Circular Carbon Feedstocks for Sustainable Carbon–based Chemicals

White paper

Trinomics

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Disclaimer

This white paper has been written by Trinomics in an independent manner and the views and opinions expressed herein are solely those of the authors.

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Executive Summary

Renewable and recycled carbon (RRC) feedstocks have a critical role to play in cutting the reliance of chemicals on fossil resources in the transition towards a sustainable and circular economy. Achieving climate neutrality and a circular economy requires addressing both energy and material systems. So far, the focus of both the public and private sectors has mainly been on decarbonising energy systems. The next frontier is to mitigate the negative impacts of material systems. Feedstocks from RRC sources can replace fossil-based feedstocks that are currently used to produce chemicals, where carbon is a universal building block.

This paper presents six high-level guiding principles for safeguarding the environmental sustainability of RRC feedstocks for carbon-based chemicals. Moving the chemical sector to RRC feedstocks will require active management of their environmental impacts to ensure their alignment with a sustainable circular economy. Table A presents six guiding principles that policymakers and companies can use as initial guidance to ensure the environmental sustainability of RRC feedstocks, categorised in the following three types:

- **Biogenic carbon feedstock:** feedstock with carbon obtained from biological sources;
- **End-of-life carbon feedstock:** carbon-containing feedstock from recycled materials that would have otherwise been considered waste; and
- **Captured carbon feedstock:** feedstock produced from carbon dioxide and other carbon containing molecules captured before being released into the atmosphere or directly from the atmosphere.

Some guiding principles are generally applicable to all three types of RRC feedstocks, whereas others are specific to one of them. These guiding principles should be considered in addition to existing principles and frameworks on the sustainability of material use. These include the cascading principle of biomass use, Lansink's Ladder for waste management, and the R-framework for a circular economy.

All guiding principles for a specific RRC feedstock type should be met for an RRC feedstock to be environmentally sustainable. The guiding principles build on each other and cannot be considered in isolation. For example, feedstock from chemically recycled waste should not be considered environmentally sustainable solely on the basis that it comes from waste that could not be reused or mechanically recycled (*Guiding principle VI*); the environmental impacts of the recycled feedstock should always be assessed on a case-by-case basis (*Guiding principle I*) and show substantial and verifiable environmental benefits over the fossil feedstock that it is replacing (*Guiding principle II*).

Table A High-level guiding principles for environmentally sustainable RRC feedstocks in carbon-based chemicals

	Guiding principles for environmentally sustainable RRC feedstocks	Relevance for the RRC feedstock type		
		Biogenic	End-of-life	Captured
I	Each renewable and recycled feedstock should be assessed on a case-by-case basis since there is no feedstock that is always the most environmentally sustainable choice	✓	✓	✓
II	Carbon feedstocks from renewable and recycled sources should only be considered sustainable if they have substantial and verifiable environmental benefits over fossil-based feedstocks	✓	✓	✓
III	Feedstock made from captured CO_2 conversion should only be considered having climate benefits if low-carbon energy is used			✓
IV	Feedstock from virgin biomass should only be considered sustainable if its sourcing does not cause adverse land-use change, deforestation and biodiversity loss	✓		
V	Biomass residues and marine biomass can generally be considered a more sustainable source than feedstock from virgin biomass from land	✓		
VI	Carbon feedstock from chemically recycled waste can generally be considered sustainable if it comes from waste that could not be reused or mechanically recycled		✓	

The adoption of environmentally sustainable RRC feedstocks will need to be supported by an enabling policy environment, with the current policy environment of the European Union (EU) and the United States (US) analysed in this paper. The EU and US show similar policy incentives to enhance the availability of RRC feedstocks through recycling targets and funding programmes for research and development in RRC feedstocks. In the EU, these supply-side policies are complemented with targets and minimum requirements for the RRC content in products to incentivise the use of RRC feedstocks. Policy measures in the US to incentivise RRC feedstock use in chemicals are much more limited. These consist of a public procurement incentive and voluntary labelling initiative for biobased chemicals and a tax credit for chemicals made from captured carbon. There are also various policy aspects in the EU and US that hinder the availability or use of RRC feedstocks for chemicals, particularly incentives to use RRC sources for energy or fuel production and the lack of recognition for chemical recycling.

The EU has recently established several policy measures that can help ensure the environmental sustainability of RRC feedstocks, while such policy developments are absent in the US. Under the EU Taxonomy Regulation, environmental sustainability criteria have been established to determine when an activity can be considered substantially contributing to achieving environmental objectives. Additionally, sustainability criteria for biomass use are in force under the Renewable Energy Directive. As part of the Sustainable Product Initiative, the EU is currently developing requirements on the environmental sustainability for products. Similar activities are taking place under the Packaging and Packaging Waste Regulation for plastic packaging, the Industrial Carbon Management strategy for products from captured carbon feedstocks, and the Bioeconomy strategy for biobased products. The guidance and criteria on environmental sustainability that the EU have established and continue working on can help solidify the guidance principles presented in this paper.

However, a coherent strategy to incentivise the adoption of RRC feedstocks and safeguard their environmental sustainability is still under development in the EU and completely absent in the US. The EU Communication on Sustainable Carbon Cycles sets an aspirational target for at least 20% of carbon used in chemical and plastic products to be from sustainable non-fossil sources by 2030. However, a comprehensive policy strategy to achieve this has yet to be developed. This will require developing detailed sustainability criteria for RRC feedstocks in a harmonised manner and ensuring that policy incentives drive the adoption of RRC feedstocks that meet these criteria. This will have to be accompanied by technical guidance to standardise life cycle assessments (LCAs) for robust and verifiable results. Foundational research will be needed to strengthen the current evidence base for setting these criteria, which could build on the guiding principles presented in this paper.

This paper intends to serve as a first step for the development of a comprehensive sustainability framework for comparing and selecting chemical feedstocks. The guiding principles outlined in this paper only offer a general direction for choosing environmentally sustainable RRC feedstocks. However, determining whether a feedstock meets certain criteria for it to be considered environmentally sustainable requires a quantification of their environmental impact. This calls for more technical guidance for conducting LCAs in a consistent manner. Moreover, the guiding principles only consider replacing fossil-based feedstocks with RRC feedstocks in existing chemical processes ("drop-in" pathway). Further guidance will be necessary to consider the environmental impacts related to the longevity of resulting products during their use, as well as their recyclability, compostability, and/or (bio)degradability at disposal. This could take the form of a sustainability framework that provides guidance not only on environmental sustainability but also on governance and social aspects. Such a framework should also consider potential future developments in new technologies.

With this paper, we hope to rapidly kickstart the conversation among policymakers on the creation of a consistent and harmonised sustainability framework for RRC feedstocks. While discussions on a holistic approach to the environmental sustainability of RRC feedstocks and products are already ongoing in the EU, the approach to RRC feedstocks is more fragmented in other major economies in the world. This highlights the urgent need to open up the conversation in the global policy landscape on an internationally harmonised framework that ensures the environmental sustainability of RRC feedstocks in a consistent manner. This will also require aligning public policy incentives around the world with such a framework to scale-up the adoption of sustainable RRC feedstocks.

1. Introduction

1.1. The need for environmentally sustainable carbon feedstocks for chemicals

Chemicals are used in many kinds of products that are an intrinsic part of our daily life. Base chemicals are the building blocks for, amongst others, plastics, which are used in numerous applications including for packaging, appliances, construction and transport vehicles. Fine chemicals are key in the preparation of personal and home care products as well as food ingredients and preservatives, among other things. More than 96% of all manufactured goods are in some way touched by chemistry.[1]

Chemicals will remain essential in a sustainable circular economy, but their reliance on fossil resources will need to be dramatically reduced. Chemicals are important in the transition to a sustainable and circular economy as they are key components in e.g., insulation materials for houses, advanced materials for wind turbines, and lighter materials for cars. However, the chemical sector is also the world's largest industrial consumer of fossil resources, accounting for about 14% of the global demand for oil and 8% of gas.[2] About half is used for energy and half as carbon feedstock.[3] The chemical sector is becoming increasing aware that it needs to move away from virgin fossil carbon resources to limit depletion of resources as well as reduce greenhouse gas (GHG) emissions. The sector has therefore started making strides in reducing its environmental impacts from energy use through energy efficiency, electrification, and decarbonisation of its energy supply.

For the chemical sector, the main challenge in the transition to a sustainable circular economy lies in reducing its use of feedstocks derived from fossil resources. Currently, about 88% of the carbon feedstocks used to make chemicals comes from fossil resources extracted from the ground.[4] This equals about 480 million tonnes of embedded carbon (Mt C) globally per year, which, when released in the atmosphere, would equal the annual CO_2 emissions of Japan, Germany and Kazakhstan combined.[5] Thus, the next frontier in the sector's path to sustainability is mitigating the negative impacts of its feedstock use. However, since carbon is a universal building block of many chemical products, it is impossible to fully decarbonise the chemical sector.

Renewable and recycled carbon (RRC) feedstocks can substitute virgin fossil sources in the production of chemicals, but their availability needs significantly expanding. Currently, only about 8% of the carbon feedstock used for making chemicals comes from biological sources, about 4% from recycled materials and less than 0.1% from captured CO_2.[6] This amounts to about 65 Mt C globally per year compared to a global demand of 550 Mt C. For RRC feedstocks to substitute feedstocks from virgin fossil sources in the chemical sector, more RRC material will therefore need to become available, particularly with the

[1] ICCA (2022). *8 Decent work and economic growth.*

[2] OECD and IEA (2018). *The Future of Petrochemicals - Towards more sustainable plastics and fertilisers.*

[3] IEA (2025). *Chemicals.*

[4] Global average for 2020 from Nova-Institute (2023). *RCI Carbon Flows Report.*

[5] 480 million tonnes of carbon equals 1762 $MtCO_2$. The CO_2 emissions from fossil resources in 2023 were 945 $MtCO_2$ for Japan, 583 $MtCO_2$ for Germany and 240 $MtCO_2$ for Kazakhstan based on the European Commission's *Emissions Database for Global Atmospheric Research*.

[6] Global average for 2020 from Nova-Institute (2023). *RCI Carbon Flows Report.*

global demand for carbon feedstocks in the chemical sector expected to more than double by 2050.[7]

Moving the chemical sector to RRC feedstocks will require active management of their environmental impacts to ensure their alignment with a sustainable circular economy. There are many impact categories that need to be considered in determining the environmental sustainability of a feedstock. For example, using biomass feedstocks to make chemicals can significantly reduce CO_2 emissions compared to fossil feedstock.[8] However, when not properly selected and managed, the use of biomass feedstocks risks increasing negative impacts on soil, water, biodiversity and land use. Recycling waste for feedstock avoids the negative impacts from waste incineration and landfill, but the recycling process could require more energy than directly using virgin fossil feedstock. In addition, if an RRC feedstock is not locally available, it could have a negative environmental impact due to the need for transportation. Thus, RRC feedstocks cannot simply be assumed to be environmentally sustainable. Choices of RRC feedstocks therefore need to be actively managed to minimise the risks of negative impacts across different environmental impact categories.

There is a need for guidance for safeguarding the environmental sustainability of RRC feedstocks, rooted in a strong evidence base, which is currently still lacking in the public domain. Various studies have been done on different aspects related to the environmental sustainability of RRC sources, as explored in this paper throughout Sections 2 and 3. However, the findings from these studies have not yet been distilled into generalisable sustainability principles or guidance on the use of RRC sources as feedstock in the chemical sector or any other sector. In addition, most studies only compare environmental impacts of RRC feedstocks with virgin fossil feedstock; studies comparing environmental impacts between different types of RRC feedstocks are scarce. The current evidence base therefore needs to be strengthened substantially to be able to create a comprehensive sustainability framework.

Adoption of RRC feedstocks for the production of chemicals further requires public policy that supports the availability and use of environmentally sustainable RRC sources. So far, public policies around the world have mainly been focussing on the decarbonisation of the energy system. As a result, policy measures may include (unintended) disincentives on the availability and/or use of RRC sources for material purposes. For example, the use of biomass for energy purposes is still strongly incentivised around the world.[9] However, studies show that the use of biomass for material production should be prioritised over energy because of higher economic and societal value.[10] Some governments have recognised such misalignments and have started taking action remedy them.[11] For example, the European Union (EU) has only recently adopted the biomass cascading principle in legislation to use of woody biomass according to its highest

[7] *Compared to the average of 2015-2020. Source: ibid.*
[8] *Material Economics (2021). EU Biomass Use in a Net-Zero Economy – A course correction for EU biomass.*
[9] *IEA (2025). Bioenergy.*
[10] *Material Economics (2021). EU Biomass Use in a Net-Zero Economy – A course correction for EU biomass.*
[11] *WEF (2022). Towards a Net-Zero Chemical Industry: A Global Policy Landscape for Low-Carbon Emitting Technologies.*

economic and environmental added value.[12] It is important that these actions do not only incentivise the use of RRC sources, but also safeguards their environmental sustainability.

1.2. Aim of this paper

This paper aims to provide initial guidance for safeguarding the environmental sustainability of RRC feedstocks[13] for carbon-based chemicals and analyse the current policy environment for their use. Specifically, this paper contains the following:

1. **A first set of high-level guiding principles** to ensure the environmental sustainability of RRC feedstocks used in the chemical sector based on publicly available evidence; and
2. **An assessment of the current policy environment in the EU and the United States (US)** for environmentally sustainable RRC feedstocks used in the production of chemicals, including potential barriers to their adoption and scale-up.

The guiding principles can serve as initial guidance for policymakers and companies on considerations for safeguarding the environmental sustainability of RRC feedstocks. The high-level guiding principles outlined in this paper only offer a general direction for selecting environmentally sustainable RRC feedstocks for carbon-based chemicals. However, determining whether a feedstock meets certain criteria to be considered environmentally sustainable requires a quantification of their environmental impact. This calls for more technical guidance for quantification in a consistent manner, what goes beyond the scope of this paper. Additionally, the choice of a feedstock does not solely depend on their environmental impacts. Other key deciding factors are the financial costs, the availability and security of supply, and social impacts, which are not discussed in this paper.

This paper can serve as a starting point for the development of a comprehensive sustainability framework for comparing and selecting RRC sources for chemical feedstocks. Ideally, such a framework should not only provide guidance on environmental impacts but also governance and social aspects. The framework should also consider potential future developments in new technologies. Developing such a sustainability framework will require foundational research to improve the current evidence base. This paper highlights several potential research areas regarding the environmental sustainability of RRC feedstocks relevant for carbon-based chemicals.

With this paper, we hope to rapidly kickstart the conversation among policymakers on the creation of a consistent and harmonised sustainability framework for RRC feedstocks. A discussion on a holistic approach to the environmental sustainability of RRC feedstocks and products has already started in the EU with the European Green Deal, the Circular Economy Action Plan and the Chemicals Strategy for Sustainability. However, in other major economies in the world, the approach to RRC feedstocks is more fragmented and focussed on scaling up specific RRC feedstock types.[14] There is therefore a need to open

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[12] *In the revised Renewable Energy Directive adopted in 2023, EU Member States are to design their national support schemes to according to the biomass cascading principle. Source: European Commission (2023). Revised Renewable Energy Directive.*

[13] *In this paper, environmentally sustainable RRC feedstocks refers to the sourcing and conversion of RRC sources into chemical feedstocks without causing any adverse effects on the environment and the climate. Environmental sustainability is used as a collective term for the avoidance of these adverse effects.*

[14] *Authors' analysis based on WEF (2022). Towards a Net-Zero Chemical Industry: A Global Policy Landscape for Low-Carbon Emitting Technologies.*

up the conversation in the global policy landscape on the creation of a consistent and harmonised sustainability framework for RRC feedstocks, as well as ensuring alignment of public policy incentives around the world to such a framework.

1.3. Scope and methodology

The scope of this paper is limited to the environmentally sustainability of RRC-based chemicals via the "drop-in" pathway. Drop-in chemicals refer to the chemicals made from alternative materials to replace virgin fossil-based carbon in existing chemical production processes. This means that in this paper, we assume that products made from RRC feedstocks will be chemically identical to their fossil-based equivalent and there is no difference in their environmental impact during their use and disposal. By focusing only on the drop-in pathway, as opposed to also completely different chemicals with the same functionality as fossil-based ones, this allows a dedicated discussion on the environmental sustainability of the sourcing of RRC and their conversion to feedstocks for existing chemical processes. In this paper, the term "chemicals" is used to refer to all products of the chemical sector, including plastics.

The focus on the "drop-in" pathway means that other factors related to the environmental sustainability of RRC-based chemicals beyond feedstock sourcing are not considered in this paper. Relevant factors that can affect environmental impact of products made from RRC feedstocks include the longevity of products during their use, as well as their recyclability, compostability and/or (bio)degradability at disposal. The environmental impacts of RRC-based products should also be assessed against competing products from other sectors that serve the same function, such as glass versus plastic bottles. However, these aspects go beyond the environmental sustainability of the sourcing of RRC and conversion to feedstocks and are therefore not discussed in this paper.

The analysis of policy incentives in this paper is limited to public policies and strategies in the EU and the US. The EU was selected as it has seen a lot of policy developments relevant to the environmental sustainability of RRC feedstocks and products over the past years. This is contrasted with the US, a major economy where limited developments have taken place so far. For the US, the analysis is limited to US federal policies and strategies only, since a comprehensive analysis of state-level policies was not feasible in the scope of this paper, except for a few state-level policies that the participating companies highlighted as particularly relevant for this paper.

This paper has been developed based on desk-based research and input from the companies that helped shape this paper. An extensive literature review of qualitative and quantitative studies on the environmental impacts of RRC feedstocks was conducted, focussing on studies relevant to RRC feedstock use for chemicals and material purposes. In addition, EU and US federal policy documents have been analysed up to 31 January 2025. The desk-based research was complemented with input gathered from the participating companies through three workshops, a survey and written feedback in 2022-2023 during the development of the 2023 white paper. No primary research was conducted as part of this paper.

1.4. Structure of this paper

This paper is structured as follows:

- **Section 2** explains the different sources for RRC and evidence of the potential environmental benefits that they can bring by replacing fossil-based feedstocks;
- **Section 3** presents the guiding principles for environmentally sustainable RRC feedstocks for carbon-based chemicals, building on the evidence outlined in Section 2;
- **Section 4** provides an overview of the main policies and strategies in the EU and the US that affect the availability and use of RRC feedstocks and their environmental sustainability; and
- **Section 5** concludes by looking ahead at the next steps that are needed for the development of a comprehensive sustainability framework for RRC feedstocks.

2. Renewable and recycled carbon feedstocks

Renewable and recycled carbon (RRC) feedstocks refers to carbon-containing feedstocks obtained from sources other than fossil resources. RRC can be defined as carbon obtained from sources that avoid or substitute the use of any additional fossil carbon from the geosphere.[15] RRC sources include renewable sources (e.g., plants and trees and crop residues) and recycled sources (e.g., discarded plastic bottles and industrial waste). A feedstock can also be from a source that is both renewable and recycled, e.g., from discarded plastic bottles made from biomass. Another emerging source for RRC is the capture and recycling of CO_2 from industrial exhaust gases or directly from the air. In this paper, the term “RRC feedstock” is used to encompass all carbon-containing feedstocks from renewable and/or recycled sources.

RRC feedstocks can be categorised in various ways to discuss their environmental sustainability. Some use colours to differentiate between feedstocks based on their source (e.g., green from living vegetation and soil, blue for carbon stored in coastal and marine ecosystems, black carbon for carbon from fossil fuels etc.).[16] However, the colour of a carbon source commonly only refer to their origin and do not directly relate to their environmental sustainability, unlike with the colour-coding used for hydrogen.[17] Alternatively, RRC feedstocks could be categorised based on the systems from which the RRC are obtained (biosphere, technosphere and atmosphere) or the type of materials the carbon is sourced from (biogenic, end-of-life and captured).[18]

In this paper, RRC feedstocks are discussed based on their three main sources: biogenic resources, end-of-life materials and captured carbon. This categorisation is used as there is a clear difference in the processes, and their related environmental impacts, required for sourcing and conversion to feedstocks. Figure 2-1 shows a schematic overview of each RRC feedstock, with the categorisation of each RRC feedstock explained in more detail in this section.

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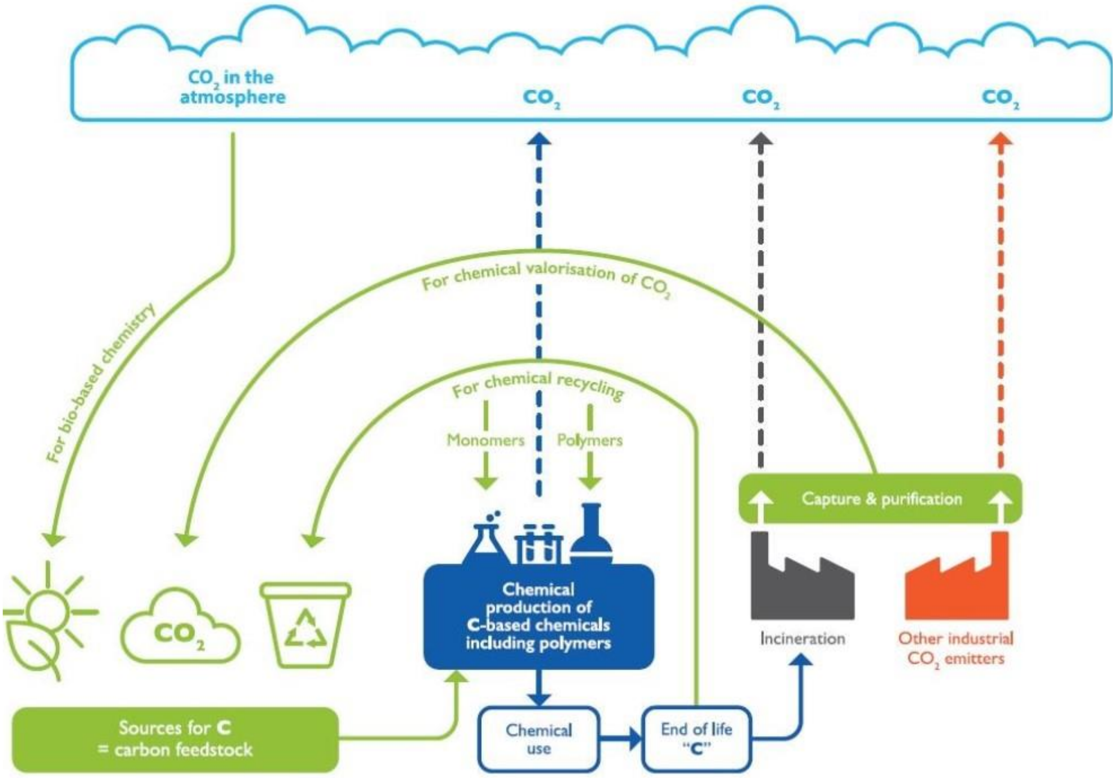
[15] *Renewable Carbon Initiative (2025). About renewable carbon.*

[16] *See for example Zinke (2020). The colours of carbon; Unilever (2020). Unilever to eliminate fossil fuels in cleaning products by 2030 – The Carbon Rainbow.*

[17] *Colours of hydrogen are used to refer to the processes that they are produced with and the energy carriers used, which relate directly to their climate impacts. See for example WEF (2021). Grey, blue, green – why are there so many colours of hydrogen?*

[18] *Renewable Carbon Initiative (2025). About renewable carbon.*

Figure 2-1 Overview of the three main sources of RRC feedstocks

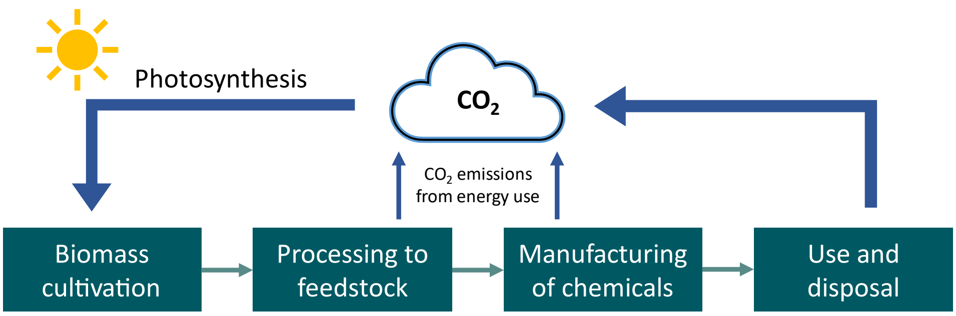


Source: CEFIC (2021). *Circular Carbon*. Note: the carbon flows shown in this figure are not fully comprehensive and only show the main flows from the perspective of RRC feedstocks for carbon-based chemicals.

2.1. Biogenic resources as renewable feedstocks

Biogenic carbon feedstock refers to feedstock with carbon obtained from biological sources such as plants and trees. Plants and trees capture CO_2 from the atmosphere through photosynthesis and store it as biomass as they grow. After harvesting the biomass, this can be used for food, directly burned for energy and/or processed into feedstocks for making fuels and materials, including chemicals. When the products made from the biogenic feedstocks have reached their end-of-life and are disposed of, the stored biogenic carbon is released into the atmosphere again through combustion or decomposition. Figure 2-2 illustrates the cycle of biogenic carbon when it is used for manufacturing chemicals.

Figure 2-2 Simplified diagram of the carbon cycle of biogenic resources for manufacturing chemicals



Source: Trinomics

There are a wide range of technologies to process biomass into feedstocks for chemicals, some of which are energy intensive. The technologies can be broadly divided into thermochemical methods (e.g., gasification and pyrolysis) and biochemical (e.g., fermentation and anaerobic digestion).[19] Thermochemical methods use heat to process the biomass into feedstocks and are therefore relatively energy intensive. Biochemical processes are less energy intensive, but the processing time is much longer. The choice of technology depends on the feedstock that is required and the biomass inputs that are available.[20] Some process technologies require certain types of biomass inputs while others are compatible with most biomass.

The use of biogenic feedstocks has the potential to significantly reduce GHG emissions compared to fossil-based feedstocks, but it can also cause more adverse environmental impacts in other areas if not properly managed. Plants and trees replacing the harvested biomass can absorb the equivalent volume of carbon that biogenic feedstocks emit during their lifecycle. However, the cultivation of biogenic sources also requires land, water and other resources such as fertilisers, which could cause environmentally harmful effects such as deforestation, soil degradation and biodiversity loss. In addition, processing biomass into feedstock also requires energy, which leads to GHG emissions when fossil-based energy is used. Therefore, substituting virgin fossil feedstocks with biogenic feedstocks cannot be assumed to inherently lead to an improvement in environmental performance. However, sustainable agricultural practices can mitigate the harmful effects from biomass cultivation and, in some circumstances, even have a positive environmental impact (e.g., the recovery and regeneration of marginal land[21] through the cultivation of crops that require limited resources). These aspects are further discussed in Section 3 as part of the guiding principles.

2.2. End-of-life materials for circular feedstocks

End-of-life carbon feedstock is carbon-containing feedstock from recycled materials that would have otherwise been considered waste. Materials that reached the end of their useful lifetime are not always directly useable or are limited in their applications. Processing end-of-life materials to be used as feedstock for making products is referred to as recycling.

The two main recycling methods for obtaining carbon feedstocks are mechanical and chemical recycling. Figure 2-3 provides a schematic overview of these two methods to obtain end-of-life carbon feedstocks using plastic recycling as an example.[22] Each has their own advantages and limitations:

- **Mechanical recycling** involves breaking down existing materials without modifying their chemical bonds, to be used as feedstocks for the manufacture of new

[19] *Osman et al. (2021). Conversion of biomass to biofuels and life cycle assessment: a review.*

[20] *Kearney (2020). Biomass to energy.*

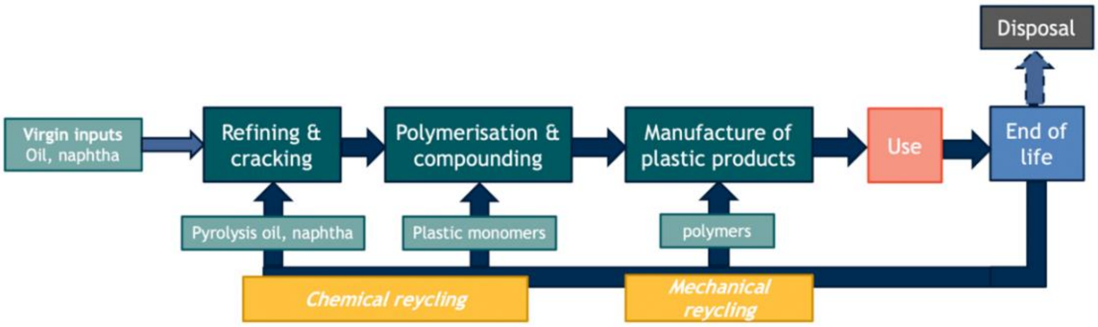
[21] *This could for example be farmland that is not used for agricultural purposes, unproductive for economic or social reasons, located in areas characterised by natural disadvantages, in mountain areas or other but which could be used for agricultural purposes through the intervention of means normally available from the farm. They are usually referred to in different terms: unused, degraded, insufficiently used, uncultivated, desolate and abandoned.*

[22] *Another form of recycling is enzymatic / biochemical recycling. This is similar to chemical recycling but instead uses a biocatalyst. It is still at an early development phase and not yet known if the process can be run economically compared to the established recycling methods. However, low energy consumption and the possibility to engineer the biocatalyst to specific types of plastics could make the enzymatic approach a promising option for recycled chemical feedstocks in the future. See e.g. Enzycle (2022). An industrial view on the suitability of enzymatic plastic recycling.*

products. Mechanical recycling primarily applies to plastics. Plastic waste streams are washed, granulated, and then re-extruded to make polymer pellets to be used as feedstock. The quality of recycled feedstocks is highly dependent on the purity and sorting of input plastic waste. Currently, mechanical recycling is the most dominant form of recycling due to the relative ease of the process. However, mechanical recycling levels are limited by the fact that plastic quality is downgraded after multiple rounds of recycling, to the point that it cannot be mechanically recycled again. This limits the applications in which mechanically recycled feedstocks could be used.

- **Chemical recycling** involves modifying the material's molecular bonds to recover hydrocarbons. Long hydrocarbon chains such as polymers (which include plastics) are broken into shorter hydrocarbon fractions (monomers) using chemical, thermal, or catalytic processes.[23] Chemical recycling is essential when waste polymers cannot be recycled in their intact structure due to mixing or contamination and need to be further broken down before they are suitable for making new chemical products. Chemicals made from chemically recycled feedstocks can achieve a higher quality compared to those from mechanical recycling. With technological advancement, the quality of chemically recycled feedstocks can even match the quality of ones from virgin materials by breaking down the hydrocarbon chains even further to naphtha.

Figure 2-3 Schematic overview of mechanical and chemical recycling of plastics to re-enter the production process



Source: Trinomics' elaboration based on Cefic (2020). Chemical Recycling: Greenhouse gas emission reduction potential of an emerging waste management route.

Currently, the main sources for recycled carbon feedstocks are through industrial symbiosis and from plastic waste. One of the most common sources of end-of-life carbon is industrial waste between different plants, which is a form of industrial symbiosis. Mechanical recycling of plastic waste is also a widely applied technique to make chemical products, particularly plastics.[24] Chemical recycling could enhance the use of end-of-life carbon as it can produce more types of feedstocks than mechanical recycling but is currently in its infancy. Recycling captured carbon from industrial waste streams could also be a promising source for recycled carbon.[25] However, this technology still needs further

[23] *Plastic Europe (2022). Recycling Technologies.*
[24] *KPMG (2021). The green deal A game changer for the waste management and plastics industries.*
[25] *CHEManager (2022). A sustainable Industrial Symbiosis in Flanders.*

development before it can be commercially rolled out as further discussed under *Captured carbon as recycled feedstock*.

The potential for using end-of-life carbon is limited by the availability of waste, although this potential is still largely untapped. An increase in recycling could expand the applicability of the waste as a feedstock, particularly chemical recycling. For instance, in 2022 only 9 million tonnes of post-consumer plastic was recycled in Europe, about a quarter of the post-consumer plastic waste collected.[26] Almost all plastics sent to recycling facilities were mechanically recycled, with plastics from chemical recycling only accounting for 0.1 million tonnes of Europe's plastic production in 2022. The rest was burned for energy or sent to landfill. However, a study estimated that there is a potential in Europe to mechanically recycle 19 million tonnes of material and chemically recycle 8 million tonnes into feedstock.[27]

Feedstocks from end-of-life carbon can be more environmentally sustainable than virgin fossil feedstocks, but a better environmental performance is not guaranteed. Using recycled materials can save energy compared to the production of virgin fossil-based chemicals, as fewer production steps would be needed.[28] Recycling also avoids emissions from waste incineration or landfill. However, collecting and processing of waste into carbon feedstocks also required energy, particularly chemical recycling. The amount of energy that is needed and other environmental impacts varies depending on the type of waste that is being recycled, the recycling technology used and the chemical feedstock that it is recycled into.[29]

2.3. Captured carbon as recycled feedstocks

Captured carbon feedstock refers to feedstock produced from carbon dioxide and other carbon containing molecules captured before being released into the atmosphere or directly from the atmosphere. CO_2 and other carbon containing molecules such as carbon monoxide from industrial point sources could be captured to process into feedstocks. Biogenic point sources or CO_2 directly captured from the air could also be used to produce captured carbon feedstocks. The conversion of captured CO_2 and other carbon containing molecules into chemicals or fuels is known as carbon capture and utilisation (CCU). This paper focusses on CO_2 (as opposed to other C-containing molecules) in the context of captured carbon feedstocks given that most CCU literature focusses on CO_2. Figure 2-4 provides a schematic representation of the CCU process for making chemical products by combining CO_2 and hydrogen (H_2), including a few examples of chemical product groups.[30]

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[26] *PlasticsEurope (2024). The Circular Economy for Plastics – A European Analysis 2024.*

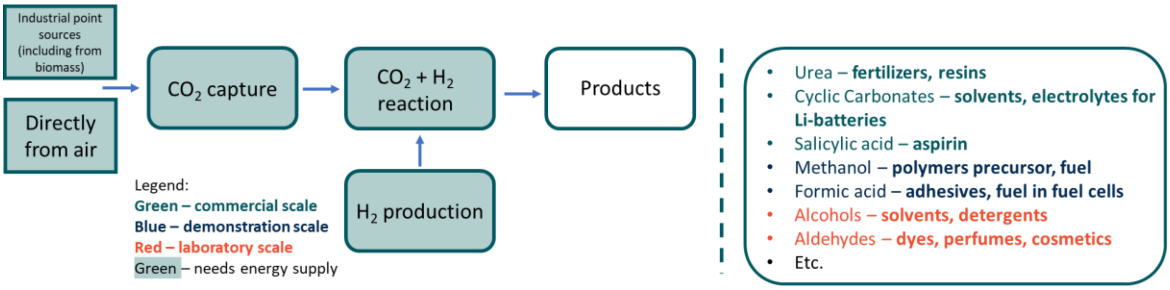
[27] *Accenture (2017). Taking the European Chemical industry into the Circular Economy.*

[28] *See for example Vora et al. (2021). Leveling the cost and carbon footprint of circular polymers that are chemically recycled to monomer; Faraca et al. (2019). Environmental life cycle cost assessment: Recycling of hard plastic waste collected at Danish recycling centres.*

[29] *Creadore and Castaldi (2021). Quantitative Comparison of LCAs on the Current State of Advanced Recycling Technologies.*

[30] *CO_2 is already being utilised directly for other purposes, for example to produce carbonated drinks, in horticulture or for enhanced-oil recovery. However, given the focus of this work on feedstock sources for production of new chemicals, these applications of CO_2 are not discussed further in this paper.*

Figure 2-4 Scope of CCU and example of products that can be made from CO_2



Source: Trinomics based on SAM (2018). Novel Carbon capture and utilisation technologies. Note: the colours of the chemical product groups indicate the technological maturity at the time of the SAM (2018) study. The technologies of some product groups may have matured to the commercial or demonstration stage since then.

Chemicals produced from CO_2 are subject to different synthetic routes and technologies, which are often at different stages of development and technological maturity. The technology of some processes to produce chemicals from captured CO_2 have already reached full commercial maturity (e.g., urea, cyclic carbonates, salicylic acid in green in figure above). Others are at the level of demonstration projects (e.g., methanol and formic acid). However, most synthetic routes that use CO_2 as a feedstock are still under development and will require further research, development and innovation to bring them closer to commercialisation.

Using feedstocks from captured CO_2 can bring climate benefits compared to using feedstocks from virgin fossil fuels, but these benefits are not guaranteed.[31] While capturing CO_2 from point sources to make products only delays its release into the atmosphere, it simultaneously avoids the release of new fossil-based carbon from the ground. However, in contrast to the chemical bonds of which fossil resources are made, the chemical bonds of CO_2 are much harder to break. Breaking these bonds to transform CO_2 into new products requires large amounts of energy. In addition, CO_2 needs to be reacted with hydrogen, which also requires energy to be produced. These energy requirements can result in captured carbon feedstocks having an environmental performance that is worse than virgin fossil feedstocks, especially if the necessary energy is generated using fossil fuels.

[31] *IEA (2019). Putting CO2 to Use: Creating Value from emissions.*

3. Guiding principles for environmentally sustainable RRC feedstocks

Six high-level guiding principles have been proposed for ensuring the environmental sustainability of RRC feedstocks for carbon-based chemicals. Some guiding principles are generally applicable to all RRC feedstocks, whereas others are specific to one of the three RRC feedstock types. Table 1 provides the six guiding principles and the RRC feedstock type for which they are relevant.

Table 1 First set of guiding principles for environmentally sustainable RRC feedstocks

Guiding principles for environmentally sustainable RRC feedstocks		Relevance for the RRC feedstock type		
		Biogenic	End-of-life	Captured
I	Each renewable and recycled feedstock should be assessed on a case-by-case basis since there is no feedstock that is always the most environmentally sustainable choice			
II	Carbon feedstocks from renewable and recycled sources should only be considered sustainable if they have substantial and verifiable environmental benefits over fossil-based feedstocks			
III	Feedstock made from captured CO_2 conversion should only be considered having climate benefits if low-carbon energy is used			
IV	Feedstock from virgin biomass should only be considered sustainable if its sourcing does not cause adverse land-use change, deforestation and biodiversity loss			
V	Biomass residues and marine biomass can generally be considered a more sustainable source than feedstock from virgin biomass from land			
VI	Carbon feedstock from chemically recycled waste can generally be considered sustainable if it comes from waste that could not be reused or mechanically recycled			

The guiding principles build on each other and cannot be considered in isolation; all guiding principles for a specific RRC feedstock type should be met for a feedstock to be environmentally sustainable. For example, feedstocks from chemically recycled waste should not be considered environmentally sustainable solely on the basis that it comes from waste that could not be reused or mechanically recycled (*Guiding principle VI*); the environmental impacts of the recycled feedstock should always be assessed on a case-by-case basis (*Guiding principle I*) and show substantial and verifiable benefits over the fossil feedstock that it is replacing (*Guiding principle II*). Similarly, feedstocks from marine biomass may generally be environmentally preferred over virgin biomass from land (*Guiding principle V*), but only if it does not cause biodiversity loss (*Guiding principle IV*) and have substantial and verifiable environmental benefits over virgin fossil feedstocks (*Guiding principle II*).

These guiding principles should be considered additional to existing principles and frameworks that are relevant to the overall sustainability of RRC feedstocks. The cascading principle of biomass use, Lansink's Ladder and the R-framework for a circular economy[32] are examples of sustainability principles that have already been tested and are widely applied. The aim of the guiding principles in this paper is to complement them by providing guiding principles that are tailored to RRC feedstocks.

In the rest of this section, each guiding principle is explained in more detail with the accompanying rationale and supporting evidence. Caveats and limitations to the guiding principles are also discussed, including current limitations to applying the guiding principles in practice.

[32] *See e.g. PBL (2017). Circular economy: Measuring innovation in the product chain.*

Guiding principle I: Each renewable and recycled feedstock should be assessed on a case-by-case basis since there is no feedstock that is always the most environmentally sustainable choice

Currently, there is no RRC feedstock that is clearly the most environmentally sustainable choice and replacing fossil carbon in chemicals will require utilising feedstocks from a mix of different RRC sources. Literature indicates that there is neither a one-size-fits-all solution, nor a clear hierarchy of preferred sources or technology routes for obtaining RRC feedstocks.[33] Rather, biogenic, end-of-life and captured carbon sources can each play an important role in the transition of the chemical sector towards sustainable and circular production.[34]

RRC feedstocks do show differences in environmental sustainability, with key determinants being geography, technological maturity and the available energy mix. A good understanding of these key determinants is necessary to identify the most environmentally sustainable RRC feedstock for a particular application:[35]

- **Geography:** the environmental sustainability of an RRC feedstock is highly dependent on geography, as it determines whether resources are locally available (and thus environmental impacts from transportation can be avoided) and if the necessary infrastructure is present. For example, in Sweden and Finland, the most sustainable carbon could come from forestry as it can be locally sourced.[36] At locations with vast plantations of sugar beet or sugar cane, these plants may be favoured for carbon feedstock. In biomass-poor locations and countries with a good supply of hydrogen, feedstocks from captured CO_2 may be preferred. In areas with an implemented waste collection and recycling system, feedstocks obtained from mechanical recycling may be the most environmentally sustainable option.[37]
- **Technological maturity:** some technological routes for RRC feedstocks are not yet sufficiently mature and their environmental performance not yet optimised for commercial scale. This is applicable to all three RRC feedstock types. The technology of processes to produce some chemicals from captured CO_2 are still at the level of demonstration projects (e.g., methanol and formic acid). Other synthetic routes that use CO_2 as feedstock are only under development and require further research. For biogenic carbon feedstock, technologies to cultivate macroalgae at large scales in the ocean are still immature and need further development to bring them to commercial phase. Regarding end-of-life carbon, some chemical recycling technologies are also still at pilot scale including hydrocracking, microwave-assisted pyrolysis, plasma pyrolysis, pyrolysis with online reforming, and plasma gasification.[38]
- **Available energy mix:** some production routes for RRC feedstocks are very energy intensive and a significant portion of their environment impact is determined by the

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[33] Renewable Carbon Initiative (2022). Renewable Carbon as a Guiding Principle for Sustainable Carbon Cycles.
[34] EC (2021). Communication on Sustainable Carbon Cycles.
[35] DECHEMA (2017). Low carbon energy and feedstock for the European chemical industry.
[36] Nova Institute (2020). Renewable Carbon – Key to a Sustainable and Future-Oriented Chemical and Plastic Industry.
[37] CarbonCure (2016). Global Roadmap for Implementing CO2 Utilization.
[38] The European Chemical Agency (2021). Chemical Recycling of Polymeric Materials from Waste in the Circular Economy.

energy that is used. This is particularly the case for carbon feedstocks from chemical recycling and captured CO_2. Therefore, the availability of low-carbon energy to supply these routes affect their overall environmental sustainability.[39]

Example 1 shows how aspects related to the key determinants geography and energy mix can lead to significantly different carbon footprints of methanol produced from RRC feedstocks.

Example 1 Differences in the carbon footprint of methanol produced from different RRC feedstocks

The Methanol Institute (2022)[40] studied the carbon footprint of different RRC feedstocks for producing methanol. The study showed that various factors affect the climate impact (GHG emissions) of the methanol produced with different RRC feedstocks. This included the type of biomass that was used for biogenic carbon feedstock, the fraction of organic waste in the end-of-life carbon feedstock, and the electricity source for captured carbon feedstock. This showed significant differences in the carbon footprint depending on the feedstocks that were used:

- Methanol from maize had a carbon footprint between 20 and 40 gCO_2e/MJ, with the range depending on the variations in the cropping system, crop yields, and in the amount and application of fertiliser.
- Methanol from cow manure showed a carbon footprint of -55 gCO_2e/MJ and pig manure -103 gCO_2e/MJ, where the negative emissions relate to the avoided methane emissions if the manure would have left untreated.
- Methanol produced from wood had a carbon footprint between 10 and 20 gCO_2e/MJ depending on the type of wood.
- Methanol produced from municipal solid waste (MWS) had a carbon footprint of 10-55 gCO_2e/MJ depending on the composition of the MSW, where the range corresponds to the fraction of organic waste between 100% and 50%.
- Methanol produced from captured CO_2 and hydrogen showed a carbon footprint of 4.4 gCO_2e/MJ when the hydrogen is produced through electrolysis using solar PV electricity, assuming no emissions related to the capture of the CO_2.
- The carbon footprint for the same methanol produced from captured CO_2 rose to 100 gCO_2e/MJ if electricity from the grid was used (assuming the average EU grid emission factor of 275 gCO_2e/kWh), which is higher than that of methanol made from natural gas.

There are always limitations for different RRC feedstocks, as well as trade-offs between their environmental impacts. Mechanically recycled end-of-life carbon feedstocks requires relatively limited energy but has limitations in the quality it can achieve.[41] Chemical recycling can achieve virgin plastic quality and therefore has more applications but is energy intensive.[42] Biogenic carbon feedstocks generally requires less energy for processing than those from chemical recycling and CCU, but can come with other

[39] *McKinsey & Company (2018). Decarbonization of industrial sectors. The next frontier.*

[40] *Methanol Institute (2021). Carbon Footprint of Methanol.*

[41] *Quantis (2020) Chemical Recycling: Greenhouse gas emission reduction potential of an emerging waste management route.*

[42] *Rollinson and Oladejo (2020). Chemical Recycling: Status, Sustainability, and Environmental Impacts. Global Alliance for Incinerator Alternatives.*

environmental impacts such as adverse land-use change, biodiversity loss, soil degradation and freshwater usage. Furthermore, the different technological routes to produce RRC feedstocks will also have different environmental impacts. Therefore, the most environmentally sustainable RRC feedstock can vary for each individual application. It is necessary to understand potential trade-offs and to look for opportunities to mitigate these. Various methods such as Planetary Boundaries-based life cycle assessments can be used to gauge the different environmental impacts and inform where to focus impact reduction efforts on.[43]

In addition to environmental impacts, there are many other factors that determine the choice of a feedstock that also need to be considered. The most important factor for any feedstock choice remains that it needs to be economically viable. Furthermore, social aspects such as human rights and anti-corruption are also important factors. Finally, customer preference plays a role. Feedstocks from recycled waste might not be accepted by customers to produce skin care products even if supported by life cycle assessments (LCAs) indicating their environmental sustainability. While a discussion of these other determining factors is beyond the scope of this paper, these should not be forgotten in the RRC feedstock choice.

Caveats and limitations

Not all environmental impacts have commonly agreed indicators yet that can be used for an impact assessment, with the most important one being biodiversity. Environmental impacts such as GHG emissions, energy consumption, water and land usage have quantifiable indictors through which these impacts could be assessed. However, indicators that quantify the effect on biodiversity are not yet well developed and not yet well captured via LCA studies.[44]

There are no universally agreed assessment methods yet that can be used to compare different environmental impacts of RRC feedstocks for determining the most environmentally sustainable choice. This complication arises when comparing different RRC feedstocks that perform better on some impacts and worse on others relative to each other. For example, one LCA study compared seven bio-based polymers and seven fossil-based polymers across seven impact categories (energy use, ecotoxicity, acidification, eutrophication, climate change, particulate matter formation and ozone depletion).[45] The study found significant variation in the different impact categories between the polymer types, and it was not possible to conclusively declare any polymer type as having the least environmental impact. Aggregation methods are being explored to aggregate impacts in a single environmental score, such as the one co-developed by L'Oréal by using Planetary Boundaries-based weighting factors[46] or the Eco-cost method[47] of the Sustainability Impact Metrics foundation by monetising the amount of environmental burden on the basis of prevention of that burden.

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[43] *For an overview of different methods, see for example Bjørn et al. (2020). Review of life-cycle based methods for absolute environmental sustainability assessment and their applications.*

[44] *Walker and Rothman (2020). Life cycle assessment of bio-based and fossil-based plastic: A review.*

[45] *Ibid.*

[46] *Vargas-Gonzalez et al. (2019). Operational Life Cycle Impact Assessment weighting factors based on Planetary Boundaries: Applied to cosmetic products. Note that this is different from Planetary Boundaries-based life cycle assessments that assess the absolute environmental sustainability from the perspective of planetary boundaries.*

[47] *Sustainability Impact Metrics (2023). Eco-cost.*

Guiding principle II: Carbon feedstocks from renewable and recycled sources should only be considered sustainable if they have substantial and verifiable environmental benefits over fossil-based feedstocks

Not all feedstocks from RRC sources are inherently more environmentally sustainable than their virgin fossil-based equivalent. Whether an RRC feedstock should be considered environmentally sustainable does not only depend on key determinants such as geography, technological maturity and the available energy mix. The environmental performance of an RRC feedstock in comparison to their conventional fossil-based equivalent is also important to consider.

For an RRC feedstock to be considered environmentally sustainable, it should offer substantial environmental benefits over fossil-based equivalents to ensure that these benefits will materialise. RRC feedstocks that only show marginal improvements in terms of environmental performance compared to fossil-based feedstocks may only exhibit these benefits under certain circumstances. For instance, if an environmental impact assessment of a particular monomer feedstock from chemically recycling local plastic waste shows that the GHG emissions are only marginally lower than monomers made from virgin fossil feedstock, the GHG emissions could also be higher than predicted. This could occur if the plastic waste used to produce the monomer feedstock has to be transported from elsewhere most of the time. Therefore, only RRC sources and technologies for chemicals feedstocks that bring substantial environmental benefits should be pursued to improve the availability of environmentally sustainable RRC feedstocks. For example, the World Wildlife Fund recommends that chemical recycling technologies pursued should achieve a minimum of 20% reduction in GHG emissions compared to the use of virgin fossil resources.[48]

It is also important that the environmental benefits of an RRC feedstock are verifiable to ensure that any claims on environmental sustainability are based on robust evidence and replicable. This is necessary to avoid the expansion of any RRC feedstock that causes more environmental harm than good, so that it truly contributes to the transition towards a sustainable and circular economy. Example 2 demonstrates the importance of verifying the environmental impacts of an RRC feedstock, with an example of PET bottles made from biogenic feedstocks having an environmental performance that is worse than conventional petrochemical PET bottles, even on climate change impact.

[48] *WWF (2022). WWF Position: Chemical Recycling Implementation Principles.*

Example 2 PET bottles made from biogenic feedstocks showing an environmental performance that is worse than conventional petrochemical PET

Gursel et al. (2021)[49] compared the environmental impact of biobased polyethylene terephthalate (PET) bottles from different biogenic sources with conventional petrochemical PET. Biobased PET bottles from Brazilian sugarcane were found have a worse performance compared to conventional petrochemical PET bottles produced in Europe in most impact categories. They only offered minor environmental benefits compared to petrochemical PET bottles in the form of a 10% reduction in abiotic depletion (fossil fuels). One of the main reasons was that the production of biobased monoethylene glycol (MEG), which is required for making biobased PET, was assumed to take place in India. At the time of the study, India had the only company producing bio-MEG on a large industrial scale for incorporation into PET. As a consequence, the use of electricity and steam (which is largely coal-based in India) to produce bio-MEG led to even the climate change impact of the biobased PET bottles being worse than petrochemical PET. Using European wheat straw yielded a better environmental performance than Brazilian sugarcane, because wheat straw is a biomass residue and therefore has lower environmental impacts than virgin biomass. However, the environmental performance of PET bottles from European wheat straw was still only comparable to that of conventional PET bottles and not better. This was mainly because the bio-MEG production was still assumed to take place in India, and the feedstock for producing bio-MEG also had to be transported from Europe to India and the bio-MEG transported back to Europe for PET production. If the bio-MEG would have been produced in Europe or if the energy mix of India would improve, this would also improve the environmental performance of the biobased PET bottles.

Caveats and limitations

Standardised guidance on methodological choices in LCAs is needed for verifying whether the environmental benefits of an RRC feedstock are substantial, which is currently still lacking. LCAs account for multiple environmental impact categories and are the commonly accepted method for evaluating the environmental impacts. However, various studies found that it was not possible to compare the results of different LCAs available in the literature, because they differ in the LCA methodologies used, assumptions and system boundary definitions.[50] This stems from the independent nature of the studies conducted, where different goals and scopes have been set. However, even if the goals and scope are the same, the choices in methodologies and approaches can affect the LCA result. The absence of standardised guidance on methodological choices for assessing RRC feedstocks makes it difficult to obtain comparable and verifiable results. There are some private initiatives that aim to improve standardisation such as the International Sustainability and Carbon Certification[51] and the Roundtable on Sustainable Biomaterials.[52] However, each of these initiatives puts an emphasis on different environmental impact factors.

[49] *Gursel et al. (2021). Comparative cradle-to-grave life cycle assessment of bio-based and petrochemical PET bottles.*

[50] *See for example: Walker and Rothman (2020). Life cycle assessment of bio-based and fossil-based plastic: A review; Bjørn et al. (2020). Review of life-cycle based methods for absolute environmental sustainability assessment and their applications.*

[51] *International Sustainability and Carbon Certification*

[52] *The Roundtable on Sustainable Biomaterials*

Although RRC feedstocks with marginal environmental improvements should not be deemed environmentally sustainable, they may still lead to positive impacts in the long run. Some RRC feedstocks may currently have an environmental performance that is worse than virgin fossil feedstocks and should therefore not be considered environmentally sustainable at this time. However, with more research and development, implementation of sustainable practices, and the decarbonisation of the energy mix, these RRC feedstocks may bring substantial environmental benefits over fossil feedstocks in the future. This could, for example, be the case for feedstocks from energy-intensive processes such as CCU and chemical recycling.[53] Additionally, the expansion of sustainable agriculture practices could also significantly enhance the environmental benefits of biogenic carbon feedstocks (See *Guiding principle IV*). While it is crucial to avoid pursuing RRC feedstocks and technologies with uncertain environmental benefits, it is equally important to investigate options and capitalise on technologies that can deliver substantial environmental improvements in the future. Conducting LCAs of RRC feedstock technologies at different stages of their technological maturity could help in identifying the most promising options.

[53] *See for example: Jeswani et al. (2021). Life cycle environmental impacts of chemical recycling via pyrolysis of mixed plastic waste in comparison with mechanical recycling and energy recovery.*

Guiding principle III: Feedstock made from captured CO_2 conversion should only be considered as having climate benefits if low-carbon energy is used

From a sustainability standpoint, the key motivation for using CO_2 as feedstock is to prevent the use of virgin fossil-based carbon while also delaying the release of the captured CO_2 molecule into the atmosphere, for at least the lifetime of the newly produced commodity. Literature shows that depending on the conversion route (i.e., what product is being made) and technology used, environmental sustainability impacts other than GHG emissions may vary significantly.[54] Therefore, this principle focusses only on possible climate benefits and not on other metrics for environmental sustainability. This principle should be regarded as complementary to the previous two guiding principle rather than a standalone principle.

Converting CO_2 into other compounds requires a lot of energy as well as hydrogen. As described briefly in Section 2.3, in contrast to (fossil based) organic chemical compounds, CO_2 is a very stable non-reactive molecule with a low energy state. Breaking the carbon-oxygen bonds to produce new products requires significant energy inputs. Consequently, large amounts of external energy, usually in the form electricity, must be used to convert it into energy-rich chemicals (and/or fuels).[55]

The energy and hydrogen used for CO_2 conversions should come from low-carbon sources, or otherwise the associated GHG emissions can be higher than those from using fossil-based feedstock. In the most extreme cases (e.g. using coal as the primary energy source), the associated GHG intensity of CO_2 conversion based on fossil-derived energy can be several times greater than that emitted by the current production routes.[56] Furthermore, not only the energy for CO_2 conversion should come from low-carbon sources, but the energy for hydrogen production as well. Currently, most hydrogen in the world is produced from steam methane reforming (SMR)—a fossil-based process. To minimise GHG emissions associated with hydrogen production, the hydrogen should be made from electrolysis using low-carbon energy. Alternatively, the hydrogen could be produced via the SMR method but coupled to carbon capture and storage to prevent the SMR-associated GHG emissions from being emitted into the atmosphere. However, in both cases, large energy inputs are required. Example 3 shows the impact of the electricity source on the potential GHG emissions savings if the fossil-based methanol would be replaced by methanol produced via CCU.

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[54] *Rosental et al. (2020) Life Cycle Assessment of Carbon Capture and Utilization for the Production of Large Volume Organic Chemicals.*

[55] *IEA (2019). Putting CO2 to use; Stevenson (2019). Thermodynamic considerations in CO2 utilization.*

[56] *DECHEMA (2017). Technologies for Sustainability and Climate Protection – Chemical Processes and Use of CO2.*

Example 3 Impact of the source of electricity on the carbon footprint of methanol produced from captured CO_2

CE Delft (2018)[57] compared carbon footprint of methanol produced from captured CO_2 with non-renewable electricity to using the same production process with renewable electricity. Both situations were compared to a situation of releasing the CO_2 into the atmosphere. The study shows that the GHG emission reductions of using captured CO_2 to produce methanol are strongly dependent on the electricity mix, as well as how long the CO_2 molecule is 'stored' in the product. When producing methanol from CO_2 with non-renewable electricity, CO_2 emissions will be higher compared to not capturing the CO_2 and just releasing it in the atmosphere. This is because the CO_2 emissions from the non-renewable electricity for capturing CO_2 and producing hydrogen is much higher than the captured CO_2 itself. In the case of 100% renewable electricity use for hydrogen and methanol production, a net reduction of CO_2 emission can be achieved ranging between 350 kg and 750 kg of CO_2 per tonne of CO_2 captured. The lower end of the range corresponds with the CO_2 being released within 100 years where the stored CO_2 is not counted as CO_2 reduction. The upper range corresponds to CO_2 storage of more than 100 years in methanol, which is counted as CO_2 reduction.

Caveats and Limitations

The high demand for low-carbon energy for captured carbon feedstocks requires a careful consideration of the most efficient use of this energy to achieve the largest GHG emission savings. Even if captured carbon feedstocks are made using only low-carbon energy, it may not necessarily result in climate benefits from a system-wide perspective. This depends on whether the low-carbon energy could have achieved higher GHG emission reductions in other sectors if it was supplied to the electricity grid instead. Therefore, only "excess" low-carbon energy should ideally be used to optimise the climate benefits that can be achieved, as explained in Box 1. While the considerations in Box 1 focus on captured carbon feedstocks, these considerations are also applicable to other RRC feedstocks, particularly ones with a high energy demand such as feedstocks from chemical recycling.

The magnitude in GHG emission savings from products made from captured CO_2 can vary significantly and the suitability of using captured carbon feedstocks need to be considered on an individual basis. The magnitude of the emission savings by utilising CO_2 as a feedstock varies across reports depending on the calculation method and chemical reaction analysed. An IEA GHG technical report[58] found that almost all CCU routes analysed could achieve lower life cycle emissions per tonne of product compared to their fossil-based equivalent. However, the scale of potential GHG savings is much higher for fuels and building materials compared to chemicals and polymers.

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[57] *CE Delft (2018). Screening LCA for CCU routes connected to CO2 Smart Grid.*

[58] *IEAGHG (2021). IEAGHG Technical Report: CO2 as a Feedstock: Comparison of CCU Pathways. Based on this study: For fuels, annual abatement levels greater than 1 $GtCO_2e$ could be achieved for direct replacement 'drop-in' fuels. For building materials, annual abatement levels greater than 100 $MtCO_2e$ could be achieved. On the other hand, apart from methanol, the total mitigation potential of polymers and chemicals was limited to below 20 $MtCO_2e$ per year.*

Box 1 System-wide considerations on using low-carbon energy for captured carbon feedstocks

In today's world, there is still a strong reliance on fossil fuels for energy, and low-carbon energy is not yet abundantly available everywhere. This calls for a careful consideration of the most optimal use of low-carbon energy to reduce fossil fuel consumption and GHG emissions. For example, using the low-carbon energy in applications like heat pumps or electric vehicles generally results in higher GHG emission savings compared to using it for making feedstocks from captured CO_2, and should, therefore, arguably be prioritised. Furthermore, GHG emissions savings from supplying low-carbon energy to the grid can be greater than using that same low-carbon energy to make feedstocks from captured CO_2. For example, according to Ravihumar et al. (2020), feeding the low-carbon energy in the electricity grid generally produces greater climate benefit than using it for methanol production.[59] Therefore, the energy used for captured carbon feedstock production should ideally come from additional[60] or excess low-carbon sources where this energy is not diverted from sectors where higher GHG emission savings can be achieved.[61] This will require determining when low-carbon energy can be considered as excess, for which there are no commonly agreed criteria yet.

[59] *Climate benefits would only greater for methanol production compared to feeding it in the grid if the CO_2 intensity is less than 67 gCO_2/kWh. For comparison, the CO_2 intensity of the electricity grid of Germany was 469 gCO_2/kWh in 2018. Source: Ravihumar, D. et al. (2020). The Environmental Opportunity Cost of Using Renewable Energy for Carbon Capture and Utilization for Methanol Production.*

[60] *Additionality can be understood as the deployment of new, unsubsidised renewable generation able to cover completely the electricity demand of the electrolyser. Bellona Europa (2021). Cannibalising the Energiewende? 27 Shades of Green Hydrogen.*

[61] *Bellona Europa (2021). Cannibalising the Energiewende? 27 Shades of Green Hydrogen.*

Guiding principle IV: Feedstock from virgin biomass should only be considered sustainable if its sourcing does not cause adverse land-use change, deforestation and biodiversity loss

The most important environmental concerns related to feedstocks from virgin biomass are related to their sourcing impacts. The increase in virgin biomass demand around the world has led to significant challenges concerning the supply of sustainable biomass. Healthy soil, sufficient water supply and the right nutrients are a few of the many requirements to achieve a high yield and, thus, efficient biomass cultivation. However, achieving these requirements can negatively affect the environment with concerns about land-use change (indirect and direct), biodiversity, soil and water quality, freshwater consumption, eutrophication, and competition with food production. For chemical feedstocks from virgin biomass to be considered environmentally sustainable, one of the key criteria should be that its sourcing does not exacerbate these negative impacts on the environment, in addition to the other guiding principles relevant to biogenic carbon feedstocks.

Most of the negative environmental concerns can be related to land-use change, which is a key determinant for the environmental sustainability of biomass feedstocks. Since agricultural land covers nearly 37% of the global land area and forest land covers 31% of the world,[62] how it is treated makes a crucial difference in preserving the planet. As a result, changes in how the land is used can lead to negative environmental impacts such as carbon loss from soils, soil erosion, nutrient depletion, freshwater consumption, ecotoxicity and eutrophication. Direct and indirect land-use changes might also lead to deforestation and biodiversity loss as native crops and species would be at risk of being displaced.[63]

Deforestation is also key determinant to which many negative environmental impacts of biogenic feedstocks can be related to. Harvesting trees may be carbon neutral in the long term. This is only under the condition that the total area of a forested land does not change, and that the trees that are harvested are replaced by new ones in a later time or another place,[64] i.e., that the forests are sustainability managed. However, the lack of sustainable forest management in combination with the growing demand for virgin biomass has resulted in deforestation all over the world. This has adversely reduced the ability of forests to store CO_2 and caused species extinction, leading to biodiversity loss and displacement of habitat populations.[65] For example, tropical deforestation is responsible for 20% of the global GHG emissions.[66] In deforested areas, the land heats up faster, enhancing the formation of clouds and increasing rainfall. In turn, extreme rainfall can lead to increased soil erosion.[67]

[62] *FAO (2020). FAO Forestry Statistics.*

[63] *Plevin et al. (2010). Greenhouse gas emissions from biofuels: Indirect land use change are uncertain but may be much greater than previously estimated.*

[64] *Vogtländer et al. (2014). Carbon sequestration in LCA, a proposal for a new approach based on the global carbon cycle; Cases on wood and on bamboo.*

[65] *UN FAO Global Forest Resources Assessment (2016): How Are the World's Forests Changing?*

[66] *Hoang et al. (2021). Mapping the deforestation footprint of nations reveals growing threat to tropical forests.*

[67] *Eekhout and de Vente (2022). Global impact of climate change on soil erosion and potential for adaptation through soil conservation.*

Biodiversity loss is another key indicator that ties many different environmental stressors together. The most significant contributors to biodiversity loss include changes in terrestrial and aquatic habitats, overharvesting of natural populations, pollution, and climate change.[68] Ecotoxicity, acidification, eutrophication, climate change, and land use are among the stressors that are considered main biodiversity loss stressors.[69] Many of these stressors are influenced by the cultivation of virgin biomass.

Caveats and limitations

The impacts on land-use change, deforestation and biodiversity loss from virgin biomass can vary significantly depending on the geographic context and the method of sourcing, as well as any actions taken to mitigate negative impacts. The environmental impact of virgin biomass will depend on how sustainable and efficient a biogenic feedstock could be produced within a particular geographic context.[70] For example, feedstock from harvested timber can cause negative impacts on surrounding wildlife with a risk of biodiversity loss. However, biodiversity loss can be avoided by leaving some of the woody biomass debris behind after a harvest, which preserves the habitat for wildlife like mice and insects. By redistributing the debris across the harvest site, food and cover is maintained for nearby wildlife.[71]

In some instances, land-use change related to biomass cultivation for feedstock use may have a positive environmental impact, although this is still at an early stage of development. This would be in cases where biomass can be cultivated on land that have already experienced negative environmental impacts such as soil erosion, biodiversity loss and deforestation, e.g., industrial areas or deserts. However, the cultivation of biomass suitable for feedstock use that could result in positive land-use change impacts is still in the early stages of development. Further research is necessary to confirm these positive impacts, as well as the absence of any other negative environmental impacts. Example 4 discusses guayule as a crop that potentially has positive land-use change impacts.

Example 4 Guayule as a promising crop with positive land-use change impacts

Guayule (Parthenium argentatum) cultivation in the desert might lead to positive environmental impact. Guayule is a rubber plant indigenous to the Chihuahuan Desert of Northern Mexico and Southwestern Texas. The plant is a potentially valuable source of biogenic carbon as biomass feedstock.[72] After the latex is extracted from the plant, the ground-up stems and branches—called "bagasse" remain, which could be used for biofuels and biogenic carbon. Guayule has a few advantages as a source of biomass. It flourishes and prospers in the desert, and can therefore grow in places where other types of crops cannot. In addition, guayule shrubs do not need much fertiliser or water to grow.[73]

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[68] Ruakamo et al. (2022). *Exploring the potential of circular economy to mitigate pressures on biodiversity.*
[69] Guest et al. (2014). *Climate Change Impacts Due to Biogenic Carbon: Addressing the Issue of Attribution Using Two Metrics With Very Different Outcomes.*
[70] Pawelzik et al. (2013). *Critical aspects in the life cycle assessment (LCA) of bio-based materials - Reviewing methodologies and deriving recommendations.*
[71] Moorman et al. (2021). *The relationship between upland hardwood distribution and avian occupancy in fire-maintained longleaf pine forests.*
[72] Rousset et al. (2021). *Guayule (Parthenium argentatum A. Gray), a Renewable Resource for Natural Polyisoprene and Resin: Composition, Processes and Applications.*
[73] Bañuelos et al. (2022). *Guayule as an alternative crop for natural rubber production grown in B- and Se-laden soil in Central California.*

While land-use change, deforestation and biodiversity loss are the most important environmental sustainability determinants for feedstocks from biomass, GHG emissions should not be neglected as it can be higher than using fossil feedstock. While biogenic carbon feedstocks themselves can be considered carbon neutral, energy is required to process the biomass into feedstock. Energy is also needed to transport the biomass and resulting feedstock. If this energy comes from non-renewable sources, this could result in higher CO_2 emissions than using fossil-based feedstock. In addition, the cultivation of biomass may result in additional CO_2 emissions from soil tillage and nitrous oxide emissions from nitrogen fertilizer application.[74] The GHG emissions from cultivation could be avoided through applying regenerative agriculture as explained in Box 2, although there is no commonly agreed definition of what regenerative agriculture exactly entails.[75] Example 5 introduces cardoon as a promising crop for application in regenerative agriculture.

Box 2 Regenerative agriculture to avoid negative environmental impacts of sourcing virgin biomass

Regenerative agriculture practices such as cover cropping, crop rotation, reduced tillage, and biological pest control minimise chemical inputs and maintain soil health, fertility, and biodiversity. Crop rotation and pest control can increase biodiversity, which increases the variety of nutrients going into the soil through roots and natural decomposition and, if well-managed, attracts insects which are the natural predators of pests.[76] Regenerative agriculture aims to integrate food, livestock, and biomass usage operations on the land, eliminating spatiotemporal soil events.[77] This can lead to positive land use changes and biodiversity conservation. Regenerative agriculture practices also contribute to carbon sequestration from the atmosphere and retrieving it back into the soil.[78]

Example 5 Cardoon as a promising crop with positive impacts on climate change mitigation

Cardoon (Cynara cardunculus) is a perennial crop that can help reduce soil erosion as produces a dense mat of roots.[79] Experimental industrial cardoon crops grown in the north-west of Sardinia confirmed the crop could increase the Soil Organic Carbon (SOC) in the land on average approximately 1 tonne of SOC/ha per year.[80] The results shows that cardoon could be used in regenerative agricultural practices to maintain, restore and improve land while having a positive impact on climate change mitigation.

There is no commonly agreed approach for a holistic assessment of all environmental impacts related to the use of biomass. Most environmental impact assessment methods, such as life cycle or carbon footprint measurements, consider biogenic CO_2 emissions as

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[74] Agiulera et al. (2014). Greenhouse gas emissions from conventional and organic cropping systems in Spain. I. Herbaceous crops.
[75] Newton et al. (2020). What Is Regenerative Agriculture? A Review of Scholar and Practitioner Definitions Based on Processes and Outcomes.
[76] Brown et al. (2022). Can regenerative agriculture support successful adaptation to climate change and improved landscape health through building farmer self-efficacy and wellbeing?
[77] Laccane et al. (2018). Regenerative agriculture: merging farming and natural resource conservation profitably.
[78] Poeplau and Don (2015). Carbon sequestration in agricultural soils via cultivation of cover crops–A meta-analysis.
[79] Rossi et al. (2022). Soil reinforcement potential of cultivated cardoon (Cynara cardunculus L.): First data of root tensile strength and density.
[80] D'Avino et al. (2020). Introduction of Cardoon (Cynara cardunculus L.) in a Rainfed Rotation to Improve Soil Organic Carbon Stock in Marginal Lands.

zero.[81] However, this ignores the dynamics of the regrowth of the biomass and the speed of release of the biogenic carbon. The release speed varies throughout with different components of biomass, e.g., biogenic carbon from dead organic matter would be released faster while the biogenic carbon in products is stored for a longer time. Often only virgin biomass is included as part of the assessment and not the remaining residues.[82]

While social considerations are beyond the scope of the guiding principles in this paper, they should not be neglected when considering the sustainability of RRC feedstocks, particularly in relation to virgin biomass. The discussion on the environmental sustainability of virgin biomass for feedstock use is inexplicably linked to the competition with food and animal feed in the context of land-use change. These include negative social implications such as price increases of food crops, income of farmers and the risk of vulnerable communities being displaced from their lands. While it is important to consider these social aspects, the growing virgin biomass for feedstock use does not always have to compete with food. For example, agroforestry with integrated feed and food production could bring both environmental and social benefits.[83] There are also other social impacts relevant to consider in the context of aspects mentioned in this section on positive land-use change and regenerative agriculture. These include job opportunities in economically depressed regions, increasing farmer well-being, and less hazardous work conditions. A future sustainability framework for RRC feedstocks should also provide guidance on these social aspects, particularly when it relates to feedstocks from virgin biomass.

[81] *Matustik et al. (2021). Is application of biochar to soil really carbon negative? The effect of methodological decisions in Life Cycle Assessment.*

[82] *Vogtländer et al. (2014). Carbon sequestration in LCA, a proposal for a new approach based on the global carbon cycle; Cases on wood and on bamboo.*

[83] *Sharma et al. (2016). Bioenergy from agroforestry can lead to improved food security, climate change, soil quality, and rural development.*

Guiding principle V: Biomass residues and marine biomass can generally be considered a more sustainable source than feedstock from virgin biomass from land

Biomass residue and marine biomass can often be considered a more sustainable biogenic feedstock, as the risk of detrimental environmental impacts that virgin biomass from land may have is significantly lower.[84] The use of biomass residue does not compete with other sectors such as food and fuel production or cause a displacement of resources, since many waste and residue resources such as manure, anaerobic lagoons, and dead leaves do not have extensive current applications.[85] In addition, biomass residues and marine biomass do not involve additional land use; therefore, they do not lead to direct and indirect land-use changes and deforestation, and the biodiversity loss that goes with it. However, further research is required to determine whether this assertion remains valid for marine biomass when it is cultivated at scale.

Feedstocks from biomass residues have stronger climate benefits than virgin biomass as it reduces GHG emissions from soil top and decomposition of the residues. Live virgin biomass can absorb and store carbon from the atmosphere. However, dead organic matter such as biomass residues, if not collected, will decompose slowly and release CO_2 into the atmosphere. Harvesting virgin biomass might increase CO_2 emissions as it increases the amount of dead organic matter.[86] For example, deadwood is a significant source of CO_2 emission from a forest, especially in the years after harvest.[87] Using residues as a feedstock can therefore reduce CO_2 emissions associated with the virgin biomass.

Marine biomass can grow a lot faster than many virgin land-based biomass while avoiding some of its negative environmental impacts. Growing marine biomass such as seaweed, kelp and macroalgae is faster, more space-efficient and does not require the use of fresh water or the addition of fertiliser. Furthermore, seaweed, kelp and macroalgae are grown in the oceans or lakes, and do not compete for land area. Most of the marine biomass can be grown on straight or circular ropes, horizontally or vertically down to 10 meters depth to retain optimal sunlight conditions. For example, kelp absorbs CO_2 from the atmosphere at a much faster rate than a lot of land-based plants, which results in a fast growth rate of up to two feet per day.[88] Seaweed could be grown in circular systems, like Integrated Multi-Trophic Aquaculture that brings together other sea production such as fish farming and offshore energy, creating a circular ecosystem. Seaweed also has a high yield, growing about 26 tonnes dry weight per hectare, compared to 2.3 tonnes soya and 5.1 tonnes corn. In addition, seaweed biomass cultivation can contribute to protecting shorelines and marine ecosystems.[89]

[84] *Biomass residues refer to the waste- and by-products of virgin biomass. Marine biomass only refers to plants in the marine ecosystem (marine flora) and not animals such as fish (marine fauna).*

[85] *Hansen et al. (2020). Biomass residues as twenty-first century bioenergy feedstock—a comparison of eight integrated assessment models.*

[86] Liu et al. *(2017). Analysis of the Global Warming Potential of Biogenic CO2Emission in Life Cycle Assessments.*

[87] *Repo et al (2015). Sustainability of forest bioenergy in Europe: land-use-related carbon dioxide emissions of forest harvest residues.*

[88] *Fieler et al. (2021). Erosion Dynamics of Cultivated Kelp, Saccharina latissima, and Implications for Environmental Management and Carbon Sequestration.*

[89] Duarte et al. *(2017). Can Seaweed Farming Play a Role in Climate Change Mitigation and Adaptation?*

Caveats and limitations

Existing environmental assessment methods are not fully able to quantify the environment benefits of biomass residue feedstocks. As mentioned under *Guiding principle IV*, there are no standardised methods within the life cycle assessment framework to consider the environmental impacts of dead organic matter.[90] This makes it difficult to quantify the environmental benefits of feedstocks from biomass residues in a consistent and verifiable manner.

The availability of biomass residue is limited and it can therefore only play a small role as a source for environmentally sustainable feedstocks. In Europe, biomass residues can only contribute to around 3-4% of the final feedstock demand in 2030.[91]

The technology for feedstocks from marine biomass is still under development and there are various practical challenges that need to be resolved. Technology to cultivate macroalgae at large scales in the ocean is still immature, and transporting and processing this biomass presents new challenges. This includes moving them from offshore farms and available techniques for dehydrating and processing due to their high moisture content.[92] There is also other marine biomass that could be used as feedstock such as water hyacinth, seaweed and duckweed, but these require further research.[93] Since marine biomass is still a novel feedstock, there are also various practical issues that need to be resolved. These include the availability of suitable areas for cultivation, regulatory requirements for seaweed aquaculture concessions, and competition for space with other marine-based activities. Finding suitable space for marine biomass cultivation is particularly a challenge, as this is limited by the availability of suitable areas that are not protected by marine conservation policies.

Processing biomass residues and marine biomass can be energy intensive, but the negative environmental impact from the higher energy use can be mitigated with low-carbon energy. A significant part of the energy demand for processing biomass residues and marine biomass is determined by their water content, which can differ significantly per biomass type, even among marine biomass. For instance, the blue mussels dry matter fraction ranges from 32.7% to 38.5%, which that of ascidians is only around 5%.[94] The energy intensity of processing different biomass types therefore needs to be evaluated on a case-by-case basis. Furthermore, energy for transporting the biomass from farm to processing also need to be considered, e.g. diesel consumed in boats. As the technologies for processing biomass residues and marine biomass develop further, these processes may become more energy efficient. Furthermore, the environmental impact of the higher energy use can be mitigated as the energy system is decarbonised further and renewable energy becomes much more available.[95]

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[90] *Brandão,M. et al.(2013). Climatic impact of land use in LCA-carbon transfers between vegetation/soil and air.*

[91] *EU Commission (2020). Sustainable and optimal use of biomass for energy in the EU beyond 2020.*

[92] *Ingle et al. (2020). Challenges for marine macroalgal biomass production in Indian coastal waters.*

[93] *Kaur et al. (2018). Aquatic weeds as the next generation feedstock for sustainable bioenergy production.*

[94] *Thomas et al. (2021). Marine biomass for a circular blue#green bioeconomy? A life cycle perspective on closing nitrogen and phosphorus land-marine loops.*

[95] *See for example Thomas et al. (2021). Marine biomass for a circular blue#green bioeconomy? A life cycle perspective on closing nitrogen and phosphorus land-marine loops.; EswaryDevi et al. (2022). Processing of marine microalgae biomass via hydrothermal liquefaction for bio-oil production: study on algae cultivation, harvesting, and process parameters. Gumisiriza et al. (2017). Biomass waste-to-energy valorisation technologies: a review case for banana processing in Uganda.*

Both potential sourcing and environmental impacts of marine biomass as a feedstock is not fully understood and need further research. Growing massive seaweed and kelp farms could have unexpected environmental effects on marine ecosystems, which are not well understood. For example, an environmental study within a commercial kelp farm on the southwest coast of Ireland[96] shows that while the local marine plants were not affected, the sediment grain size and total organic matter did change as a result of the farm cultivation. How this affects the marine ecosystem is unclear. Furthermore, algae and kelp farming could potentially disrupt the marine carbon cycle, although there has not been studied in sufficient detail yet.

[76] *Walls et al. (2017). Impact of kelp cultivation on the Ecological Status of benthic habitats and Zostera marina seagrass biomass.*

Guiding principle VI: Carbon feedstock from chemically recycled waste can generally be considered sustainable if it comes from waste that could not be reused or mechanically recycled

Reuse and mechanical recycling should be generally preferred over chemical recycling due to their lower energy demands, resulting in a smaller carbon footprint. They also produce fewer toxic by-products that can occur with chemical recycling. Chemical recycling should only be used for waste that cannot be reused or recycled by mechanical recycling systems. Therefore, chemical recycling should only be considered if prevention, reuse and mechanical recycling are not feasible option.

For chemical recycling to add value to waste management systems, waste processed by chemical recycling should be a new processing stream for waste that would have otherwise not been recycled. The use of chemical recycling should be complementary to existing waste management systems and not compete for feedstocks with higher hierarchical waste management solutions. Chemical recycling could achieve virgin plastic quality to produce plastics that could be used for sensitive applications such as food packaging. In addition, contaminated polymers that cannot be recycled via mechanical recycling can be recycled chemically.[97] As a result, chemical recycling can help increase the recycling rates of products.

Studies show that applying chemical recycling can have environmental benefits over incineration and landfilling, and should therefore be above them in the waste management hierarchy. Under current waste management hierarchy, also known as Lansink's Ladder, waste that cannot be recycled is treated through incineration for energy recovery and landfilling, respectively. Hereby recycling generally refers to mechanical recycling as chemical recycling is not fully recognised in the waste hierarchy. However, chemical recycling could reduce the amount of plastics going to incineration and landfilling and hence the associated GHG emissions. On other environmental impacts, the performance of chemical recycling depends on the energy mix used for chemical recycling and assumptions on the status quo that the chemically recycled feedstock is replacing, as shown Example 6. The environmental impacts of chemical recycling further depend on the type of technology that is used.[98]

Example 6 Potential of feedstocks from mechanical and chemical recycling to reduce GHG emissions

Jeswani et al. (2021)[99] compared the environmental impact of plastic (low-density polyethylene) made feedstock from mechanical and chemical recycling (via pyrolysis) of mixed plastic waste, and virgin fossil-based plastic with incineration of mixed plastic waste for energy recovery. The study showed that in terms of climate change impact (GHG emissions):

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[97] *Quanties (2020). Chemical Recycling: Greenhouse gas emission reduction potential of an emerging waste management route*

[98] *Cefic (2021). Shining a light on the EU27 chemical sector's journey towards climate neutrality.*

[99] *Jeswani et al. (2021). Life cycle environmental impacts of chemical recycling via pyrolysis of mixed plastic waste in comparison with mechanical recycling and energy recovery.*

- Mechanical recycling has the lowest climate change impact and virgin fossil plastic with energy recovery has the highest (1.99 vs 3.65 tCO_2e per tonne of plastics).
- Chemical recycling has a slightly higher climate change impact (7%) than mechanical recycling, but 42% lower than the virgin fossil plastic with energy recovery.

For most other environmental impacts considered (which include acidification, eutrophication, photochemical and ozone formation), these were significantly higher for chemical recycling compared to mechanical recycling and virgin fossil plastic with energy recovery. This is explained by the relatively high energy demand in the pyrolysis in chemical recycling. However, sensitivity analyses in the study show that the better performance of virgin fossil plastic with energy recovery over chemical recycling is strongly related to the assumptions on the energy mix of the region, carbon conversion efficiency of pyrolysis and quality of the mixed plastic waste. The study indicates that as the energy mix is decarbonised over time and pyrolysis technology improves, the environmental benefits of plastics from chemical recycling over virgin fossil plastic with energy recovery will improve.

Caveats and limitations

The high energy inputs required for chemical recycling remain a contentious point of discussion on its potential environmental benefits. Research advocating against the use of chemical recycling argue that since it is an energy-intensive process, it will always require an external energy source for its processes.[100] If this would be fossil-based energy, this could lead to adverse environmental impacts. Different assumptions on the energy mix can therefore lead to significantly different results on the environmental impact of feedstocks from chemical recycling compared to virgin fossil feedstock. For example, if the energy system is assumed to be coal-based, recovering energy from incinerating plastic waste + making virgin fossil plastics results in lower GHG emissions than plastic from chemically recycled waste. This is because coal use is avoided through energy recovery while chemical recycling leads to more use of coal.[101] However, with further decarbonisation of the energy system, these avoided environmental impacts from energy recovery will be reduced over time and the environmental benefits of feedstocks from chemical recycling compared to virgin fossil feedstocks increased. Such energy should ideally be additional low-carbon energy to also ensure that GHG emission savings are obtained from a system-wide perspective as discussed in Box 1.

[100] *Rollinson and Oladejo (2020). Chemical Recycling: Status, Sustainability, and Environmental Impacts.*
[101] *See for example Sphera (2022). Life Cycle Assessment of Chemical Recycling for Food Grade Film.*

4. Policy incentives in the EU and US for environmentally sustainable RRC feedstocks

This section presents an analysis of the policy environment in the EU and the US regarding the availability and use of RRC feedstocks for carbon-based chemicals and their environmental sustainability. Relevant policies and strategies have been identified based on desk-based research and input from the participating companies. Policies on the environmental sustainability of RRC feedstocks are discussed separately from incentives on their availability and use, as most incentives only include limited requirements for environmental sustainability. The policies in this section should not be regarded as a comprehensive list but rather the most relevant policies as of 31 January 2025. Private or voluntary initiatives are not covered.

The subsections below highlight the most relevant policy incentives in the EU and the US, with significantly more relevant policies identified in the EU compared to the US. Policy incentives related to the availability of RRC feedstocks are discussed in section 4.1, followed by incentives for their use in section 4.2. Section 4.3 provides a summary of policy initiatives relevant to ensuring the environmental sustainability of RRC feedstocks in the EU only, given the lack of developments in US federal policy in that area. Box 4 concludes this section with a summary of the policy areas in the EU and US require further attention to incentivise the availability and use of environmentally sustainable RRC feedstocks for carbon-based chemicals. For a full overview of all direct and indirect incentives identified in government policies and strategies in the EU and the US for RRC feedstocks (including ones not highlighted in this section), please see the Annex.

4.1. Incentives related to the availability of RRC feedstocks

Policy incentives in the EU and the US that can enhance the supply of RRC feedstocks in the short term primarily relate to end-of-life materials through increased recycling. The waste recycling targets under the EU Waste Framework Directive (WFD) help increase the availability of end-of-life carbon material for feedstock use. Additionally, the WFD introduces “extended producer responsibility” (EPR), making manufacturers responsible for their products’ end-of-life management, which can also enhance recycling. The supply of end-of-life carbon material is further boosted by the Waste Shipments Regulation (WSR). The WSR simplifies intra-EU shipments for recycling of waste and puts restrictions on waste exports to non-EU countries, of which the latter implicitly forces EU countries to increase their recycling capacity. EU countries are also incentivised to increase recycling via a collection target of 90% by 2029 for single use plastics bottles under the Single Use Plastics Directive and a fee on non-recycled plastic packaging waste via the Plastic Levy. Similarly, the National Recycling Strategy in the US and state-level EPR laws focus on improving and harmonising the recycling infrastructure, which could increase the availability of waste to be used as feedstock.

The EU and the US have several research and development (R&D) funding programmes in place to increase the availability of RRC feedstocks in the long term, particularly

biogenic and captured carbon feedstocks. As part of its Industrial Carbon Management strategy, the EU is scaling up efforts related to industrial carbon management. This includes creating a more attractive environment for investments in technologies for producing captured carbon feedstocks. This is supported, among other initiatives, by Horizon Europe, the EU's key R&D funding programme, which includes several research initiatives aimed at increasing the availability of RRC feedstocks. Moreover, demonstration projects related to RRC feedstocks can be funded by the Innovation Fund of the EU Emissions Trading System (ETS), which financially supports demonstration projects aimed at substituting carbon-intensive technologies, including RRC feedstock projects. The development of biogenic feedstocks for fossil-free products is further stimulated through the EU Bioeconomy strategy. Similarly, the US National Biotechnology and Biomanufacturing initiative includes financial assistance for R&D in raw materials for biobased chemicals. Additionally, the US Carbon Conversion Program invests in technologies that make economically valuable products from biogenic and captured carbon feedstocks.

The EU and the US also have policies that incentivise to use RRC sources for energy purposes or fuel production, which competes with RRC feedstock use for chemicals. In the EU, biofuel production and using biomass for heating and electricity generation are counted towards the achievements of renewable energy targets. Furthermore, the latest revision of the EU Renewable Energy Directive includes incentives to use captured carbon feedstocks to make fuel. Additionally, emitters covered under the EU ETS do not have to pay for emissions from burning biomass for energy[102] or emissions from incineration of municipal waste. In the US, the identified R&D programmes include support for the developing fuels made from RRC feedstocks. These incentives to use of RRC sources for energy and fuel production reduces their availability for use in other sectors, including as feedstock for chemicals.

A lack of clarity on certain waste recycling aspects, particularly chemical recycling, in the EU and the US are further hindering the development of RRC feedstocks. The EU WFD defines the criteria when an end-of-life material ceases to be considered as waste and start becoming a product or feedstock. Materials meeting these end-of-waste criteria face less administrative burden. For waste that can be used as a chemical feedstock, such criteria are yet to be developed. Furthermore, chemically recycled waste does not count towards the recycling targets of EU Member States. Chemical recycling is also not recognised as recycling under the EU WSR, which discourages intra-EU transport of waste for chemical recycling. The Ecodesign for Sustainable Product Regulation (ESPR) does not currently provide a clear framework for incorporating chemically recycled materials into recycling targets, further limiting incentives for innovation in this area. In the US, the recognition of chemical recycling as a recycling method to count towards recycling targets varies per state. The lack of recognition of chemical recycling in policy may particularly pose challenges for recycling targets regarding contact-sensitive plastic packaging; plastic from mechanical recycling may not be able to meet the required health standards. This is especially the case for processing mixed plastic waste into high quality feedstocks suitable for making contact-sensitive products such as food wraps.

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[102] *Biomass used in the EU must meet certain sustainability criteria to count towards renewable energy targets or to be considered as zero under the EU ETS.*

4.2. Incentives for the use of RRC feedstocks

Targets and minimum requirements on the RRC content in products are the main policy instruments in the EU for incentivising the use of RRC feedstocks. The EU Communication on Sustainable Carbon Cycles (SCC) sets an aspirational target for at least 20% of carbon used in chemical and plastic products to be from sustainable non-fossil sources by 2030. To achieve this target, various EU policies have been implemented or proposed, which have so far focussed on end-of-life materials. The Single Use Plastic Directive mandates that single use plastic bottles should contain a minimum of 30% recycled content by 2030. The Packaging and Packaging Waste Regulation (PPWR) requires plastic packaging to incorporate a certain percentage of recycled content to be sold on the EU market. Additionally, the ESPR aims to expand incentives for using recycled carbon feedstocks and enables setting minimum requirements for the recycled content in all physical products. This does not only incentivise the use of feedstocks from end-of-life materials, but could also incentivise captured carbon feedstock use if that would also count towards "recycled content". Furthermore, the Fertilising Products Regulation create additional pathways for integrating RRC feedstocks into a broader range of fertiliser products.

In the US, public procurement, voluntary labelling and financial incentives are the primary policy instruments used to encourage the substitution of fossil resources with RRC feedstocks. As part of the US BioPreferred Program, federal agencies and their contractors have mandatory purchasing requirements for biobased products, including those made from biogenic feedstocks. The BioPreferred Program also contains a voluntary labelling initiative for biobased products, which aims to make it easier for consumers to choose biobased products. The US also has the 45Q tax credit, which specifically incentivises the use of captured carbon feedstocks. Companies receive a tax credit when captured carbon is used for industrial applications, including the production of chemicals, provided that emission reductions can be clearly demonstrated. The credit increases if the carbon used was obtained from direct air capture technologies.

The EU also has policies with financial incentives to reduce fossil resource consumption, but these do not encourage the use of RRC feedstocks and could even discourage their use. The EU ETS and the EU Carbon Border Adjustment Mechanism (CBAM) are the main EU policies pricing the use of fossil resources. However, both policies only cover the GHG emissions directly (and for some products the indirect CO_2 emissions from the electricity consumed) related to the production of a product. Other climate impacts such as sourcing and end-of-life emissions and other environmental factors associated with feedstock use are not considered. In contrast, manufacturers are disincentivised to use RRC feedstocks under the EU ETS and CBAM if they lead to higher direct GHG emissions compared to using fossil-based feedstocks, even if the overall lifecycle emissions would be lower.

4.3. Policies relevant to the environmental sustainability of RRC feedstocks

The EU has recently proposed several policy measures to disclose the environmental impact of products, which will help to ensure the environmental sustainability of RRC feedstocks. The Sustainable Product Initiative is the main legislative framework to improve the environmental sustainability and circularity of products placed on the EU market. At its centre is the ESPR, which introduces digital product passports. These passports will include detailed information on the environmental sustainability of products such as their carbon footprint, material composition, and recyclability. This disclosure of information is supported by the SCC communication, which urges the reporting and accounting of any tonne of CO_2 captured, transported, used and stored by its fossil, biogenic or atmospheric origin by 2028. Additionally, the EU policy framework on biobased, biodegradable and compostable plastics recommends that any products labelled biobased should only refer to their exact and measurable share of biogenic material. The PPWR already requires packaging to be traceable throughout its whole supply chain, including whether the packaging meet specific environmental sustainability requirements. The WFD and WSR further support the environmental disclosure objectives for end-of-life materials used as feedstocks by enhancing the traceability of waste. For captured carbon feedstock, a part of the EU Industrial Carbon Management strategy is to develop a framework to track the source, transport and use of the captured CO_2 to ensure its environmental integrity. These measures will enable consumers and businesses make more informed choices when purchasing products, including choosing chemicals made from environmentally sustainable RRC feedstocks.

Various existing and proposed EU policies aim to establish criteria for environmental sustainability, with the Product Environmental Footprint (PEF) method at its centre. Already, the EU Taxonomy Regulation has established the conditions for economic activities to qualify as substantially contributes to achieving environmental objectives. The Renewable Energy Directive has also established criteria for biomass to be considered sustainable. Efforts are being made to also develop sustainability criteria for products, with the ESPR enabling the EU to set requirements on the maximum carbon and/or environmental footprint that products can have. Furthermore, the EU Bioeconomy Strategy requires the development of environmental standards for biobased products, the PPWR for packaging and the Industrial Carbon Management strategy for feedstocks from captured CO_2. The requirements for environmental sustainability under these policies could be set in a way that only products made from environmentally sustainable RRC feedstocks meet the criteria. For determining whether products meet the criteria for environmental sustainability, many of these policies refer to the PEF as the main assessment method. However, there are a few issues regarding the PEF that could hamper the use of environmentally sustainable biogenic carbon feedstock, as explained in Box 3.

Box 3 Key issues regarding the PEF that hinder environmentally sustainable biogenic carbon feedstock use

There are several key issues with the current PEF methodology that hinder the use of environmentally sustainable biogenic carbon feedstock. **Firstly, the PEF does not currently take into account the impact of products on biodiversity.**[103] The preservation of biodiversity is a key determinant for the environmental sustainability of biogenic feedstocks from virgin biomass as per *Guiding principle IV*. Therefore, if the environmental sustainability of chemicals from biogenic feedstocks is solely assessed using the PEF, the risk of biodiversity loss may be overlooked.

Secondly, manufacturers have no incentivise to choose biogenic carbon feedstocks over virgin fossil feedstocks from a climate perspective under the current PEF method.[104] The PEF considers CO_2 emissions from biogenic materials to be zero at every lifecycle stage.[105] This means that the GHG emission reductions of using biogenic materials over virgin fossil feedstocks are mainly accounted for in the end-of-life emissions. However, since manufacturers usually cannot be sure how their products will be used or disposed of, they may be required to determine the environmental footprint of their products up to the stage they leave the factory (cradle-to-gate) instead to the end-of-life stage (cradle-to-grave). As a result, the GHG emission reductions of using biogenic materials would not be accounted and the environmental footprint of the products using biogenic feedstocks would be identical to that of using fossil feedstocks if the sourcing and production emissions are the same. An alternative approach, advocated by industry, would be to subtracting the CO_2 absorbed by biological sources during growth in the sourcing stage and adding it back when released at the end-of-life stage. This alternative method would make products made from biogenic materials appear more climate-friendly compared to fossil-based alternatives.

Finally, the current PEF method does not provide a clear incentive for recycling biogenic materials. This is due to how biogenic CO_2 emissions are accounted for under the PEF. Since the PEF considers CO_2 uptake in and emissions from biogenic materials as neutral over its lifecycle, it does not differentiate between reuse/recycling and incineration at the end-of-life stage in terms of climate impacts. As a result, there is no incentive to prioritise recycling over energy recovery.

The criteria and recommendations on environmental sustainability that have been established in EU policy so far are well-aligned with the guiding principles presented in this paper. Specifically:

- The **EU Taxonomy Regulation** specifies that for renewable feedstock use in chemicals to be considered to substantial contribution to climate change mitigation, the life cycle GHG emissions need to be lower than equivalent chemicals manufactured from fossil feedstocks and independently verified. This is consistent with *Guiding principle II*. For other environmental impacts, the regulation requires

[103] *Pederson and Remmen (2022). Challenges with product environmental footprint: a systematic review.*
[104] *Joint Statement (2024). Biogenic carbon accounting in the Product Environmental Footprint.*
[105] *European Commission (2021). Commission Recommendation (EU) 2021/2279. The biogenic carbon content of products is only to be reported as additional technical information.*

environmental impact assessment or screening to be done on a case-by-base basis, which is in line with *Guiding Principle I*.

- The **EU communication on Industrial Carbon Management** recognises the need to accurately reflect the climate impact of CCU applications in the development of a framework for ensuring the environmental integrity of products made from captured carbon feedstocks. This is also emphasised through *Guiding Principle III*.
- The **policy framework on biobased, biodegradable and compostable plastics** recommends producers to prioritise the use of organic waste and by-products over virgin biomass, which is consistent with *Guiding principle V*. Where virgin biomass is used, the biomass should be environmentally sustainable and avoid any harm biodiversity or ecosystem health, in line with *Guiding principle IV*.
- The **EU Biodiversity Strategy** encourage sustainable harvest of biomass from the land and sea to capture and store carbon, if there is a clear re-harvesting and restoring plan for the used biomass. This aligns with *Guiding principles IV* to avoid biodiversity loss. The EU Biodiversity Strategy also recognises the potential of marine biomass as a promising source of environmentally sustainable biogenic carbon, in line with *Guiding principles IV and V*, with algae are recognised as a go-to feedstock for sustainable industrial applications.
- The **WFD** brings forwards "waste hierarchy" for managing waste prioritising prevention, preparation for reuse, recycling, energy recovery and lastly disposal. This aligns with *Guiding principle VI*, where reuse and recycling are prioritised over incineration for energy and landfill disposal.

The guidance and criteria on environmental sustainability that the EU is working on can help with the development of a future sustainability framework for RRC feedstocks, but additional research will be needed. As part of the Sustainable Product Initiative and the ESPR, the EU is in the process of establishing requirements on environmental sustainability for products. Similar activities are taking place under the PPWR, Industrial Carbon Management strategy and the EU bioeconomy strategy for the relevant RRC feedstocks and products these policies cover. The research and discussions taking place as part of these policy developments could serve as a basis for a framework for comparing and choosing RRC feedstocks for carbon-based chemicals. However, as the environmental criteria that are being developed are for specific products, additional research will be needed to ensure their applicability for RRC feedstocks.

Box 4 summarises the policy areas in the EU and US that require further attention to incentivise the availability and use of environmentally sustainable RRC feedstocks for carbon-based chemicals.

Box 4 Summary of policy areas in the EU and US that require further attention to incentivise the availability and use of environmentally sustainable RRC feedstocks for carbon-based chemicals

The analysis of the policy landscape in the EU and the US shows that there is a general recognition on the need to replace fossil-based products with ones made from environmentally sustainable RRC sources. However, there are various policy areas where incentives to promote the availability and use of environmentally sustainable RRC feedstocks are lacking or where other policy incentives are hindering their availability or use.

Policy areas in both the EU and US that need further attention are:

- **Competition for RRC resources:** existing policy incentives in the EU and US for using RRC sources for energy and fuel production reduce their availability for use in other sectors, including as feedstock for chemicals.
- **Lack of recognition for chemical recycling:** chemically recycled waste does not count towards the recycling targets in the EU and in some US states, which hinders its development as a technology for obtaining RRC feedstocks.
- **Lack of RRC targets and/or minimum requirements:** minimum requirements on RRC content in products in the EU are limited to recycled content so far, and such targets or requirements are even largely absent in the US.
- **Lack of financial incentives for using RRC feedstocks:** there are no financial incentives for using RRC feedstocks in the EU, and their use is disincentivised if they lead to higher direct GHG emissions compared to using fossil-based feedstocks, even if the overall lifecycle emissions would be lower. In the US, these financial incentives are limited to the use of captured carbon feedstocks and via public procurement.

Specifically in the EU, the following policy aspects also need to be addressed:

- **Additional administrative burden for end-of-life materials as chemical feedstocks:** criteria are yet to developed for when end-of-life material stops being waste and start becoming a chemical feedstock, which leads to an additional administrative burden.
- **Issues hindering the use of environmentally sustainable biogenic carbon feedstock:** the PEF, the main assessment method for environmental sustainability proposed in the EU, does not yet take into account the impact of products on biodiversity. It also lacks the incentive for manufacturers to choose biogenic carbon feedstocks over fossil-based ones, and for products made biogenic materials to be reused or recycled.

Finally, a **comprehensive policy strategy to ensure the environmental sustainability of RRC feedstocks is lacking** in both the EU and US. The EU has set an aspirational target for at least 20% of carbon used in chemical and plastic products to be from sustainable non-fossil sources by 2030. A wide range of different policy measures are being developed to achieve this, but a comprehensive strategy where these policy efforts are consolidated still absent. In the US, such aspirational targets or strategy to safeguard the environmental sustainability of RRC feedstocks is even completely absent; most US policy incentives for RRC feedstocks have no or limited requirements on environmental sustainability.

5. Looking ahead

Achieving climate neutrality and a circular economy requires addressing both energy and materials systems. So far, the attention of the public and private sector has primarily been on the decarbonisation of energy systems. The next frontier in the path towards a sustainable and circular economy is to mitigate the negative impacts of material systems by dramatically reducing their reliance on fossil resources. For the chemical sector, RRC feedstocks can substitute ones derived from fossil resources, but their environmental impacts need to be actively managed to ensure their alignment with a sustainable circular economy.

The guiding principles in this paper are a first step towards establishing a comprehensive and robust framework to ensure the environmental sustainability of RRC feedstocks for carbon-based chemicals. Using public reports and studies from literature, only high-level guiding principles for the three main RRC feedstock types (biogenic, end-of-life and capture carbon) could be formulated. However, the environmental impacts can also vary significantly within a certain RRC feedstock type. Key determinants include the geography from which they are sourced, the maturity of the technology used for processing them into feedstocks, and the availability of low-carbon energy. Therefore, the environmental sustainability of a particular RRC feedstock needs to be assessed on a case-by-case basis. This requires more technical guidance to be developed to ensure such assessment is done in a consistent manner.

Various issues and barriers have been identified in this paper that need to be tackled for establishing a sustainability framework. The main ones can be summarised as follows:

- **Standardised LCA methods:** the LCA results from literature of different RRC feedstocks, where this was available, was found to be largely incomparable due to different LCA methodologies used, assumptions made and system boundary definitions. A framework therefore needs to be accompanied with technical guidance to standardise LCA assessments for robust and verifiable results. The EU has advanced most in this area with the Product Environmental Footprint method, but this method was found to be lacking for incentivising the use of environmentally sustainable biogenic carbon feedstocks.
- **Recognition of chemical recycling:** while chemical recycling is not yet widely recognised as a method to meet targets on recycling or recycled content in a product, it can be a valuable option when reuse and mechanical recycling are not feasible. While there are still uncertainties about the environmental benefits of chemical recycling, the guiding principles in this paper can help safeguard the environmental sustainability of feedstocks made from chemical recycling.
- **Harmonised indicator for biodiversity loss:** currently, there is no consistent or harmonised LCA methodology to determine the environmental impact on biodiversity. However, biodiversity is one of the key determinants for the environmental sustainability of biogenic carbon feedstock.
- **Further research in marine biomass:** marine biomass has been identified as a promising source for environmentally sustainable biogenic carbon feedstock. It avoids two key detrimental environmental impacts from virgin biomass from land: land-use change and deforestation. In addition, it can grow much faster than land-

based biomass. However, the impact of marine biomass cultivation on the marine carbon cycle is not yet fully understood and requires further research.

- **Further policy support and recognition**: while there is a general recognition on the need to replace fossil-based products with ones made from environmentally sustainable RRC sources, a comprehensive policy strategy to achieve this is still lacking. Steps are being taken in the EU to shape such an approach with the Sustainable Products Initiative from the product side, but a coherent strategy on the feedstock side is yet to be developed. In the US, these developments are even completely absent. Moreover, there are also aspects in the EU and the US policies that could hinder the development and use of RRC feedstocks for chemicals, particularly incentives to use RRC sources for energy or fuel production.

Such a sustainability framework could be supported by a separate product classification for chemicals made from environmentally sustainable RRC feedstocks to distinguish them from their fossil-based equivalent. Product classifications are based on the characteristics of a product instead of how it is made or the feedstocks that were used to make it. In the case of drop-in chemicals, products made from RRC feedstock are chemically identical to their fossil-based equivalent and would be classified as the same product. Separating chemicals made from RRC feedstock and virgin fossil fuels allows for a clearer distinction between fossil and non-fossil products, which can help incentivise the uptake of RRC feedstock. Such a classification could even include a scoring or new colour-coding system as an indicator for their environmental sustainability performance.

Ultimately, a framework for environmentally sustainable RRC feedstocks for carbon-based chemicals will need to go beyond the drop-in pathway discussed in this paper. This will require analysing the environmental impacts of RRC feedstocks in the use and disposal phase of a product to capture its entire lifecycle. Aspects that will play a role include the longevity and fate of the carbon molecule as well as the recyclability, compostability and (bio)degradability of a product. These environmental impacts not only need to be compared to the virgin fossil equivalent but also to products from other sectors that have the same functionality as the chemical product. Establishing such a comprehensive and consistent framework will require further research to strengthen the evidence base on the environmental impacts of different RRC feedstocks throughout their entire lifecycle. It will also require ensuring alignment of public policy incentives with such a framework to drive the availability and use of environmentally sustainable RRC feedstocks. This should ideally be done in internationally harmonised manner to ensure a consistent incentive for adopting environmentally sustainable RRC feedstocks, accelerating the transition to a global circular economy.

Annex

This Annex contains key public policies and strategies across the EU and the US relevant to the availability and use of RRC feedstocks for carbon-based chemicals and their environmental sustainability up to 31 January 2025. These policies and strategies have been identified based on desk-based research and input from the participating companies.

A.1 Key EU policies and strategies

Since the adoption of the EU Circular Economy Action Plan (CEAP) in 2020 and the European Green Deal (EGD) in 2021, RRC feedstocks are featured much more prominent in EU polices and strategies. The CEAP announced policy initiatives along the entire life cycle of products. This ranges from how products are designed to encouraging sustainable consumption and preventing waste to keep resources in the EU economy for as long as possible. The CEAP is one of the main building blocks for the EGD, a set of policy initiatives to make the EU climate neutral by 2050. In both the CEAP and EGD, RRC feedstocks are recognised as an important component for the transition to a circular and climate neutral economy.

The EU has a wide range of public policies and strategies that affect the availability and use of RRC feedstocks and their environmental sustainability. Some of these policies are relevant to all types of RRC feedstocks, whereas others are only relevant to specific sources. In addition, some policies provide direct incentives for RRC feedstocks through e.g. specific targets for renewable or recycled content in products. Other policies indirectly support the availability or use of RRC through research funding or making alternative use of RRC sources (e.g. for energy or fuels) less appealing. Finally, some policies aim to ensure that the RRC feedstocks used is environmentally sustainable in line with the guiding principles of this paper.

Table 2 provides an overview of the identified policies in the EU and an indication whether they include incentives for the availability and/or use of (environmentally sustainable) RRC feedstocks in green, disincentives or gaps in red, or a mix both incentives and misalignments/disincentives in yellow.

Table 2 Relevant EU policies and strategies for each RRC feedstock type

EU policy or strategy	Relevance for the RRC feedstock type		
	Biogenic	End-of-life	Captured
Sustainable Products Initiative	✓ (yellow)	✓ (green)	✓ (green)
EU Communication on Sustainable Carbon Cycles	✓ (green)	✓ (green)	✓ (green)
EU Communication on Industrial Carbon Management			✓ (green)
EU Emissions Trading System	✓ (yellow)	✓ (yellow)	✓ (yellow)
Carbon Border Adjustment Mechanism	✓ (yellow)	✓ (red)	✓ (red)
Renewable Energy Directive	✓ (yellow)		✓ (yellow)
Policy framework on biobased, biodegradable and compostable plastics	✓ (green)		

EU policy or strategy	Relevance for the RRC feedstock type		
	Biogenic	End-of-life	Captured
EU Bioeconomy Strategy	✓		
Land Use, Land-use Change and Forestry Regulation	✓		
EU Biodiversity Strategy	✓		
Waste Framework Directive		✓	
Waste Shipment Regulation		✓	
Single Use Plastic Directive		✓	
Plastic Levy		✓	
Packaging and Packaging Waste legislation	✓	✓	
Horizon Europe	✓	✓	✓
Taxonomy Regulation	✓	✓	✓
Fertilising Products Regulation	✓		

A.1.1 Sustainable Products Initiative

The Sustainable Product Initiative (SPI) is the main legislative framework to improve the environmental sustainability and circularity of products placed on the EU market. At the centre of the SPI is the Ecodesign for Sustainable Product Regulation (ESPR) which entered into force in July 2024.[106] ESPR extends the existing Ecodesign framework to set product-level requirements that promote energy and material efficiency and circularity, with a reduction of the environmental footprint as a result. ESPR further enables the setting of mandatory green public procurement criteria, introduces digital product passports, and prevents the destruction of unsold durable consumer goods. Other relevant policies proposed under the SPI include rules for consumers to be better informed about the environmental sustainability of products, the EU Strategy for Sustainable and Circular Textiles, the revision of the Construction Products Regulation and an upcoming Green Claims Directive.[107]. All these policies are, however, yet to be adopted into law.

The SPI, and particularly the ESPR, has the potential to boost the use of environmentally sustainable RRC in products. The SPI and ESPR contain various elements to incentive the use of RRC, although all these elements will still need to be worked out in further legislation:

- **Recycled content in products:** the ESPR enables the setting of minimum requirements for the recycled content in products. This could incentive the use of feedstocks from end-of-life carbon, and potentially even captured carbon if that would be covered under "recycled content".
- **Ease and quality of recycling:** similarly, the ESPR enables requirements to be set on products that can improve the ease of recycling and/or the quality of the resulting recyclate. This could increase the availability of high-quality end-of-life feedstocks from recycling.

[106] *European Commission (2024). Ecodesign for Sustainable Products Regulation.*
[107] *European Commission (2025). Green claims.*

- **Products' carbon and environmental footprints:** the ESPR also enables the EU to set requirements on the maximum carbon and/or environmental footprint that products can have. Manufacturers are required to minimise the carbon footprint of their products and reduce GHG emissions by making informed choices regarding materials, production methods, logistics, and other related processes. The requirements could be set in a way that only products made from environmentally sustainable RRC feedstocks meet the criteria.
- **Digital product passports:** the digital product passports intend to improve the information on the environmental sustainability of products. Complemented by the upcoming Green Claims Directive, this enables consumers and businesses to make better informed choices when purchasing products. This could include choosing products made from environmentally sustainable RRC sources.
- **Green public procurement:** the ESPR enables public entities to set mandatory criteria on the environmental sustainability of products they procure. This could increase demand for products made from environmentally sustainable RRC sources.

Potential misalignments with the guiding principles relate to the proposed method for environmental footprinting under the SPI framework, the Product Environmental Footprint (PEF). The EU's PEF method is central to determining the environmental sustainability of products in the proposed policies under SPI. However, there are a few issues under the PEF that could hamper the use of environmentally sustainable biogenic carbon feedstock:

- **Biodiversity:** the PEF does not (yet) consider the impact on biodiversity of products,[108] which is a key determinant for the environmental sustainability of biogenic feedstocks from virgin biomass as per *Guiding principle IV*.
- **Biogenic carbon:** carbon emissions from biogenic materials are considered zero at every lifecycle stage under the PEF. When the environmental sustainability of products from a producer is determined up to the stage the product is put on the market (cradle-to-gate), the climate benefits from using biogenic carbon feedstocks would not be accounted for (see Box 3). This would not incentivise the choice for biogenic carbon feedstocks if all impacts related to the use of biogenic and virgin fossil feedstocks in production are the same.

A.1.2 EU communication on Sustainable Carbon Cycles

The EU communication on Sustainable Carbon Cycles[109] focuses on providing support for establishing sustainable and climate resilient carbon cycles. Key actions identified in the communication are reducing the EU's economy reliance on carbon, substituting fossil carbon in sectors that cannot be decarbonised by recycled carbon from waste streams, sustainable biomass or captured from the atmosphere as well as on upscaling carbon removal solutions.

Several elements of the communication provide relevant incentives for the use of renewable and recycled carbon feedstock. These include:

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[108] *Pederson and Remmen (2022). Challenges with product environmental footprint: a systematic review.*
[109] *EC (2021). Sustainable Carbon Cycles.*

- **Introducing reporting and accounting of the origin of embedded carbon in products:** The communication introduced the Industrial Sustainable Carbon challenge under which any tonne of CO_2 captured, transported, used and stored should be reported and accounted by its fossil, biogenic or atmospheric origin by 2028. This measure could provide incentives for the use of RRC feedstocks by making it easier to account for and potentially, in the future, certify products made from renewable or recycled carbon. This could potentially build on the newly adopted **Carbon Removals and Carbon Farming (CRCF) Regulation**,[110] a key legislation stemming from the communication. This is an EU-wide voluntary framework to certify permanent carbon removals, carbon farming and soil emission reductions, and carbon storage in long-lasting products. The CRCF Regulation currently does not foresee covering the use of RRC in chemical products. Nonetheless, a future legislation for accounting the origin of embedded carbon in products could potentially build on the certification methods developed under this legislation.
- **Targets for non-fossil based carbon used in chemicals and plastics:** Under the same industrial challenge, at least 20% of carbon used in the chemical and plastic products should be from sustainable non-fossil sources by 2030. This aspirational target will incentivise the use of RRCs as feedstocks for chemicals and plastics.
- **Support for developing infrastructure required for developing a CCU market:** The communication also incentivises the development of the necessary infrastructure for wide-spread deployment of CCU (and CCS) by launching a study on the development of CO_2 transport networks and reemphasising support for deploying CCUS technologies at scale. This is being operationalised through the **Industrial Carbon Management** strategy (see A.1.3), which can help increase the availability of environmentally sustainable captured carbon feedstock.
- **Support for developing methodologies to assess EU bio-economy land-use:** It highlights the need for ensuring consistency across national and EU policies and targets in this area and commits to providing technical assistance to Member States to carry out national assessments. This supports the reliability and verifiability of the environmentally sustainable biogenic carbon feedstock.

A.1.3 EU communication on Industrial Carbon Management

The EU communication on Industrial Carbon Management presents a strategy to scale up carbon management in the EU industry. The communication identifies a set of actions to be taken to establish a single market for CO_2 in EU and to create a more attractive environment for investments in industrial carbon management technologies. The aim of these actions is to support hard-to-abate sectors that need to apply CCS, CCU or industrial carbon removal to become climate neutral. Particularly, the communication recognises that the use of captured carbon to replace fossil fuels as a feedstock can contribute to emission reduction, energy security and autonomy of the EU.

The communication envisages establishing a framework to reflect the climate benefits across all industrial carbon management activities, which includes captured carbon feedstocks. The communication indicates that the benefits of CCU technologies is not yet

[110] *EU (2024). Carbon Removals and Carbon Farming Regulation.*

fully recognised or sufficiently available. A framework for CCU is therefore envisaged to tracks the source, transport and use of the captured CO_2 to ensure its environmental integrity. The framework should also create a price incentive that accurately reflects the climate benefit of a solution across the industrial carbon management value chain. This includes taking into account the energy consumption to power the energy-intensive processes of CCU applications as an alternative to a fossil-based product (in line with *Guiding Principle III)*. Such a framework could help safeguard the environmental sustainability of feedstocks from captured CO_2 and incentivise their demand.

A.1.4 EU Emissions Trading System

The EU Emissions Trading System (ETS) is a cornerstone of EU climate policy to reduce GHG emissions from large emitters in a cost-effective manner. The EU ETS is a cap-and-trade system covering the power, manufacturing, aviation and maritime sectors.[111] Large emitters in these sectors must surrender emission allowances for the GHGs that they emit directly, i.e., from their own fuel consumption and production processes. These allowances can be bought from auctions or other entities in the EU ETS. Emitters that are exposed to a significant risk of carbon leakage receive (some) allowances for free.[112]

There is no direct incentive under the EU ETS to use environmentally sustainable RRC feedstocks and it even indirectly hinders the application of some RRC feedstocks. These all relate to the emissions coverage of the EU ETS:

- **Direct GHG emissions only:** ETS-emitters only have to surrender allowances based on their direct emissions. Climate impacts such as end-of-life emissions and other environmental factors associated with feedstocks used are not considered. The EU ETS therefore does not incentivise manufacturers to use RRC feedstocks if it does not lead to reductions of direct GHG emissions compared to using virgin fossil feedstocks. On the contrary, manufacturers are disincentivised to use RRC feedstocks under the EU ETS if it leads to higher direct GHG emissions, even if the overall lifecycle emissions would be lower.
- **No emissions from municipal waste incineration and landfill:** incineration of municipal waste is currently exempted from the EU ETS and landfill emissions are not covered under the EU ETS. In contrast, ETS-emitters have to surrender emission allowances for direct GHG emissions associated with the reuse and recycling of end-of-life materials. This particularly discourages the chemical recycling of waste, an energy-intensive process, compared to incineration and landfill. The EU ETS Directive includes provisions for considering the ETS-inclusion of municipal waste incineration and other waste management processes such as landfill, but only from 2028 at the earliest.
- **Biomass emissions as zero:** emissions from biomass that meet the sustainability and GHG emission saving criteria of the *Renewable Energy Directive* are considered zero under the EU ETS. ETS-emitters do not have to surrender allowances for these emissions and therefore have a financial incentivise to use such biomass as a fuel.

[111] *Additionally, the EU has a separate ETS, commonly referred to as ETS2, that covers CO_2 emissions from fossil fuels consumed in the sectors buildings, road transport and several additional sectors not covered under the EU ETS.*
[112] *Carbon leakage refers to when an emissions reduction policy inadvertently causes an increase in emissions in other jurisdictions that do not have equivalent emissions reduction policies.*

This competes with the biomass demand for RRC feedstocks, for which their use is not incentivised under the EU ETS.

The EU ETS does contain a few incentives for the development of RRC feedstocks, but not all have provisions for safeguarding the environmental sustainability of RRC feedstocks. The incentives are provided through:

- **The Innovation Fund:** this programme provides grants for the demonstration of innovative low-carbon technologies.[113] This includes demonstration projects on CCU and substitutes to carbon-intensive projects such as ones made from RRC feedstocks. If biomass is used in the projects, it needs to meet the sustainability criteria of the *Renewable Energy Directive* and originate from feedstocks with a low risk of causing indirect land-use change. This aligns with the guiding principles in this paper.
- **CCU provisions:** in the current EU ETS, companies also have to surrender emission allowances for CO_2 that is captured and used to make products, with only precipitated calcium carbonate production exempted. More CCU applications are being considered for an exemption where the captured carbon is permanently chemically bound in a product and the carbon does not enter the atmosphere under normal use. In the draft regulation for determining products meeting these requirements, so far only mineral carbonates used in certain construction products have been specified.[114] Expanding the list to more products could bolster the case for feedstocks from captured carbon. The CCU provisions currently do not include any safeguards to ensure their environmental sustainability.

A.1.5 Carbon Border Adjustment Mechanism

The EU Carbon Border Adjustment Mechanism (CBAM) is a new climate measure to prevent the risk of carbon leakage by pricing embedded GHG emissions of imported products. Under the CBAM, importers of products manufactured outside of the EU have to buy certificates for the embedded GHG emissions associated with the manufacturing of those products. The price of these certificates mirrors the price of emission allowances under the EU ETS. The products currently covered under the CBAM belong to the sectors iron and steel, cement, fertiliser, aluminium, hydrogen and electricity generation.[115] The transitional period of the CBAM is from 1 October 2023 until 31 December 2025, during which importers only have to report the embedded emissions of imported products covered under the CBAM. From 1 January 2026, importers will also have to purchase and surrender certificates for the embedded emissions of these goods.

The CBAM is currently limited in the environmental impacts priced and does not incentivise the use of environmentally sustainable RRC sources for most imported products. For imported iron and steel, aluminium, hydrogen and electricity products, the CBAM will only price the direct GHG emissions associated with the production of these goods. For fertilisers and cement, the CBAM will price both direct GHG emissions and indirect CO_2 emissions related to the electricity consumed for producing the covered

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[113] European Commission (2025). What is the Innovation Fund?

[114] European Commission (2024). Annex to the Commission Delegated Regulation supplementing the EU ETS Directive regards the requirements for considering that greenhouse gases have become permanently chemically bound in a product.

[115] European Commission (2023). CBAM Regulation.

goods. The CBAM also covers various downstream products such as steel screws and drums and aluminium tubes. For these products, the CBAM only covers the emissions related to manufacturing of the crude steel or aluminium that are also covered under the CBAM. Other climate impacts such as end-of-life emissions and other environmental factors associated with feedstocks use are not taken into account. The only exception is ammonia, where emissions stemming from the use of sustainable biogas or biomass as feedstock can be considered as zero.[116] At the same time, the use of sustainable biomass as a fuel is also incentivised under the CBAM by considering it as zero rated and thus directly competing with biomass demand for RRC feedstocks.

As the CBAM continues to evolve, it could potentially incentivise manufacturers of products imported into the EU to use environmentally sustainable RRC sources in the future. The CBAM Regulation includes a future mandate for the European Commission to develop methods of calculating embedded emissions based on environmental footprint methods. This could include extending the scope of the CBAM to embedded emissions associated with the feedstocks used for manufacturing products imported into the EU. However, the coverage of the CBAM is currently limited to GHG emissions and would need to be expanded to other environmental factors to be able to fully incentivise the use of environmentally sustainable RRC sources.

A.1.6 Renewable Energy Directive

The Renewable Energy Directive (RED) is the legal framework for the development of renewable energy across all economic sectors of the EU. The RED was revised in 2023 and entered into forced in November 2023. The current version of the directive specifies a binding renewable energy target for the EU for 2030 of at least 42.5%, with an aspiration to reach 45%.[117] The revised RED includes rules to ensure the uptake of renewable energy. This is required to support the availability of captured carbon feedstocks from low-carbon energy as discussed under *Guidance Principle III*. It also specifies sustainability criteria for biomass.

The revised RED includes a focus on Renewable Fuels of Non-Biological Origin (RFNBOs), which could decrease the availability of captured carbon feedstocks from low-carbon energy for chemicals. RFNBOs refer to synthetic fuels generated from captured CO_2 and hydrogen using renewable energy not from biomass. They therefore directly compete with captured carbon feedstock for chemicals. The RED revision sets a target for RFNBOs in the transport sector of at least 1% by 2030. In addition to the revised RED, regulations for the aviation and maritime sectors also promote the use of RFNBOs.[118] The incentives to use captured carbon feedstock from low-carbon energy for fuel would reduce its availability for use in other sectors including for chemicals.

The sustainability criteria for biomass use in RED can inform the development of sustainability requirements for biomass as a feedstock. The sustainability criteria for bioenergy will, on the one hand, increase the demand for environmentally sustainable

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[116] Biogas or biomass used need the sustainability and GHG emission saving criteria of the Renewable Energy Directive to be considered zero rated. European Commission (2024). CBAM Implementation Regulation during the transitional period.

[117] European Commission (2023). Revised Renewable Energy Directive.

[118] ReFuelEU Aviation set a minimum binding target for aviation fuel suppliers per volume share for RFNBOs of 0.7% by 203, with the share increasing to 10% in 2040 and 35% by 2050. FuelEU Maritime sets binding GHG reduction targets for ships of 2% in 2025, 6% in 2030, 31% in 2040 and 80% in 2050 and allows RFNBOs to reach these targets.

biomass for energy, decreasing its availability for feedstock. On the other hand, the sustainability criteria for biomass under the RED can serve as a starting point to develop sustainability criteria for biogenic carbon feedstocks for chemicals.

A.1.7 Policy framework on biobased, biodegradable and compostable plastics

The policy framework on biobased, biodegradable and compostable plastics sets out the conditions to ensure the environmental impact of their production and consumption is positive. The policy framework aims to clarify under what conditions plastics should be considered biobased, biodegradable and/or compostable. This should help future EU policy developments where these plastics are relevant to have consistent definitions. It also aims to reduce the confusion of consumers with regards to the terminology used.

The policy framework indirectly encourages the use of environmentally sustainability biogenic carbon feedstocks in plastics. The framework recommends that any products labelled biobased should only refer to their exact and measurable share of biogenic material. It also recommends producers to prioritise the use of organic waste and by-products over virgin biomass, which is consistent with *Guiding principle V*. Where virgin biomass is used, the biomass should be environmentally sustainable and avoid any harm biodiversity or ecosystem health, in line with *Guiding principle IV*. Although the policy framework does not set these recommendations into law, it provides the direction EU policy is moving towards, which helps incentivise the use of environmentally sustainable biogenic feedstocks in plastics.

A.1.8 EU Bioeconomy Strategy

The EU bioeconomy strategy aims to strengthen and scale up the bio-based sector, usage of biomass feedstocks and ensure its environmental sustainability.[119] Under the strategy, standardised assessment methods for products are to be developed and financing is provided for research and development of fossil-free products. This includes providing investment through launching a €100 million circular bioeconomy thematic investment platform and markets through the analysis of enablers and deployment of biobased innovations. It also includes promoting and developing standards and substitutes to fossil-based materials that are biobased, recyclable and marine biodegradable. The strategy aims to create value-added products out of residual biomasses like crop residues, industrial side-streams, and food waste, as well as discarded aquatic/marine animals and resources to fully realise the potential of all forms of sustainably derived biomass.

While the strategy will help promote the availability and use of environmentally sustainable biogenic feedstock, the use of the PEF as the key assessment method may hinder this development. As explained under the *Sustainable Products Initiative*, the PEF does not provide producers with an incentive to switch from virgin fossil feedstocks to biogenic carbon feedstocks as the climate benefits from biomass are not credited to the feedstock choice. In addition, the PEF does not yet account for biodiversity impacts yet.

[119] *EU (2018). EU Bioeconomy Strategy.*

A.1.9 Land Use, Land-use Change and Forestry Regulation

The Land Use, Land-use Change and Forestry (LULUCF) Regulation sets binding climate commitments in the LULUCF sector for each EU Member State.[120] The sector covers the use of soils, trees, plants, biomass and timber that are responsible for emitting and absorbing CO_2 from the atmosphere. The regulation aims to incentivise EU Member States to decrease GHG emissions and increase carbon removals from land-based activities. The regulation tries to strike a balance between more incentives to capture carbon in agricultural soils, forests, and wetlands and the need to maintain land use intact.

The LULUCF Regulation indirectly improves the availability of forestry for biogenic carbon feedstocks by accounting emissions of biomass used for energy towards a Member States climate commitment.[121] Previously, emissions from biomass for energy use were not accounted for in EU law and considered net zero. With the LULUCF Regulation, biomass emissions from energy use do not count as zero by default anymore for the 2030 target and will be accounted for at Member State level. This may incentivise Member States to implement policies to disincentivise the use of forest for energy, resulting in improved availability of biogenic carbon feedstocks for materials.

A.1.10 EU Biodiversity Strategy

The EU Biodiversity strategy aims to put biodiversity on the path to recovery while recognising the usage of biomass sustainably within ecological limits.[122] The strategy establishes binding targets for EU countries to restore damaged ecosystems and rivers, improve the health of protected habitats and species, bring back pollinators to agricultural land, reduce pollution, green cities, enhance organic farming and other biodiversity-friendly farming practices, and improve the health of European forests. The EU Biodiversity Strategy also emphasises the restoration of primary and old-growth forests, which are critical for biodiversity and carbon sequestration. The strategy includes mapping and monitoring these forests to ensure their protection, aligning with broader EU climate goals, such as achieving net-zero emissions by 2050. This includes a target to protect at least 30% of the EU's land area and 30% of its seas, focussed on areas of very high biodiversity value or potential. The strategy does encourage sustainable harvest of biomass from the land and sea to capture and store carbon, if there is a clear re-harvesting and restoring plan for the used biomass. This aligns with *Guiding principle IV* to avoid biodiversity loss.

The EU Biodiversity strategy encouraging costs of environmental externalities, including biodiversity loss, to be reflected in national tax systems, which could enhance the use of environmentally sustainable biogenic feedstock. This implies that polluters should carry the responsibility and pay for their production's negative environmental externality. This could disincentivise the use of virgin fossil feedstocks and incentivise environmentally sustainable RRC feedstocks use.

The EU Biodiversity strategy also recognises the potential of marine biomass as a promising source of environmentally sustainable biogenic carbon. The policy supports the restoration of carbon-rich marine habitats while incentivising the usage and cultivation

[120] EU (2023). Land use and forestry regulation
[121] EU (2023). Regulation (EU) 2023/839 amending the Land use and forestry regulation.
[122] EU (2020). Biodiversity Strategy.

of algae in marine and coastal ecosystems; as long as the marine interventions are aligned with the biodiversity protection in marine biodiversity hotspots. This is in line with *Guiding principles IV and V*. Within this strategy, algae are recognised as a go-to feedstock for sustainable industrial applications, as its production helps improve marine health by reducing CO_2 and nitrogen. Algae are also recognised to provide habitat and nursery for marine animals promoting underwater biodiversity.

A.1.11 Waste Framework Directive

The Waste Framework Directive (WFD) constitutes the basic principles for waste management within the EU. It brings forwards "waste hierarchy" for managing waste prioritising prevention, preparation for reuse, recycling, energy recovery and lastly disposal. This is consistent with *Guiding principle VI*, where reuse and mechanical recycling are prioritised over incineration and landfill. An amendment was proposed to the WFD in 2023 mainly to emphasise the need to tackle waste of textile, footwear and food.[123]

The WFD includes targets for reuse and recycling, which helps increase the availability of end-of-life carbon material for feedstock use. This includes targets for household waste, non-hazardous construction and demolition waste and municipal waste with increasing ambitions over 2020, 2025, 2030 and 2035.[124] It also introduces the "extended producer responsibility". This entails that manufacturers of products become responsible for their products over the entire lifecycle, and importantly, they must pay for the end-of-life management. The recycling targets and the extended producer responsibility enhance recycling, increasing the availability of end-of-life carbon material.

Chemical recycling is not yet acknowledged in the waste hierarchy of the WFD and does not count towards recycling targets, which hinders the development of feedstocks from chemical recycling. Mechanical recycling is currently implicitly the only recycling methodology recognised in the WFD. The recognition of chemical recycling as viable recycling option is still heavily debated in the EU.[125] Therefore, chemical recycling of waste does not count towards the recycling targets at this moment and the WFD does not provide any incentives to develop and deploy chemical recycling. However, the 2023 proposed amendments to the WFD specifically focus on fibre-to-fibre recycling for textiles. This could open the door for the recognition of chemical recycling as a recycling method under the WFD, since fibre-to-fibre recycling cover both mechanical and chemical recycling methods. Recognition of chemical recycling, next to mechanical recycling, would be necessary to increase the recycling rate. This is especially important for processing mixed plastic waste to produce high quality feedstocks suitable for making contact-sensitive products such as food wraps, which is difficult to achieve with mechanical recycling.

The development of waste as a feedstock source is further hindered by the uncertainty when a recycled carbon feedstock stops being waste and becomes a feedstock. The end-of-waste criteria under the WFD specify under which criteria end-of-life materials cease to be considered as waste and start becoming a product or secondary raw material.

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[123] *EU (2023), Amending Directive 2008/98/EC on waste*

[124] *European Commission (2008). Waste Framework Directive.*

[125] *Zero waste Europe (2025). Chemical Recycling.*

These criteria have only been laid down for iron, steel and aluminium scrap, glass cullet and copper scrap. For waste that can be used as chemical feedstocks such as plastics, such criteria are yet to be developed. The proposed 2023 amendments prioritise expanding the end-of-waste criteria to waste streams related to textiles and footwear. As these waste streams contain materials such as rubber and synthetic fibres that can be used as recycled carbon feedstocks, this could set the basis for other waste streams suitable as chemical feedstocks. Materials meeting the end-of-waste criteria face less administrative burden.

A.1.12 Waste Shipments Regulation

The Waste Shipments Regulation (WSR) covers practically all types of waste shipped between EU countries, transiting through the EU, and imported or exported to the EU from non-EU countries. A revised WSR entered into force in May 2024, significantly updating the EU framework for waste shipments to address circular economy and environmental objectives.[126] The revised WSR now explicitly integrates the principles of the EU Green Deal, prioritising environmentally sound waste management practices and reducing the adverse impacts of waste shipments on human health and the environment. It also makes it easier for Member States to ship waste for recycling and reuse within the EU as well as from and to non-EU OECD countries.

The revised WSR includes various provisions that can help increase the availability of end-of-life material for feedstock in the EU. The revised WSR establishes pre-consented facilities for recycling operations to streamline intra-EU waste shipments to these facilities, reducing administrative burdens and ensuring timely processing of waste. In addition, a centralised digital waste tracking system is introduced to improve transparency, enhance monitoring, and facilitate real-time reporting of waste shipments across the EU. These provisions can facilitate recycling (and reuse) of waste such as mixed municipal waste and unsorted plastic waste across the EU, increasing end-of-life material available for chemical feedstocks.

The stricter measures on shipping of waste to non-EU countries further support the availability of end-of-life material for feedstock within the EU and safeguard their environmental sustainability. The revised WSR enables export of waste to non-EU OECD countries with insufficient waste management standards to be suspended. In addition, a general ban on the export of non-hazardous waste to non-OECD countries will come into effect in 2027, unless certain specific environmental conditions are met. This aims to ensure that such waste is processed under environmentally sound conditions equivalent to EU standards. These restrictions implicitly force EU countries to increase its recycling capacity, because the current recycling capacity within the EU is insufficient to meet the recycling targets under various EU legislations.[127] These restrictions on waste exports could therefore increase the availability of end-of-life carbon material for feedstock. In addition, they support *Guiding Principle II* as it will make it easier for the environmental benefits of utilising end-of-life materials to be verified.

The WSR does not recognise chemical recycling as recycling, which complicates intra-EU transport of plastic waste for chemical recycling. The WSR only facilitates intra-EU

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[126] *EU (2024), New Waste Shipment Regulation*

[127] *EEA (2019). The plastic waste trade in the circular economy.*

shipments of waste when these flows are destined for recycling as defined under the WFD. This means waste destined for chemical recycling is subject to similar stringent rules as waste for disposal, discouraging chemical recycling of waste. This, in turn, hinders the development of feedstocks from chemical recycling.

A.1.13 Single Use Plastic Directive

The Single Use Plastic (SUP) Directive provides for a progressive phase out of single use plastics, to be replaced by reusable products and systems. The SUP aims to reduce pollution from the resulting plastic waste commonly found in the environment. The scope of the directive is limited to 'single-use plastic product', which are products typically intended to be used just once or for a short period of time before being disposed. Examples of single use plastic products include food containers and boxes, beverage bottles, composite drink packaging, tobacco product filters, and caps and lids made of plastic.

The SUP specifies separate collection and design requirements for single use plastics, which supports the availability of recycled waste for feedstock and incentivises its use in plastic products. The SUP sets a collection target of 90% recycling for single use plastic bottles by 2029, with an interim target of 77% by 2025. The separate collection of waste plastic bottles will help decrease contamination and increase plastic waste suitable for mechanical recycling to be used as feedstock. Furthermore, single use plastic bottles need to contain at least 30% recycled content by 2030 and any caps or lids need to be attached to the bottle. This will increase the demand for feedstocks from recycled plastic waste.

A.1.14 Plastic Levy

The EU Plastic levy is a financial contribution that Member States have to make to the EU budget based on their non-recycled plastic packaging waste, indirectly incentivising recycling of plastic packaging waste. A uniform call rate of € 0.80/kg is applied to the weight of plastic packaging waste that is not recycled.[128] Individual Member States are left to establish their own regulatory measures to cover this cost. The levy financially incentivises EU Member States to take measures to reduce their plastic packaging waste or increase the recycling of it. This could increase availability of end-of-life material for feedstock.

A.1.15 Packaging and Packaging Waste Regulation

The Packaging and Packaging Waste Regulation (PPWR) aims to ensure that all packaging on the EU market is reusable or recyclable in an economically viable way by 2030.[129] The PPWR was adopted in December 2024, replacing the Packaging Directive. The PPWR establishes the requirements for the entire life-cycle of packaging regarding environmental sustainability and labelling for it be allowed on the EU market. It also regulates packaging waste management and prevention measures. This is done through measures harmonising packaging labelling, preventing packaging waste, and establishing targets for reuse, refill, and recycling, as well as requirements for recycled content in packaging. It also bans several single-use packaging formats that contribute to waste generation.

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[128] *EU (2020). Plastics own resource.*

[129] *EU (2024), Packaging and Packaging Waste Amending Regulation.*

The PPWR targets for recycled material content for plastic packaging directly incentivises the uptake of recycled carbon feedstock, with opportunities for chemical recycling. The PPWR dictates that each unit of packaging that contains a plastic part would be required to include a certain percentage of recycled content recovered from post-consumer plastic waste for it to be allowed on the EU market. Targets for recycled content in products go up to 35% in 2030 and 65% in 2040 depending on the type of plastic packaging product, incentivising the use of end-of-life carbon feedstock. This includes contact-sensitive plastic packaging, such as for food. These targets may pose challenges for contact-sensitive plastic packaging if feedstocks from chemical recycling would not be taken into account in the recycled content; plastic from mechanical recycling may not be able to meet the required health standards for contact-sensitive plastic packaging.

The PPWR also mandates the development of sustainability criteria for biogenic feedstock and recycled material used in plastic packaging. The PPWR recognises that safeguards are needed to ensure that the way in which recycled content is obtained, does not cancel out the environmental benefits of using such recycled content in plastic packaging, which is in line with *Guiding principle II*. The PPWR therefore requires the European Commission to develop sustainability criteria for plastic recycling technologies and biobased feedstock in plastic packaging. Once these criteria are in place, they will directly incentivise the availability and use of environmentally sustainable RRC feedstock in plastic packaging.

A.1.16 Horizon Europe

Horizon Europe is the EU's key funding programme for research and innovation, with several programmes that can help increase the availability of RRC feedstocks through research. The programme is composed of a strategic plan and underlying work programmes. Most relevant to research and innovation of RRC feedstocks is Pillar II: Global Challenges and European Industrial Competitiveness, the thematic clusters on 'Digital, Industry and Space', 'Climate, Energy and Mobility' and 'Food, Bioeconomy, Natural Resources, Agriculture and Environment'. Additionally, Horizon Europe also funds CCU-related topics through individual programme calls.

Horizon Europe also encompasses partnerships between the EU and associated countries, the private sector, foundations and other stakeholders that could advance research in RRC feedstocks. These partnerships are focused on thematic areas to tackle global challenges and modernise industry. Specifically relevant partnerships include:

- **The Circular Bio-based Europe Joint Undertaking (CBE JU)**, which brings together various actors from bio-based industries and funds projects on producing renewable bio-based products and materials from waste and biomass in an innovative, sustainable and circular way.[130] The research topics under the CBE JU include 'food, feed, and cosmetics', 'bio-based polymers & plastics', 'bio-based chemicals' and 'market, policies & awareness' among other topics, which could advance the availability of environmentally sustainable biogenic carbon feedstock.
- **Processes4Planet**, which aim is to transform the European process industries to achieve circularity and overall climate neutrality at the EU level by 2050 while

[130] *CBE JU (2025). Circular Bio-based Europe Joint Undertaking.*

enhancing their global competitiveness.[131] The partnership supports, among others, the development and deployment sustainable circular solutions through technological and non-technological innovations and cross-sectoral collaboration. Strategic research and innovation themes include advancing the availability and environmental sustainability of captured and end-of-life carbon feedstocks.

A.1.17 Taxonomy Regulation

The EU Taxonomy Regulation establishes a framework to facilitate sustainable investment, which including criteria when to consider RRC feedstock use for chemicals environmentally sustainable. The EU Taxonomy Regulation aims to establish a common language and a clear definition of what is "environmentally sustainable" to direct investments towards specific sustainable projects and activities.[132] The most relevant criteria is that for renewable feedstock use in chemicals to be considered to substantial contribution to climate change mitigation, the life-cycle GHG emissions need to be lower than equivalent chemicals manufactured from fossil feedstocks, and independently verified (consistent with *Guiding Principle II*). For determining the lifecycle GHG emissions, the use of the PEF is recommended but alternative carbon footprinting methods approved in the regulation are also accepted. For the other environmental objectives of the EU Taxonomy Regulation, the regulation specifies that an environmental impact assessment or screening should be conducted on a case-by-base basis (in line with *Guiding Principle I)*.

A.1.18 Fertilising Products Regulation

The Fertilising Products Regulation (FPR) lays down rules on the manufacturing of fertilising products available in the EU, including fertilisers made from biogenic carbon feedstock. The latest revision of the FPR entered into force in November 2024, updating the framework to further align with circular economy principles and promote sustainable agricultural practices.[133] The FPR opens the markets for bio-based and waste-derived fertilising products which previously had not been covered by harmonisation rules, such as organic and organo-mineral fertilisers, soil improvers, inhibitors, plant biostimulants or growing media. This creates opportunities to replace synthetic components with biogenic alternatives and enhancing their sustainability.

The revised FPR promotes the use of renewable and recycled materials in fertilisers, supporting end-of-life organic materials as RRC feedstocks. The harmonised safety and quality standards in the FPR remove market barriers for fertilisers made with RRC feedstocks, ensuring their acceptance across the EU. Specifically, the end-of-waste criteria in the FPR enable waste-derived materials like biochar and struvite to be used as fertilising products once they meet safety standards, promoting the reuse of biogenic and recycled carbon. This aligns with circular economy goals by repurposing carbon-rich materials that would otherwise be discarded. Furthermore, the inclusion of plant biostimulants under the FPR supports the use of RRC feedstocks, such as bio-based additives, to enhance crop

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[131] *A.SPIRE (2022). About Processes4Planet.*

[132] *EU (2025). EU taxonomy for sustainable activities.*

[133] *EU (2024), Fertilising Products Regulation Consolidated Text*

resilience and nutrient efficiency. These measures enable a wider adoption of recycled carbon-based products in the fertiliser market.

A.2 Key US policies and strategies

There are only a limited number of US policies and strategies at the federal level relevant for the availability and use of RRC feedstocks. Most policies are related to funding research programmes or direct financial incentives to develop products made from RRC feedstocks. One set of state-level policies was highlighted by the participating companies as particularly relevant for this paper, which is also analysed.

Table 3 provides an overview of the identified policies in the US with an indication whether they include incentives for the availability and/or use of (environmentally sustainable) RRC feedstocks in green, or a mix both incentives and misalignments/disincentives in yellow.

Table 3 Relevant US policies and strategies for each RRC feedstock type

US policy or strategy	Relevance for the RRC feedstock type		
	Biogenic	End-of-life	Captured
National Biotechnology and Biomanufacturing Initiative	✓		
BioPreferred Program	✓		
National Recycling Strategy		✓	
Extended Producer Responsibility laws (state-level)		✓	
Carbon Conversion Program	✓		✓
US Section 45Q Tax Credit for Carbon Oxide Sequestration			✓

A.2.1 National Biotechnology and Biomanufacturing Initiative

The National Biotechnology and Biomanufacturing Initiative is a coordinated government approach to advance biotechnology and biomanufacturing, which includes initiatives to advance the use of biogenic feedstocks through research.[134] This includes providing financial assistance for specific research activities and large-scale financial incentives (financial investment) for the industry sector, including chemical industries. It aims to substitute fossil fuels with renewable biomass or bio-based raw materials in the production of energy, chemicals, and materials. It also aims to increase the efficiency of biomass use and reduce waste by supporting the advanced development of bio-based materials. For example, the Department of Energy provides up to US$100 million for R&D in conversion of biomass to fuels and chemicals, including to improve production and recycling of biobased plastics.

A.2.2 BioPreferred Program

The BioPreferred Program encourages the increased use of biobased products through federal procurement and voluntary labelling.[135] The BioPreferred Program was established in 2002 to increase the purchase and use of biobased products consisting of two parts. One part consists of mandatory purchasing requirements for federal agencies

[134] US Department of Energy (2022). *FACT SHEET: The U.S. Government Invests in Biotechnology and Biomanufacturing Innovation: Department of Energy*.
[135] USDA (2025). *What is the BioPreferred Program?*

and their contractors for biobased products, incentivising the demand for these products. The other part is voluntary labelling initiative for biobased products, which aims to make it easier for consumers to choose biobased products.

The BioPreferred Program was revised in 2024 to include renewable chemicals as biobased products, incentivising a stronger demand for chemicals made from biogenic feedstock.[136] Prior to the revision, renewable chemicals were separately defined as chemicals produced from renewable biomass and not included in the definition of biobased products. This resulted in ambiguities as the federal purchasing requirements and labelling initiatives only applied to biobased products, and may or may not have included chemicals. The inclusion of renewable chemicals in the definition of biobased products provided better clarity, which could incentivise the demand for chemicals made from biogenic feedstock.

A.2.3 National Recycling Strategy

The National Recycling Strategy is the first part of a strategy to advance the US towards a circular economy and focusses on enhancing and advancing the national municipal solid waste recycling system.[137] The strategy is organised based on five strategic objectives: A) Improve Markets for Recycling Commodities, B) Increase Collection and Improve Materials Management Infrastructure, C) Reduce Contamination in the Recycled Materials Stream, D) Enhance Policies to Support Recycling, E) Standardize Measurement and Increase Data Collection.

The Strategy emphasises the importance of recycling, which could increase the availability of feedstocks from recycled waste. Recycling systems are not standard across the United States. A product that could be recycled in one state is not necessarily recyclable in another. There is also no standard recycling labelling system across the United States, which creates confusion at the consumer end of which products to dispose at recycling bins. By improving and harmonising the recycling infrastructure as part of the strategy, this could enhance recycling of waste to be used as a feedstock.

A.2.4 State-level Extended Producer responsibility laws

Extended Producer Responsibility (EPR) laws focus on the improvement of the collection and recycling infrastructure in the given state, for which legislation is absent at the federal level. EPR laws require manufacturers to be engaged in the entire life cycle of their products including end-of-life waste management. This stems from the idea that manufacturers are best suited to recover materials to incorporate them back into the economy and avoid adverse environmental impacts. EPR laws at state level various products such as batteries, carpets, mattresses, electronics, packaging and pharmaceuticals.[138]

EPR laws vary significantly across states whether they have recycled content targets and if they recognise chemical recycling towards the target. Most EPR state laws tend to encourage recyclability for packaging but do not necessarily require particular levels of

136 Federal Register (2025). Biobased Markets Program.
137 EPA (2024). National Recycling Strategy.
138 GreenBlue (2025). Introduction to the Guide for EPR Proposals.

recycled material in new products. However, in California[139] and Washington State[140] for example, EPR fees for packaging are based on the use of recycled content in products, incentivising the use of recycled carbon feedstocks. How the recycled content is determined also varies per state as feedstocks from chemical recycling does not count toward the recycled content in e.g. California. At the same time, there are 25 states that promote chemical recycling.[141]

A.2.5 Carbon Conversion Program

The Carbon Conversion Program is a federal program that invests in technologies that make economically valuable products from biogenic and captured carbon feedstocks.[142] The programme funds research, development and demonstration of technologies that convert carbon emissions captured through technology and microorganisms into products such as chemicals, fuels, building materials, plastics, and bioproducts. Other key components of the programme include creating techno-economic analysis and life cycle analysis tools, facilitate the widespread adoption of effective carbon conversion technologies, and accelerating the deployment of products made from captured carbon feedstocks. The programme is funded, amongst others, by the Infrastructure Investment and Jobs Act enacted in 2021. The Act, also known as the Bipartisan Infrastructure Law, provides the Department of Energy with about $6.5 billion over five years in new funding for carbon management.[143]

A.2.6 US Section 45Q Tax Credit for Carbon Oxide Sequestration

The 45Q tax credit constitutes an important incentive to promote CCUS in the US, which enhances the availability and use of captured carbon feedstocks. This is a tax credit provided to businesses that permanently store captured CO_2 or use it for industrial applications, which could include producing chemicals, provided emission reductions can be clearly demonstrated. The credit amount significantly increases when direct air capture technologies are used to capture the CO_2.[144]

[139] *California (2021). Solid waste: reporting, packaging, and plastic food service ware.*
[140] *Washington (2021). RCW 70A.245.020: Postconsumer recycled content.*
[141] *American Chemistry Council (2024). With Wyoming, Half the Country Open to Advanced Recycling.*
[142] *US Department of Energy (2025). Carbon Conversion.*
[143] *Department of Energy (2021). Infrastructure Investment and Jobs Act.*
[144] *United States Code (2025). USC 45Q: Credit for carbon oxide sequestration.*

Glossary

Chemicals / chemical products	Products made by companies that fall under the chemical sector, including plastics.
Embedded carbon	Carbon that is stored with the feedstock or product. In this paper, this does not include the CO_2 emissions associated the energy that is used to produce the feedstock or product unless specifically indicated.
Environmental sustainability / Environmentally sustainable	Environmentally sustainable RRC feedstocks refers to the sourcing and conversion of RRC sources into chemical feedstocks without causing any adverse effects on the environment and the climate. In this paper, environmental sustainability is used as a collective term for the avoidance of these adverse effects.
Feedstocks / raw materials	Resources that have been converted and processed into materials suitable for using as input for the manufacturing of intermediate and (semi-)finished products. In this paper, feedstocks and raw materials are used interchangeably.
RRC feedstocks	Carbon-containing feedstocks made from RRC sources.
RRC sources	A collective term for biogenic resources, end-of-life materials and captured carbon.

List of Abbreviations

CBAM	Carbon Border Adjustment Mechanism
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CEAP	Circular Economy Action Plan
CRCF	Carbon Removals and Carbon Farming
CO_2	Carbon dioxide
EPR	Extended Producer Responsibility
EGD	European Green Deal
ESPR	Ecodesign for Sustainable Product Regulation
ETS	Emissions Trading System
EU	European Union
GHG	Greenhouse Gas
LCA	Life Cycle Analysis
LULUCF	Land Use, Land-use Change and Forestry
PEF	Product Environmental Footprint
PPWR	Packaging and Packaging Waste Regulation
R&D	Research and Development
RED	Renewable Energy Directive
RFNBO	Renewable Fuel of Non-Biological Origin
RRC	Renewable and Recycled Carbon
SCC	Sustainable Carbon Cycles
SPI	Sustainable Products Initiative
US	United States
WFD	Waste Framework Directive
WSR	Waste Shipments Regulation

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