entire industry, from feedstock providers, intermediates, and suppliers of finished goods. The industry should engage with policymakers for support of this transformation by creating appropriate incentives. In return, this promise helps to achieve the overarching climate goals, create new job opportunities, and reduce political dependencies linked to importing fossil resources.

Glossary

More detailed terminology is available in the technical appendix.

1. Carbon (dioxide) removal:	Carbon dioxide removal is synonymous with carbon sequestration. GHG Protocol and IPCC use both. As per IPCC: Anthropogenic activities that remove CO_2 from the atmosphere and durably store it in geological, terrestrial, or ocean reservoirs, or in products. It includes existing and potential anthropogenic enhancement of biological or geochemical sinks and direct air capture and storage but excludes natural CO_2 uptake not directly caused by human activities.
2. Closed carbon loop:	Process by which carbon is continuously exchanged amongst carbon pools with economic value while minimizing or eliminating its release into the atmosphere.
3. Climate-aligned:	Actions, strategies, or initiatives that are in line with or contribute to meeting the objectives set by the Paris Agreement and broader global efforts to limit global warming below 1.5 degrees Celsius above pre-industrial levels.
4. Cradle-to-gate:	System boundaries of a full life cycle assessment study that consider the life cycle stages from raw material extraction to the production of the end product (before use phase).
5. Cradle-to-grave:	System boundaries of a full life cycle assessment study that consider all life cycle stages from a linear model including raw material extraction, production, transport, use and final disposal.
6. Embedded carbon:	Carbon content that is physically present in a product, not considering the carbon emissions associated with its life cycle stages (e.g., production, transportation, use or disposal).
7. End-of-life emissions:	Greenhouse gas emissions associated to the stages of a product's lifecycle following the use phase.
8. Externality:	An indirect cost to a third party or a cost that is not priced in by the producer.
9. Fossil feedstock:	Raw resources derived from fossil resources, such as coal, oil, or natural gas, that are used as a source of energy or as a material for chemical production.
10. Non-fossil feedstock:	Renewable feedstocks that are not derived from fossil resources (coal, oil, natural gas). When used as carbon material for chemical production, these feedstocks can be derived from sources such as biomass, direct air capture, point source carbon and waste.
11. Low-emissions product:	Product that has a significantly lower level of greenhouse gas emissions compared to traditional or conventional products.
12. Net-zero:	Situation in which a product, organization or industrial sector releases no net CO_2eq emissions into the atmosphere. After minimizing emissions wherever feasible, any residual emissions that cannot be removed are typically compensated via negative emissions.
13. Net carbon negative:	Activities or systems made by deliberate human action that result in a net reduction in the overall stock of atmospheric CO_2eq (in addition to the removal that would occur via natural carbon cycle or atmospheric chemistry processes). A product is net carbon negative if its emissions across the whole lifecycle are negative. Any positive emissions are outweighed by negative emissions contributions.
14. Non-food biomass:	Organic matter, i.e., biogenic material, available on a renewable basis from living or recently living organisms, which excludes biomass used for food or food production purposes.
15. Planetary boundary:	Environmental limits or thresholds that define the safe operating space for humanity on Earth.

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Change runs on renewables