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Sustainable Carbon Utilization for a Climate-Neutral Economy–Framework Necessities and Assessment Criteria

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Abstract: The need to limit anthropogenic climate change to 1.5–2 °C, as agreed in the Paris Agreement, requires a significant reduction of CO_2 emissions resulting from the use of fossil carbon. However, based on current knowledge, carbon is expected to remain crucial in certain industrial sectors, e.g., the chemical industry. Consequently, it is essential to identify and utilize sustainable carbon sources in the future. In this context, various carbon sources were examined and classified in terms of their disruption of the Earth's (fast) carbon cycle. Furthermore, the examined carbon sources were qualitatively analyzed with regard to their technical readiness level, their energy expenditure, and their current and future availability, as well as legal regulation within the European Union. As a result, only biogenic and mixed carbon from the ambient air can be considered genuinely sustainable within the Earth's (fast) carbon cycle. Mixed carbon streams, e.g., from waste recycling, fall into a gray area. The same applies to certain process-related emissions that originally descend from fossil fuel energy. In terms of energy considerations, technical maturity, and exploitable potentials, prioritizing the utilization of biogenic carbon sources is advisable for the time being, especially for CO_2 produced as a by-product originating from biogenic carbon carriers.

Keywords: sustainable carbon; defossilization; carbon capture and utilization (CCU); carbon neutrality; carbon cycle; sustainability criteria

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1. Introduction

The greenhouse gas CO_2 is largely responsible for anthropogenic climate change and its far-reaching consequences. Scientific results summarized by the Intergovernmental Panel on Climate Change (IPCC) show that the amount of CO_2 and other greenhouse gases (GHG) within the atmosphere must be stabilized in the long term to reduce the further rise in temperature and all the most likely resulting secondary effects [1]. To achieve the 1.5 or 2.0 °C target agreed years ago by the international community of states, only a small CO_2 emission budget remains. In addition, the currently already implemented and most likely foreseeable measures of the international community to reduce GHG emissions are not sufficient, with a very high probability, to stick to these emission budgets. Thus, an additional significant reduction of CO_2 and other GHG emissions is urgently required to achieve the climate targets, implying a fundamental transformation of the global industrial and energy sector.

The logical consequence of this is a far-reaching abandonment of the use of fossil carbon (reduction of global GHG emissions by 43% by 2030 relative to the 2019 level) [2]. However, according to current knowledge, carbon or hydrocarbons will continue to play an important role in our highly industrialized society [3–5]; this is true, e.g., for the chemical industry as well as other parts of our industrial sectors, because a significant share of industrial products sold on the global market is based on various types of hydrocarbons. In the year 2020, for example, the demand for naphtha and petroleum derivatives to be used as a raw material only within the German chemical industry was about 14.3 Mt [6].

Furthermore, this transformation towards carbon neutrality would involve a switch from the carbonaceous reactants currently used for the production of specific goods towards new and innovative technologies (e.g., substitution of fossil fuel-based coke with green hydrogen in primary steel production). The consequence is that the overall demand for carbon within, e.g., German industry (as well as globally) will most likely be reduced to a certain extent in the future compared to today [7–9]. In addition to such an industrial use of (so far) fossil fuel-based carbon, the transportation sector will most likely continue to use a contingent of hydrocarbons within some specific fields where transformation to direct use of electricity is challenging. For example, according to current knowledge, in international maritime and long-haul air traffic, a clear demand for fuels with high volumetric and/or gravimetric energy density will persist into the future [10].

Synthetically or biologically produced hydrocarbons can be a suitable sustainable alternative to, e.g., "green" hydrogen or ammonia to satisfy the difficult-to-decarbonize markets/sectors in the years to come [11,12]. Captured CO_2 can serve as a carbon source for the production of such synthetic or biologically produced hydrocarbons. From a GHG reduction perspective, it is essential that the carbon to be used in such a more GHG-neutral society/production system is obtained from renewable as well as sustainable sources, and thus from the Earth's recent (fast) carbon cycle. Therefore, an unequivocal regulatory framework with sustainability criteria to be applied for the use of carbon in industrial products such as synthetic fuels is essential. Several studies have already been carried out on various aspects of providing alternative carbon that does not further exacerbate climate change. For example, various studies [13–15] focus on assessment within the technosphere. In this case, analyses on closing the carbon cycle are conducted, from the manufacturing of a product to the reuse of carbon in various forms, including recycling, carbon replacement and reduction (decarbonization), the bioeconomy, and the discussion of technologies for achieving carbon neutrality via, e.g., carbon capture and utilization (CCU). One study [16] also discusses the sources from which "renewable" carbon can originate and how it must be defined as "renewable". A distinction is made between "renewable" carbon from the biosphere, atmosphere and technosphere. Carbon from the geosphere is defined as "non-renewable". A more nuanced differentiation of the various carbon sources with regard to the carbon cycle as part of the Earth's biogeochemical cycle has not yet been undertaken in the literature. Against this background, an analysis and evaluation of various carbon sources is conducted (Section 4.1), to ascertain their impact on the carbon cycle. Specifically, the analysis aims to ascertain whether the utilization of these carbon sources disrupts or circumvents the carbon cycle. A carbon source is considered sustainable if its use does not disrupt the carbon cycle. In addition, these different sources are classified with regard to relevant aspects for future use. The available literature addressing alternative carbon sources and the "sustainability" of carbon was also reviewed for this purpose (Section 4.2). On this basis, a series of assessment criteria are proposed to better classify the use of different carbon sources in order to enable the development of a GHG-neutral carbon-based society (Sections 4.3 and 4.4).

2. Carbon Cycle

The carbon cycle is one of the various biogeochemical cycles on Earth. Over long periods of time (a few 100,000 years), the balance of carbon remains approximately steady due to this carbon cycle, resulting in a more or less stable temperature regime. However, over long periods of time (several 10,000 to 100,000 years), Earth's temperature has varied between ice ages and warmer interglacial periods [17,18].

In the magnitude of millions to tens of millions of years, the balance of carbon can vary greatly due to tectonic plate movement and resulting phenomena, e.g., volcanic eruptions, which lead to extreme warm climate (Cretaceous time) and glacial climates (Pleistocene) [17,18].

Depending on the time required for the respective processes to absorb and release carbon and its compounds, the global carbon cycle can be subdivided into the slow and fast carbon cycles.

- The fast carbon cycle consists of the carbon removed by plants from the atmosphere during their growth and released again into the atmosphere during the degradation of biomass.
- The slow carbon cycle describes the carbon embedded in geological formations and released back into the atmosphere/biosphere over geological time intervals.

The slow and fast carbon cycles are driven by various forces over different periods of time. A detailed description of the respective cycle and corresponding mechanism is given in Sections 2.1 and 2.2. The emitting of anthropogenic CO_2 and its impact and effects on the carbon balance of the Earth and thus also on the climate can be explained by the respective cycle [18,19].

2.1. Slow Carbon Cycle

Within the slow carbon cycle, about 10 to 100 Mt/a of carbon is moved globally. This cycle shows an overall timescale of several millions of years. The slow cycle is mainly characterized by the transport and transformation of carbon through tectonics and chemical weathering [18].

The first step of this cycle begins with the transfer of carbon from the atmosphere to the lithosphere. Carbon in the form of CO_2 dissolved in rain (carbonic acid) falls down on the Earth's surface as a slightly acidic rain, dissolving rocks (limestone and silicate rocks). This results in the formation of ions of various alkali and alkaline earth metals being transported via rivers into the oceans. There, the ions form carbonates from reactions with hydrogen carbonate from ocean water resulting in, e.g., calcium carbonate. Organisms, e.g., shells, plankton and corals, which use the precipitation of calcite to build their skeletons also perform this process. When these organisms die, they sink to the seafloor and over time result in the formation of limestone [18–20].

Another process of the slow carbon cycle is the formation of rocks via organic carbon from organisms (e.g., shale). The organic material grown on (wet-)land and/or within water either by plants or by animals must become sediment on the ground of oceans/lakes/wetlands to avoid oxidation (i.e., release of the organic carbon back into the atmosphere). Within these sediments, the organic material can be oxidized only to a limited extend over longer time periods, due to missing oxygen. In parallel, more inorganic material piles up; the organic carbon is increasingly embedded in layers of sediment within geological formations. This process is a substantial part of the formation process of fossil energy carriers, such as coal (hard coal and lignite), crude oil and/or natural gas, if certain conditions, such as, e.g., high pressure and high temperatures, exist. This embedded carbon might be released back to the atmosphere due to tectonic and other geological activities (e.g., volcanic activities), closing the slow carbon cycle [18–20]. The different processes and carbon fluxes can be seen in Figure 1.

The slow carbon cycle is more or less self-adjusting. This means that an increase of CO_2 within the atmosphere leads to a temperature rise resulting in more rain which dissolves more rocks. The time to rebalance this carbon cycle through weathering takes typically several millions of years [18–20].

2.2. Fast Carbon Cycle

The amount of carbon moved by the fast carbon cycle is around 1 to 1000 Gt/a. The time period of this cycle is about 0 to 1000 years. The driving force behind this cycle is photosynthesis on the one side and natural degradation of organic matter on the other [18,21].

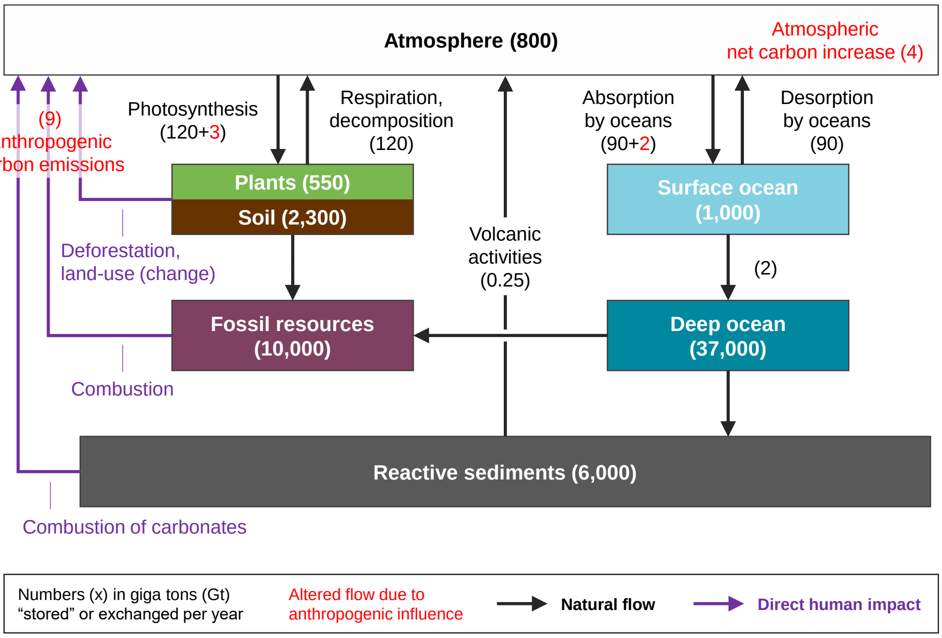

Figure 1. Scheme of the carbon cycle, based on [18,19,21–23].

Land- and water-based plants and micro-organism (e.g., plankton) use the energy of sunlight to form sugar, as the basic building block of organic material, out of carbon dioxide (CO_2) and water (H_2O) coming from the environment (Equation (1)) [18].

$$6\,CO_2 + 12\,H_2O + \text{energy} \rightarrow C_6H_{12}O_6 + 6\,O_2 + 6\,H_2O \quad (1)$$

When plants and plankton decay, biocatalysts use the energy from the respective biomass/organic matter by oxidizing it, resulting in the release of H_2O and CO_2 back into the environment (Equation (2)) [18].

$$C_6H_{12}O_6 + 6\,O_2 \rightarrow 6\,CO_2 + 6\,H_2O + \text{energy} \quad (2)$$

Thus, the fast carbon cycle moves carbon between the atmosphere and the biosphere comprising the ocean and its surface sediments as well as the soils on land. The key processes that influence the fast carbon cycle besides photosynthesis and decay/decomposition are respiration, digestion and combustion of plants and animals [18,21].

2.3. Carbon Classification

Based on this, a distinction between fossil and biogenic carbon as well as carbon from ambient air is made in this study.

- Fossil carbon is defined as carbon circulating within the slow carbon cycle; i.e., mainly from rocks or minerals as well as crude oil, natural gas and coal (hard coal and lignite).
- Biogenic carbon is defined as carbon that circulates within the fast carbon cycle; i.e., this type of carbon is primarily bound in organic matter/biomass.
- Carbon contained within ambient air/the atmosphere (mainly CO_2) is, according to this definition, a mixture of fossil and biogenic carbon. The same applies for CO_2 from the incineration of mixed carbon stocks (e.g., municipal solid waste incineration).

3. Carbon Demand within a Defossilized Society

Globally, the largest share of carbon is currently used to provide energy (i.e., electricity provision, heat provision, fuels, e.g., for the transportation sector) followed by the chemical industry (i.e., carbon as a raw material) [24,25]. Even considering the fact that some sectors might be decarbonized in the years to come, a certain (significant) amount of carbon will continue to be required even within a defossilized society. The overall carbon amount depends on numerous factors and several (e.g., market-oriented and societal) framework conditions as well as the legal framework.

Various already mature technological options that do not rely on carbonaceous energy carriers/fuels are available for the provision of energy (e.g., photovoltaic (PV) systems, wind turbines, hydro power stations). The same is also true for the provision of transport services; selected solutions which do not rely on the use of carbon-based fuels already exist today and are slowly gaining market shares [26,27].

It can be assumed with a high probability that the chemical sector will continue to require carbon for the production and supply of certain products in the future. The following explanations provide an overview of the current carbon requirements in this sector, as well as an overview of the currently used and future required quantities of CO_2 as a carbon source.

3.1. Carbon Demand

The average global carbon demand for chemicals and derived products is about 450 Mt (average 2015 to 2020). The majority of this carbon, 380 Mt (85%), is obtained from fossil sources (crude oil, natural gas, coal). The amount of 47 Mt carbon (10%) comes from biogenic sources (plant oil, natural rubber, starch/sugar, bioethanol, other biomass) and 23 Mt carbon (5%) results from carbon recycling [24]. The carbon feedstock used only by the German chemical industry as a raw material amounted to 18 Mt (2017) where 16 Mt (close to 90%) are of fossil, and 2 Mt of biogenic, origin [28]. This amount of carbon used by the German chemical industry is expected to decrease in the future, resulting in a demand ranging from 15 to 17.4 Mt carbon in the year 2050. Compared to that, the carbon demand of the global chemical industry is expected to grow from today's 450 Mt to about 1000 Mt in the year 2050 [24,28].

3.2. CO_2 Demand

Today, CO_2 is already used in various processes and applications for different purposes in various niche markets within the industrial sector; examples of different uses are given in Table 1.

Table 1. Applications of CO_2 in different industries [29].

Industry	**Application/Process**
Food industry	Dry ice for blast freezing and cooling Inert gas for packaging Carbonic acid in beverages Solvents for supercritical extraction
Agriculture	Fumigation in greenhouses
Chemical industry	Urea production *Chemical intermediates: methane, methanol* *Polymers*
Oil/petro industry	Enhanced oil recovery *Methane* *Methanol* *Gasoline, diesel, kerosene*
Other industrial application	Refrigerant/heating agent Inert gas for welding
Construction industry	*Cement* *Concrete*

New or future applications of CO_2 are in italics.

In Germany, for example, CO_2 is already used to a limited extent within the various fields of application shown in Table 1 (except enhanced oil recovery). Nevertheless, the actual amount of CO_2 already used in Germany is not reported in detail. Globally, the demand for CO_2 was about 230 Mt (2015). The greatest share was used for the production of urea (130 Mt (2015)) and enhanced oil recovery (70 to 80 Mt (2015)) [29].

The future demand for CO_2 as a resource for the production of synthetic carbon-containing compounds, such as hydrocarbons, varies depending also on the implementation level of the respective syntheses as well as many other influencing factors. If the amount of fossil carbon demanded by the German chemical industry (16 Mt fossil carbon) were to be covered exclusively by (sustainable) CO_2 as an alternative carbon source, almost 60 Mt of CO_2 would be required on a yearly basis by neglecting efficiency losses during downstream processing, assuming undisturbed development.

Different studies regarding the future CO_2 demand for different industrial applications and the prospects of substituting fossil carbon in different goods have been published in recent years. Table 2 provides an overview of the results of the analyzed literature. The table makes it obvious that there is already a significant demand for CO_2 today, which will most likely increase in the future and exceed the current demand by several orders of magnitude.

Table 2. CO_2 in 2050 as a raw material for the various sectors.

Study	Scope	CO_2 Demand
Putting CO_2 to use–IEA [29]	World, total demand	1 to 7 Gt/a by 2030
Galimova et al. [5]	World, total demand	6 Gt/a by 2050
Nova Institut [24]	World, chemical industry	918 Mt/a by 2050
Huo et al. [30]	World, chemical industry	2.2 to 3.1 Gt/a by 2050
Hepburn et al. [31]	World, chemicals and fuels	1.3 to 4.8 Gt/a by 2050
Schmid et al. [32]	Germany, total demand	420 Mt/a by 2030
Wuppertal Institute [33]	Germany, total demand	80.3 Mt/a by 2050
Ifeu [34]	Germany, total demand	8.3 Mt/a by 2050
MWV [35]	Germany, total demand	180.2 Mt/a by 2050
VCI—Roadmap [36]	Germany, chemical industry	10 to 41 Mt/a by 2050
Zukünftige Nutzung von CO_2 als Rohstoffbasis–Universität Kassel [28]	Germany, chemical industry	3 to 17 Mt/a by 2030 12 to 49 Mt/a by 2050

4. Framework and Criteria for the Use of Carbon

Criteria have been determined defining "renewable" electricity for the production of hydrogen from "renewable sources" within the revised Renewable Energy Directive II (RED) [37]. Similar definitions/specifications and criteria for "renewable" carbon/the sourcing and application of "renewable" carbon (i.e., CO_2 from biogenic sources within the fast carbon cycle) to be used for carbon-containing compounds (e.g., hydrocarbons) in a sustainable way within a defossilized world need to be defined.

Recently, and importantly in this context, the European Parliament and the Council of the European Union adopted the Directive (EU) 2023/2413, commonly referred to as the Renewable Energy Directive III (RED III) [38]. This directive aims to enhance the promotion of energy from renewable sources. This directive also includes a methodology to assess GHG emissions from renewable fuels of non-biological origin (RFNBO) and recycled carbon fuels (RCF) to be used within the transport sector but also for the first time for non-energy purposes as feedstock or raw material in industries to meet the target of a reduction of net GHG emissions.

Against this background, various possible sources of carbon supply, divided into fossil and biogenic origins, are discussed in Section 4.1 according to their impact on the carbon cycle (Section 2.3) and their use as future carbon sources is addressed. Additionally, existing considerations from different studies about climate benefits and other impacts of the use of alternative carbon sources are reviewed in Section 4.2. Furthermore, considerations concerning the various sources beyond the origin and impact on climate of the respective carbon are discussed in Section 4.3. The different sources are further classified according to the current criteria from the respective directive (EU) in Section 4.4.

4.1. Carbon Source Classification

To avoid any disturbance of the global average temperature regime due to the fast carbon cycle, the following criteria need to be fulfilled from a purely scientific point of view.

- From the point of view of the physico-chemical processes realized within the atmosphere/the natural environment, it makes no difference whether the CO_2 comes from energy-related processes or is released during the production of goods (e.g., production of cement).
- The atmosphere/the natural environment "sees" only the overall sum of CO_2 released. Thus, a removal and use of CO_2 from ambient air (DAC—Direct Air Capture) is equivalent to a use of CO_2 from biomass as long as the biomass is produced in a sustainable way; i.e., the living (plant-based) carbon stock stays stable on average over several years.

4.1.1. Fossil Carbon

Fossil carbon can be categorized into gaseous, liquid and solid carbon carriers. Furthermore, these can be subdivided into (a) primary, (b) secondary and (c) tertiary sources, representing (a) naturally occurring carbon carriers (raw materials), (b) products and (c) the end of use stage (highest oxidation state; i.e., CO_2). Examples of these different carbon carriers and their respective classification can be seen in Figure 2.

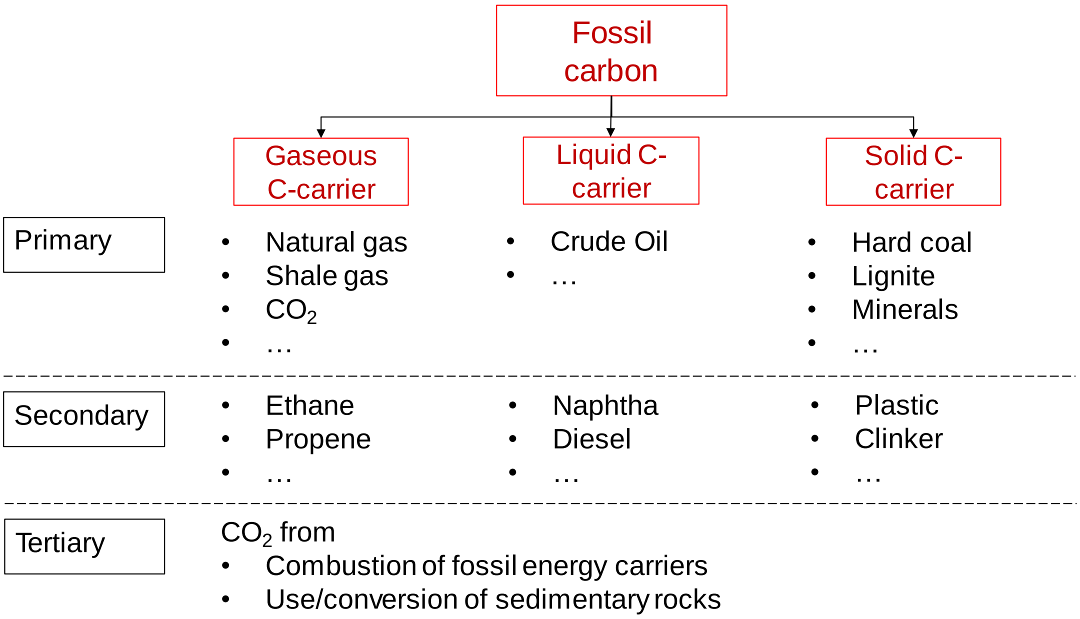

Figure 2. Classification of fossil carbon sources.

Below, the most relevant fossil carbon carriers, in terms of secondary use, are discussed in detail. These are mainly the tertiary CO_2 emissions from different sources as well as secondary solid carbon carriers.

Fossil carbon from tertiary gaseous carbon carriers. The majority of anthropogenic CO_2 emissions of fossil origin result from burning fossil energy carriers such as hard coal and/or lignite, natural gas and crude oil—as well as its derivates—for the provision of electricity and/or heat as well as for transportation purpose [39,40]; i.e., these tertiary CO_2 emissions (Figure 2) are mainly energy related. Further emission sources are the use of these fossil carbon resources for specific industrial applications (as a raw material) as well as emissions from the deacidification of carbonate-containing minerals; i.e., these CO_2 emissions are process-related.

CO_2 emissions from electricity and heat provision resulting from the energetic use of fossil fuel energy should strictly be excluded as a possible carbon source for subsequent industrial application (e.g., as a feedstock for the production of synthetic hydrocarbons). In terms of climate impact, the use of these CO_2 emissions as a resource for products will inevitably lead to an increase in the GHG emission inventory within the biosphere/atmosphere/natural environment. Furthermore, the mid- to long-term availability of such CO_2 from e.g., electricity generation from coal, is not ensured (and should be unlikely if the legal GHG reduction goals, like the Paris agreement, are fulfilled) due to the necessary and partly already announced complete switch to electricity generation from renewable sources of energy; the necessary alternative (mainly: carbon-free) technologies are available on a large scale and even show economic advantages under certain conditions [41–43].

The use of process-related fossil CO_2 is widely discussed to allow a further cascade use as an educt for the production of synthetic carbon-containing compounds [29,44,45]. The reason is that even within a highly defossilized energy and production system, small amounts of CO_2 of fossil origin are still likely to be emitted. Possible sources are primarily the mineral industry, mainly including the production of cement clinker and quicklime as well as glass and ceramics [46,47]. These process-related emissions emitted during the production of such products result from driving out CO_2 from the various carbonate compounds used as raw materials. The properties of the burnt or sintered products are essential for their use and thus there is a need for such a treatment. In addition, for most of these processes no technological alternatives are available yet, and additionally these products are needed within our global industrial society. However, the release of these CO_2 emissions clearly contributes to an increase of the overall GHG emission inventory within the atmosphere [47,48].

Fossil carbon from secondary solid carbon carriers. Carbon of fossil origin can also be obtained from other secondary sources. A widely discussed example is plastic recycling or—in more general terms—the recycling of carbon-containing waste streams of originally fossil origin. The direct use of carbon via material recycling is only feasible for certain (limited) applications, such as the production of new plastics from granulate obtained from plastic waste (mechanical recycling) in some specific cases [24,49]. A further distinction can be made if this carbon is directly used (e.g., production of new plastic products from old plastic products) or via the intermediate state of CO_2 by, e.g., combustion, pyrolysis, or gasification, since these might result in a near-term increase of fossil GHG emissions if the resulting CO_2 or syngas stream is used for the production of fuels.

The secondary use of carbon of fossil origin helps to keep this carbon within the industrial use cycle in case of material recycling. Nevertheless, over the years, the respective carbon is necessarily released into the atmosphere/natural environment and contributes there to the additional, anthropogenic greenhouse effect.

4.1.2. Biogenic Carbon

During their photosynthesis activity, plants remove carbon from the ambient air/the atmosphere and integrate this carbon in a reduced form within the respective macromolecular building blocks (e.g., cellulose, hemicellulose, lignin). Thus, the biomass/organic material provided by nature is basically a huge carbon carrier. Based on the availability of this carbon, the following biogenic carbon sources can be distinguished.

- Gaseous carbon carrier. Gases containing carbon of biogenic origin are, e.g., biogas consisting of methane und carbon dioxide, CO_2 from bioethanol production, CO_2 from composting processes and CO_2 from biomass combustion/thermal conversion. A further distinction can be made between energy-related (e.g., thermal conversion of solid biofuels) and process/product-related CO_2 (e.g., bioethanol, biomethane).
- Liquid carbon carrier. Plant-based biomass can also be used as a source for the provision of liquid carbon carriers. This is true for, e.g., plant-based oils and fats as well as for different types of alcohols.
- Solid carbon carrier. Lignocelluloses, like wood, are also a carbon carrier. Therefore, the overall existing solid (lignocellulosic) biomass—available as a product, as a by-

product, as a waste-product and/or as a residue—could be potentially used as a biogenic carbon source.

In line with the previous classification of fossil carbon, a further subdivision of the carbon carriers into (a) primary (raw material), (b) secondary (processed products) and (c) tertiary (end of use phase/highest oxidation state, i.e., CO_2) is also applied here (Figure 3).

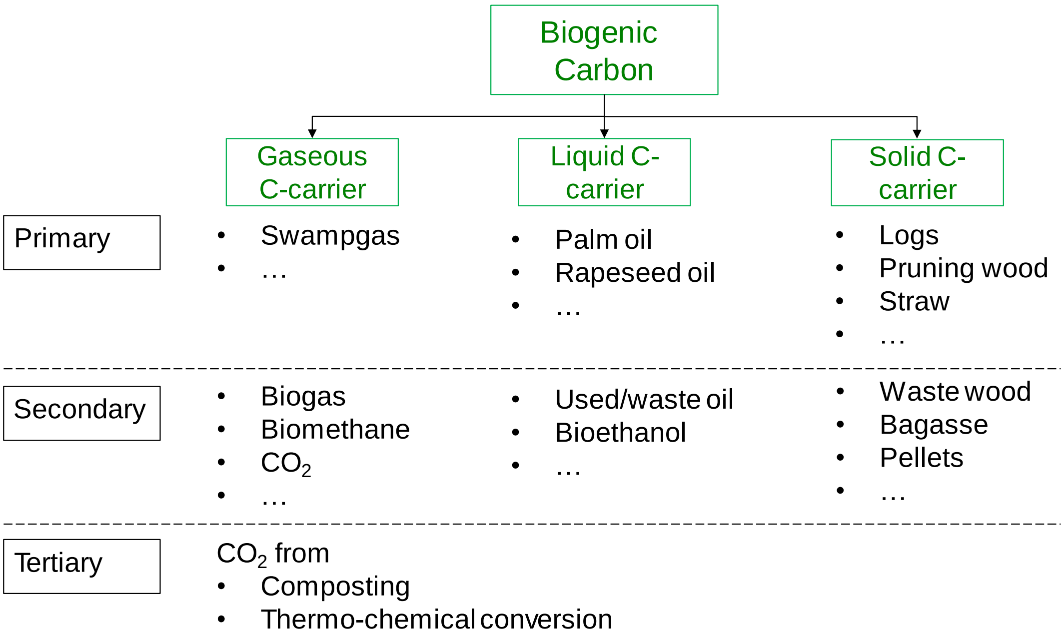

Figure 3. Classification of biogenic carbon sources.

Biogenic CO_2 emissions do not increase the amount of climate-active CO_2 emissions within the atmosphere/the natural environment, since the biogenic carbon is fully embedded into the (theoretically closed) fast carbon cycle. However, the use of biogenic carbon/CO_2 within our current industrial system might lead to an increase of fossil fuel-based GHG emissions, since, e.g., biomass cultivation, harvesting, transportation and processing consumes fossil energy carriers through, e.g., the application of fertilizer, transportation fuel, process-related energy demand, etc. [50–52]. The share of the GHG emissions of fossil origin resulting from the pre-chains of biomass provision therefore depends on the implementation level of a defossilized system and of the respective cultivation methods. Since additional climate-active GHG emissions of fossil origin from the supply chain of biogenic carbon/of biomass are expected to decrease with an increasingly defossilized global energy system, biogenic carbon becomes more and more climate-neutral. Nevertheless, certain limitations or rather concerns should be considered, especially in the early stage of carbon utilization, to avoid negative long-term impacts, like first-generation biofuels, for example [53].

Thus, related to the given demands, biogenic carbon can be used as a resource to substitute fossil fuel-based carbon. Therefore, at a minimum, the following requirements must be fulfilled, which are comparable to certain sustainability aspects contained in the Renewable Energy Directive II for the provision of sustainable biomass [37].

- Biomass must be provided in a sustainable way; i.e., organic carbon coming from rainforest being converted into grassland does not count as this because the carbon stock active on a specific piece of land is reduced due to its conversion into a less carbon-demanding use.

- Most likely, all biomass waste streams, organic residues and by-products emerging throughout the overall provision chain from agricultural production via the food processing industry until final use can be used, as long as the food production is realized in a sustainable way.
- The same is true in a figurative sense for wood from forests, if the latter are managed under sustainability criteria.

4.1.3. Mixed Carbon Sources

Carbon from mixed sources. One conceivable possibility of utilizing CO_2 from the production of electricity and heat is thermal waste treatment. Typically, as long as municipal solid waste is used, these CO_2 emissions are a mixture of biogenic and fossil carbon [54]. Thus, the (additional) climate impact depends on the proportion of carbon of fossil and biogenic origin within the respective waste streams.

Carbon from ambient air. Ambient air currently contains roughly 420 ppm of CO_2 (global monthly mean, November 2023) with a clearly increasing trend [55]. This carbon (CO_2) can be removed from the air and used as a carbon source. The use of airborne carbon does not disturb the fast carbon cycle in a negative way concerning global warming, and thus it is not expected that any negative effects will occur due to the technical use of the CO_2 contained within the atmosphere.

4.2. Literature Review

In addition to the EU's efforts, various stakeholders are already considering and suggesting how the carbon needs of the various industrial sectors could be met in the future if they can no longer rely on fossil carbon. Other studies look at the goods produced by CCU and evaluate them according to various criteria. Table 3 gives an overview of the consideration made by the respective studies.

Table 3. Overview of studies about the use of alternative carbon for future application in different products.

Study	CO_2-Derived Products/Origin of CO_2	Consideration
IEA Putting CO_2 to use [29]	CO_2-derived product	Climate benefits: • Source of CO_2 • Type of product or service the CO_2-based product or service is displacing • How much and what form of energy is used to convert the CO_2 • How long the carbon is retained in the product (temporary or permanent) • Scale of the opportunity for CO_2 use
IEAGHG Technical Report CO_2 as a feedstock: Comparison of CCU pathways [56]	Mainly CO_2-derived product, also origin of CO_2 is mentioned	CO_2 mitigation potential: • Emissions avoided • Total addressable market Other impacts: • Energy demand • Water & land use • Social & environmental impacts

Table 3. *Cont.*

Study	CO_2-Derived Products/Origin of CO_2	Consideration
VTT [57]	CO_2-derived products & origin of CO_2	Carbon reuse economy based on three drivers: • Need to reduce CO_2 emissions into atmosphere • Expanding regional resource base and securing energy demand for carbon-dependent industries • Developing new businesses based on sustainable supply and use of carbon
Nova Institute [16]	Origin of CO_2	Carbon circular economy (where CO_2 comes from) • Biomass • Atmosphere • Recycling
VDI Industrielle CO_2 Kreisläufe [58]	CO_2-derived products & origin of CO_2	Environmental aspects: • Usage of chemicals and energy for capture process • Share of regenerative electricity • Life cycle assessment (LCA) of CO_2-derived products
National academic press—gaseous carbon waste streams utilization [59]	CO_2-derived products	Environmental aspects: • LCA of CO_2-derived products
Öko-Institut [60]	CO_2-derived products & origin of CO_2	Climate benefits and resource criticality: • CO_2 from sustainable biomass and air are the only renewable options • Currently valid framework for CO_2 use in PtX insufficient for GHG reduction • Sustainable and cheap CO_2 likely to become scarce resource

The considerations listed in the table only show a selection of the considerations of the respective literature.

The majority of the analyzed literature considers the origin of carbon and electricity, or rather the carbon intensity of the life cycle of the CO_2-derived product, as most relevant for the climate benefits of the respective synthetic products. There is a general agreement that CO_2 capture from biomass and from the atmosphere are the only renewable ways to provide carbon without increasing GHG content and/or have a better GHG balance than their fossil equivalents. Some studies also consider the use of CO_2 from industrial processes that are rather difficult to defossilize in the short- to mid-term, e.g., CO_2 from the mineral industry. One study also mentions the possibility of carbon recycling from waste streams such as plastics. Life cycle assessment is considered by some studies to be a suitable means of quantifying sustainability, especially that of final carbon-containing products. In the literature, there are various areas in which life cycle assessments have been carried out with regard to the capture or provision of carbon. In [61], a review of different LCAs is carried out, which however focuses on carbon dioxide removal (CDR), e.g., afforestation/reforestation, production and use of biochar, bioenergy with carbon capture and storage or direct air carbon and capture. Among other things, it is emphasized that it is crucial for the LCA of CDR that a clear distinction is made between avoided and negative emissions and that more comprehensive and more stringent life cycle assessments are required in order to be able to derive a well-founded and comprehensive assessment of different CDR. The effects of an alternative carbon supply for the petrochemical industry were examined in [62]. Nine impact categories/planet boundaries were investigated and 50 different supply paths were examined. The results show that the supply paths with the lowest carbon footprint also significantly exceed other planetary boundaries, such as biodiversity.

LCA can provide a good indication of the degree of sustainability of the carbon used or the resulting product if the scope of the study is appropriately comprehensive and multiple environmental impact categories are addressed within the methodological decisions. Since a complete LCA for all different carbon supply options goes beyond the scope of this paper, other important selected aspects that play a decisive role in the supply of carbon are described in Section 4.3.

4.3. Assessment Related to Technical Demands and Availability

In the following, the technology readiness level (TRL), energy demand and availability of the different carbon sources are analyzed.

4.3.1. Technology Readiness Level

The technology readiness level (TRL) is a rating scale for the development status of new technologies based on a systematic and comparable analysis. This criterion rates the status of technical maturity and market implementation of the respective technology. The scale ranges from TRL 1 (low technical maturity) to 9 (high technical maturity) [63].

Fossil and biogenic carbon. The TRL of the CO_2 capture technologies from concentrated fossil and biogenic sources is typically high; most of the technological solutions are market-mature and used within selected industry branches on a large scale. CO_2 capture via e.g., amine scrubbing or pressure swing adsorption is available on the market and operated on a commercial level [64]. Thus, the TRL for these technologies is 9. However, technologies such as membrane separation are described as promising options with the drawback of being not yet fully commercialized (current TRL is ca. 7). In general, the direct utilization of carbon from mixed sources via material recycling of, e.g., plastic waste is a mature, commercially available and practiced technology. However, it is limited because of sorting efforts and the often low quality of waste streams (i.e., contamination and degradation) [24,49].

Carbon from mixed sources. The TRL of post-combustion capture integrated into waste incineration plants is comparable to fossil and biogenic sources. The specific TRL depends on the implemented technology; e.g., amine-based scrubbing shows the highest TRL.

Carbon from ambient air. Direct air capture (DAC) technology has a lower TRL compared to, e.g., amine scrubbing, since only a few demonstration and pilot plants with rather low capacities already exist [65,66]. For DAC, a distinction between low- and high-temperature technologies can be made, of which the latter shows a lower TRL. The TRL for the most advanced low temperature processes is currently between 7 to 9 and the TRL for high-temperature DAC systems is roughly at 7.

4.3.2. Energy Demand

The assessment of energy demand focuses on the analysis of the respective energy demand of the various technologies to obtain carbon in order to evaluate/compare the different carbon sources. As carbon capture is an energy-intensive process characterized by, e.g., a considerable thermal energy demand, the relative energy demand of each process step is of high importance to realize a high overall process efficiency—and thus possibly low costs. Since the energetic effort required to capture CO_2 from gas streams correlates with the partial pressure of the CO_2 present in the gas stream (i.e., due to thermodynamic reasons, as a rule of thumb, it is valid that the lower the content of the gas component to be removed from a specific gas mixture, the higher is the respective energy demand) [64], the respective CO_2 concentration is examined for the extent of the energetic effort required to capture it from different sources.

Fossil carbon. In general, energy requirement for CO_2 capture from a gas stream depends greatly on the concentration of CO_2 in the respective gas streams [64]. CO_2 concentrations in the exhaust gas from the combustion of fossil fuels for power generation varies between 3 and 15% [67]. The CO_2 concentration of off-gases/flue gases/residual gases from industrial sources depends on the respective production process; typical examples are, e.g., about 20% from cement and about 15% from iron and steel production [68]. A listing of various CO_2 concentrations from different processes is given in Table 4.

Table 4. CO_2 concentration of different off-gases, based on [67–71].

Origin of Carbon	Process	CO_2 Concentration [Vol-%]
Fossil carbon	Power	
	Coal combustion	12–15
	Natural gas combustion	3–10
	Fuel oil combustion	3–8
	Industries	
	Cement production	14–33
	Refineries	3–20
	Integrated steel mills	20–27
	Ethylene production	12
	Ammonia production process	up to 100
	Aluminum production	1–10
	Ethylene oxide	8
	Carbonates production	20
	Glass production	7–10
	Lead production	15
	Lime/quicklime production	20
	Magnesium production	15
	Soda ash production	36–40
	TiO_2 production	13
	Zinc production	15
Biogenic carbon	Power	
	Bioenergy/Biomass combustion	3–8
	Biomethane production	40–50
	Industries	
	Fermentation process	up to 100
Mixed carbon		
	Waste incineration	6–12
	Pulp and paper production	10–15
	Atmosphere	0.04

Biogenic carbon. CO_2 from bioethanol production is characterized by a concentration of nearly 100%. This results in a relatively small energy consumption for the clean gas provision, since pure CO_2 can be provided by removing, e.g., the remaining water by, among other options, using condensation [71]. The concentration of CO_2 in biogas, which can be upgraded to biomethane by separating CO_2 (and other impurities), is about 40 to 50%. CO_2 from the combustion of biomass shows a concentration level between 3 and 8% within the flue gas; i.e., CO_2 capture results in a greater energy demand compared to the capture from bioethanol or biomethane production.

Carbon from mixed sources. Depending on the technology used for thermal waste treatment, the percentage of CO_2 in the various potentially usable gas streams varies greatly. The CO_2 content of waste incineration plants is 6 to 12%, which is comparable with the CO_2 content of the flue gas from power plants operated by fossil fuel energy (e.g., pulverized coal power plants). The gasification of municipal waste might result in a CO_2 content of up to 40% [59].

Carbon from ambient air. By far the greatest specific energy demand for CO_2 capture results from capture from the atmosphere, since ambient air shows the lowest CO_2 concentration of all possible CO_2 sources, with 0.04% [72].

4.3.3. Availability

In ranking the availability of the various carbon sources, it can be estimated how much carbon could be available for a technical use from the different sources. Thus, the status quo as well as possible future availability is addressed below. A qualitative estimate is made, which is based on the current as well as possible future regulatory and supply conditions.

Fossil carbon. The amount of fossil CO_2 emissions emitted every year is currently still very high; and for decades, every year new emission records are announced (except when a global crisis occurs, like the world financial crisis in 2007/08 or the COVID-19 pandemic in 2020/21). This is especially true for countries where electrical energy is provided by (inefficient) coal-fired power plants and/or which have a large share of heavy industry (e.g., iron smelting, chemical industry, cement production) [73]. Fossil CO_2 point sources might decrease to a great extent in the future due to alternative processes characterized by lower CO_2 emissions to obtain the respective desired product endorsement enforced by the legal GHG reduction commitments. This is especially true for fossil fuel-based CO_2 emissions from energy provision and to some extent for CO_2 emissions from the producing industry.

Carbon from other sources, e.g., plastic, is assumed to be available in bulk in the future since it is likely that plastic will still be used like today in the years to come for multiple applications [24]. Nevertheless, compared to the available amount today, the total amount might decrease in the future since some areas of application could be eliminated because alternative materials might be developed and used.

Biogenic carbon. The availability of biogenic CO_2 emissions depends on various factors. Since a direct use of CO_2 emissions from combustion/thermo-chemical conversion might not be a favorable option due to low value enhancement compared to, e.g., bioethanol production, the available amount might not be that much. But this also depends on the regulatory framework valid in the years to come. A prominent example is the production of biogas and biomethane in Germany, which will most likely decrease noticeably in the years to come due to strong changes within the legal regulatory framework. The overall potential for biogenic CO_2 also depends strongly on the amount of unused biomass; for economic reasons, this is especially true for organic waste streams (e.g., municipal solid organic waste, agricultural byproducts). In general, it can be assumed that there is a certain potential in organic waste materials, residues and/or by-products; widely discussed examples of these groups of organic matter is straw and sewage sludge [71,74–76].

Furthermore, since solid and especially liquid carbon carriers are already widely used, it is likely that gaseous carbon carriers have and will have a relatively higher availability. This hypothesis is supported, among other things, by the fact that gaseous carbon carriers (i.e., biomethane, CO_2) are produced in most cases as a by-product from organic waste streams/biomass residues occurring during production and in some cases even use of solid and/or liquid carbon carriers [71].

Mixed carbon sources. Within the EU as well as in other industrialized countries (e.g., Japan and the US), there are high-capacity thermal waste treatment plants today, which might be a source for carbon provision (i.e., CO_2). The amount of usable carbon from mixed sources might decrease in the future compared to the status quo. Under the assumption of a serious implementation of a circular economy (e.g., [77]) on the one hand, and an ongoing defossilization to fulfill the GHG reduction goals (i.e., the goals of the Paris agreement) on the other, a decreasing availability of waste can be expected in the mid to long term characterized by—on average—a clearly decreasing share of fossil carbon. However, the probability that the necessity to incinerate some fractions of waste (e.g., medical waste) will persist into the future is relatively high (i.e., the removal of hazardous waste represents a system-relevant task) [78]. Thus, in the future, carbon from such mixed sources can still be expected.

Carbon from ambient air. The amount of carbon that can be made available by direct air capture (DAC) units in the form of CO_2 is currently and most likely also in the future unlimited, if it is assumed that a reduction of the current CO_2 concentration from over 420 ppm to about 280 ppm, as it was in pre-industrial times (before about 1750), is easily possible [79]. This corresponds roughly to an increase of 289 Gt of carbon (ca. 1.1×10^{12} t of CO_2) during that period, which would result in a cumulative amount of 879 Gt of carbon in 2021 [80]. Since it is foreseeable that more CO_2 emissions will continue to be emitted in the coming years, because most countries have set the achievement of the net zero CO_2 emissions target as not before 2050, it can be assumed that the amount of carbon in the atmosphere will continue to rise (considerably) in the future (and thus even more CO_2 can be removed from the atmosphere, assuming that DAC systems become available (and affordable) on a large scale).

In principle, DAC offers the possibility of providing carbon on site, independently of point sources located in the vicinity; for example, to exploit particularly favorable production conditions for renewable electricity for synthetic fuel production.

4.4. Assessment Related to Regulatory Demands

Below, the various carbon sources are discussed against the background of the given regulatory demands. For this purpose, the regulatory demands are summarized first.

In December 2021, the Commission of the European Union (EC) adopted the concept of "Sustainable Carbon Cycles", including an action plan for the development of sustainable carbon removal solutions [81]. The EC published a final draft regulation at the end of the year 2022 for an EU-wide certification framework for carbon removal from the atmosphere. In early 2024, the European parliament and the Council of the EU reached a provisional agreement on this regulation, leading to an EU-wide voluntary framework for the certification of carbon removals, carbon farming, and carbon storage in products [82].

As part of the concept of "Sustainable Carbon Cycles", the EC plans that by 2028 the origin of CO_2 used or stored by industries has to be reported and accounted as biogenic, fossil or atmospheric. It aims that by the year 2030, a minimum of 20% of the overall used carbon in chemical and plastic products should be of non-fossil origin. Additionally, by the year 2030, the removal and permanent storage of 5 Mt/a of CO_2 from the atmosphere is targeted. In order to support the achievement of these ambitious targets, the following activities are planed [81].

- Development of a standard methodology allowing a robust and transparent quantification of the climate benefit of sustainable wood construction products as well as other building materials that show the possibility of carbon storage.
- Development of a methodology and an integrated evaluation of land use for EU bioeconomy aiming to ensure the accordance of aggregated national and EU policies and targets.
- Providing financial support for industrial carbon removals via the Innovation Fund.
- Extend the Horizon Europe calls in its next work program to support CO_2 capture, transport, use and storage.
- Initiate a study on the development of CO_2 transport networks.
- Update the guidance documents for the Carbon Capture and Storage (CCS) Directive, including risk management, monitoring, as well as financing.
- Organization of an annual carbon capture utilization and storage (CCUS) forum.

The Carbon Removal Certification Framework (CRCF) [82] incorporates the need for a consistent methodology to evaluate and ensure the climate benefit of the respective carbon removal activity. The following types of certified activities are distinguished here.

- Carbon farming (including temporary carbon storage activities and soil emission reduction activities).
- Temporary carbon storage in long-lasting products.
- Permanent carbon removal.

Additionally, carbon removals need to meet certain quality criteria regarding quantification, additionality, long-term storage, and sustainability. Building on this, the EC will devise methodologies for certifying various carbon removal methods and recognize certification schemes.

Furthermore, the EC communication about an overall strategy, namely the Industrial Carbon Management strategy, was adopted in early 2024 [83]. This strategy aims to lay the first steps to create universal conditions for the development and deployment of industrial carbon dioxide removal (CDR). In general, it comprises sections about what is necessary to scale carbon capture and storage as well as utilization, CO_2 storage and transport infrastructure, considerations about developing and introducing a separate carbon removal trading system and the boosting of research, innovation and demonstration of new technologies for CDR. For the 90% emissions reduction recommended for the year 2040, it stated that the EU has to capture at least 50 Mt CO_2/a by 2030, approx. 280 Mt CO_2/a by 2040, and about 450 CO_2/a by 2050. Therefore, different specific measures and tools are focused on the development of an EU CO_2 value chain, which is described below in more detail.

- Deployment of a CO_2 transport infrastructure
    - Development of a regulatory framework, market structure, and infrastructure planning system
    - Implementation of emissions accounting rules under the EU ETS to facilitate the transportation of CO_2
    - Baseline standards for CO_2 streams applicable across all industrial carbon management solutions
    - Evaluation of the feasibility of reusing or repurposing existing infrastructure for CO_2 transportation and storage
    - Appointment of European coordinators to assist in the initial development of infrastructure
- Boosting carbon capture and storage
    - Creation of a dedicated voluntary platform for demand assessment and aggregation to connect CO_2 transport and storage providers with emitters
    - Investment atlas of possible CO_2 storage locations
    - Sequential instructions for navigating permission procedures for CCS net-zero strategic projects
    - Formulation of sector-specific roadmaps through a knowledge-sharing platform for industrial CCUS projects
- Supporting carbon removals
    - Evaluation of overarching goals aligned with the 2040 climate ambition
    - Creation of policy alternatives to bolster industrial carbon removals
    - Enhancement of research and innovation efforts via Horizon Europe and the Innovation Fund
- Fostering carbon utilization
    - Increasing adoption of sustainable carbon as a resource within industrial sectors
    - Setting regulations for accounting all industrial carbon management activities

The European parliament and the Council of the European Union adopted the Renewable Energy Directive III (RED III) in 2023. Here, more precisely within the delegated regulation (EU) 2023/1185 [84], the calculation basis for the GHG emissions of RFNBOS and CRF is given in addition to the electricity consumption criteria for accountable hydrogen production; here, for example, for consideration as a sustainable fuel, a minimum GHG saving of 70% (max. 28.2 gCO_{2eq}/MJ) must be achieved compared to the fossil reference value (94 gCO_{2eq}/MJ). The total emissions of the corresponding fuels are added up across the different emission sources. These include emissions from the provision of inputs, emissions from processing, transport and distribution, and emissions from the combustion of the fuel in its end use. Savings from CCS are subtracted from the resulting total emissions. Within the calculation of emissions for the inputs, so-called "ex-use" emissions can be deducted; i.e., if, for example, CO_2 is used as an input and meets certain criteria, these GHG emissions can be deducted from those of the remaining input. One of the following criteria must be met.

(a) The CO_2 has been captured in an activity listed in Annex I of Directive 2003/87/EC (ETS), is included in an effective carbon price upstream, and has entered the chemical composition of the fuel before the year 2036. CO_2 resulting from other cases than from the combustion of fuels for electricity production can enter the chemical composition (i.e., be used) until 2041.

(b) CO_2 from the atmosphere.
(c) CO_2 from geological sources that are naturally released anyway.
(d) CO_2 from the production and combustion of biofuels or biomass that meet sustainability and GHG criteria and whose CO_2 capture has not yet received credit (under RED II Annex V and VI).
(e) CO_2 from the combustion of renewable liquid and gaseous transport fuels of non-biological origin or recycled carbon fuels complying with the GHG saving criteria, set out in Article 25(2) and Article 28(5) of Directive (EU) 2018/2001.

CO_2 from the thermal treatment of waste (e.g., municipal waste incineration) has not been addressed specifically within these criteria yet. Since municipal waste incineration plants are currently not covered under the EU Emissions Trading System, these CO_2 emissions do not fulfill the criteria described in (a). However, CO_2 generated from biological sources, including the portion resulting from the burning of municipal waste, qualifies as a permissible carbon source as long as it meets sustainability criteria as well as criteria for reducing GHG emissions.

In Table 5, the carbon sources are categorized into different options for their use as "ex-use" CO_2 emissions defined in the delegated regulation (EU) 2023/1185 [84].

Table 5. Classification of different carbon sources according to the Earth's carbon cycle and the criteria for use in RFNBO and CRF from delegated regulation (EU) 2023/1185.

Carbon Sources	RED III DA Ex-Use Compliant Sources	Carbon Cycle
Iron and steel production	(a)	Fossil
Cement production	(a)	Fossil
Quicklime production	(a)	Fossil
Pulp and paper production	(a) or (c)	Fossil/biogen
Ceramic and glass production	(a) *	Fossil
Aluminium production	(a)	Fossil
Zinc production	(a)	Fossil
Lead production	(a)	Fossil
Copper and silica production	(a)	Fossil
Soda production	(a)	Fossil
Carbon black production	(a)	Fossil
Fossil fuel production	(a)	Fossil
Bulk chemicals production	(a)	Fossil
Plastic production	(a)	Fossil
Ammonia production	(a)	Fossil
Ethylen oxide production	(a)	Fossil
Bioethanol production	(c)	Biogen
Biogas production	(c)	Biogen
Biomass-fired power plants	(c)	Biogen
Coal-fired power plants	(a)	Fossil
Gas-fired power plants	(a)	Fossil
Fuel oil-fired power plants	(a)	Fossil
Waste incineration plants	Not defined *	Fossil/biogen
Hazardous waste incineration plant	Not defined *	Fossil/biogen
RDF plant	Not defined *	Fossil/biogen
Direct Air Capture	(b)	Biogen

(a) EU ETS sources from Annex I (Directive 2003/87/EC); (b) CO_2 from Direct Air Capture (DAC); (c) CO_2 from the production or combustion of biofuels, bio-liquids or biomass fuels; *: not necessarily mandatory part of EU ETS.

4.5. Summary

Various industrial processes and power plants constitute a possible source of carbon in the form of CO_2. In Table 5, these sources are summarized and classified related to the carbon origin (fossil or biogenic) in terms of the slow and fast carbon cycles. The majority of possible carbon sources emit carbon of fossil origin. Within industrial processes, a significant proportion of biogenic carbon is used in pulp and paper production. Other processes mainly use fossil carbon (i.e., emit fossil CO_2). (Several industrial processes use refuse-derived fuels, e.g., waste tires, for the provision of heat and electricity in their respective process. These fuels may have a certain biogenic carbon content. In principle, these amounts are negligible compared to the use of fossil carbon, which is why the classification is based on the dominant fossil proportion). Carbon from CO_2 emissions emitted by processing biomass (e.g., production of bioethanol and/or biogas, the provision of heat and/or electricity from burning solid biofuels) is solely biogenic. Waste incineration facilities usually emit a mixture of fossil and biogenic carbon depending on the input waste streams. The provision of carbon via direct air capture from the atmosphere is considered biogenic, though the CO_2 content is also a mixture of fossil and biogenic origins, since the use and re-emission of this carbon is comparable to the fast carbon cycle.

Table 6 gives a qualitative summary of the different assessments for use of CO_2 according to their respective carbon origin. The different categories of carbon origin are evaluated with regard to the technical readiness level, energy demand, regulatory situation, and availability, as analyzed in Sections 4.3 and 4.4.

Table 6. Qualitative assessment of different CO_2 carbon sources.

Origin/Sources of Carbon	Technical Readiness Level	Energy Demand	Availability Status Quo	Availability Defossilized Society	Regulatory
Fossil					
Tertiary gaseous	+	+	+	-	o/-
Secondary solid	+	+	+	+/o	+/o
Biogen					
Gaseous	+	o	o	+	+
Liquid	+	+	-	-	+
Solid	+	+	o	-	+
Mixed carbon sources					
Ambient air	o	o/-	+	+	+
Other sources	+	+	o	o/-	Undefined

Specific evaluation explanation: in terms of TRL, this corresponds to a subdivision into high TRL, average TRL and low TRL; in terms of energy demand, the different sources are evaluated in relation to each other, reflecting a relatively low (+), average (o) or high energy demand (-), respectively; in terms of availability, the status quo of possible usable quantities or possible severe competition for use, whereby the classification is made according to large available quantity/low competition (+), medium availability (o) and low availability/high competition (-); in terms of regulation, the framework conditions defined in the delegated regulation of the EC [84] are used as the basis for evaluation, whereby a distinction is made between unrestricted (+), partly restricted (o) and restricted (-) use.

- The TRL of capture and utilization technologies for fossil and biogenic carbon is greater than the TRL of DAC technologies, which is why point sources (e.g., bioethanol production sites) are more favorable for the short-term application of CCU compared to ambient air/DAC.
- The energy demand for capturing CO_2 from the flue gas released by utilizing fossil and/or biogenic sources is clearly lower than for DAC. Even when the maturity of DAC technologies improves in the coming years, concentrated sources will most likely show a (much) better energy performance due to higher partial pressure of CO_2, thus resulting in a clear thermodynamic advantage.

- At the moment, fossil carbon sources are available in a great variety and quantity; but most likely, they will decrease in the future as a result of alternative green technologies gaining market shares due to the legally binding GHG reduction goals. However, the current availability of biogenic carbon sources is limited. This might change to some extent in the future by exploiting more biogenic waste streams, especially CO_2 of biogenic origin. Nevertheless, the total amount of sustainable biogenic carbon will most likely remain limited. In general, carbon from DAC shows a great availability today and in the future—but at the expense of a relatively high energy demand for the provision of a pure CO_2 stream easily usable in technological processes. Considering regulatory aspects, carbon from biogenic sources and ambient air have no restriction.
- The use of fossil carbon is possible to a certain extent and the use of carbon from mixed sources has not yet been addressed in the existing regulatory framework. However, there are currently no binding regulations in place and therefore substantial changes might still be possible in the time to come.

5. Conclusions

Due to the dependence on carbon in some industrial sectors as well as parts of the fuel supply, a certain share of carbon is still needed in the future within a defossilized energy system. In such an energy system, certain amounts of fossil carbon remain in the form of CO_2 from process-related emissions as well as carbon from biogenic sources and from the atmosphere. In order to create a set of regulations for the use of alternative carbon sources in the near future, discussions are already underway at the European and global level. Various stakeholders from industry and science are already addressing the problems of carbon sourcing and the associated consequences for energy demand, achievable implementation levels, and the resulting environmental impacts. It is obvious that the origin of the carbon has a significant influence on the climate impact of the goods produced from it. However, the literature to date has not addressed the link between different usable carbon sources and their impact on the biogeochemical cycle, focusing instead on the importance or significance of the LCA results for the respective sources. In contrast, one result of this study is the categorical exclusion of a large proportion of fossil carbon sources due to their disruption of Earth's carbon cycle. Other decisive factors are the type of energy supply and the technical maturity as well as the availability of the various supply options. There is a widespread agreement that, in order to make an in-depth statement about GHG savings from the use of alternative carbon sources, LCA must be conducted. Nevertheless, the results of previously conducted LCA demonstrate that even the provision of alternative carbon with a low carbon footprint continues to exert significant adverse effects on the planet, including the reduction of biodiversity.

Within legal regulations, a full consideration of various possible negative aspects of the use of biogenic carbon should take place to avoid a long-term framework that works against the goal of a more sustainable industry, possibly causing more damage than the fossil reference. For the determination of the overall GHG savings, energy demand and further environmental impacts of the different possible carbon supply chains, a comprehensive analysis (e.g., life cycle analysis) might be a suitable approach for each respective supply chain. In order to estimate the possible future reduction potential compared to the fossil reference, certain framework assumptions should be made, such as a largely defossilized energy supply. The results could serve as a benchmark for the extent of GHG reduction that is potentially possible through the provision of sustainable carbon.

In fundamental terms, the following main conclusions are drawn.

- Only biogenic and mixed carbon from the ambient air can be defined as truly sustainable in terms of the Earth's (fast) carbon cycle. Mixed carbon streams, such as those from waste recycling, form a gray area. The same applies to certain process-related emissions originating originally from fossil fuel energy.

- From an energy perspective, the level of technical maturity, and the size of the exploitable potentials, biogenic carbon sources should be utilized with priority for the time being. This applies above all to CO_2, resulting as a by-product in the refinement or use of primary and secondary biogenic carbon carriers. Additionally, the free delivery of nature provided through photosynthesis during plant growth can be used to the benefit of humankind.

Due to the relatively small residual budget of CO_2 emissions that remains to limit global warming to 1.5–2 °C to fulfill the demands of the Paris agreement, the focus in the future must primarily be on avoiding further fossil CO_2 emissions. To avoid a further increase of the total amount of CO_2 within the atmosphere, only CO_2 based on biogenic carbon/carbon from the atmosphere should be considered for further use in the long term in general. In the short and medium term, certain process emissions could be used transitionally as a CO_2 source. To avoid lock-in effects, this option should be subjected to a more in-depth analysis in alignment with the remaining emissions budget.

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References

1. Pörtner, H.-O.; Roberts, D.C.; Tignor, M.; Poloczanska, E.S.; Mintenbeck, K.; Alegría, A.; Craig, M.; Langsdorf, S.; Löschke, S.; Möller, V.; et al. (Eds.) *IPCC, 2022: Climate Change 2022: Impacts, Adaptation, Vulnerability: Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2022.
2. Shukla, P.R.; Skea, J.; Slade, R.; Al Khourdajie, A.; van Diemen, R.; McCollum, D.; Pathak, M.; Some, S.; Vyas, P.; Fradera, R.; et al. (Eds.) *Climate Change 2022—Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2023.
3. Purr, K.; Garvens, H.-J.; Bernicke, M.; Brieschke, J.; Kaliske, J.; Kessler, H.; Malsch, D.; Plickert, S.; Proske, C.; Rothe, B. Contribution to the Discussion on the Evaluation of Carbon Capture and Utilisation. Dessau-Roßlau, Background, September 2021. Available online: https://www.umweltbundesamt.de/en/publikationen/contribution-to-the-discussion-on-the-evaluation-of (accessed on 25 March 2024).
4. Gabrielli, P.; Gazzani, M.; Mazzotti, M. The Role of Carbon Capture and Utilization, Carbon Capture and Storage, and Biomass to Enable a Net-Zero-CO2 Emissions Chemical Industry. *Ind. Eng. Chem. Res.* **2020**, *59*, 7033–7045. [CrossRef]
5. Galimova, T.; Ram, M.; Bogdanov, D.; Fasihi, M.; Khalili, S.; Gulagi, A.; Karjunen, H.; Mensah, T.N.O.; Breyer, C. Global demand analysis for carbon dioxide as raw material from key industrial sources and direct air capture to produce renewable electricity-based fuels and chemicals. *J. Clean. Prod.* **2022**, *373*, 133920. [CrossRef]
6. Verband der Chemischen Industrie e.V. Daten und Fakten zu Energie und Rohstoffen: Energiestatistik im Überblick. Available online: https://www.vci.de/die-branche/zahlen-berichte/vci-statistik-grafiken-energie-klima-rohstoffe-chemie.jsp (accessed on 27 March 2023).
7. Fleiter, T.; Rehfeldt, M.; Neuwirth, M.; Herbst, A. Deep Decarbonisation of the German Industry via Electricity or Gas? A Scenario-Based Comparison of Pathways. 2020. Available online: https://publica.fraunhofer.de/handle/publica/409071 (accessed on 1 April 2024).
8. Joas, F.; Witecka, W.K.; Lenck, T.; Peter, F.; Seiler, F.; Samadi, S.; Schneider, C.; Holtz, G.; Kobiela, G.; Lechtenböhmer, S.; et al. *Klimaneutrale Industrie: Schlüsseltechnologien und Politikoptionen für Stahl, Chemie und Zement; Studie*; Agora Energiewende: Berlin, Germany, 2020. Available online: http://nbn-resolving.de/urn/resolver.pl?urn:nbn:de:bsz:wup4-opus-76758 (accessed on 20 March 2023).

9. Benndorf, R.; Bernicke, M.; Bertram, A.; Butz, W.; Dettling, F.; Drotleff, J.; Elsner, C.; Fee, E.; Gabler, C.; Galander, C.; et al. Treibhausgasneutrales Deutschland im Jahr 2050. Dessau-Roßlau. 2014. Available online: https://www.umweltbundesamt.de/sites/default/files/medien/378/publikationen/07_2014_climate_change_dt.pdf (accessed on 1 April 2024).
10. Stolz, B.; Held, M.; Georges, G.; Boulouchos, K. Techno-economic analysis of renewable fuels for ships carrying bulk cargo in Europe. *Nat. Energy* **2022**, *7*, 203–212. [CrossRef]
11. Breuer, J.L.; Scholten, J.; Koj, J.C.; Schorn, F.; Fiebrandt, M.; Samsun, R.C.; Albus, R.; Görner, K.; Stolten, D.; Peters, R. An Overview of Promising Alternative Fuels for Road, Rail, Air, Inland Waterway Transport in Germany. *Energies* **2022**, *15*, 1443. [CrossRef]
12. Kistner, L.; Bensmann, A.; Minke, C.; Hanke-Rauschenbach, R. Comprehensive techno-economic assessment of power technologies and synthetic fuels under discussion for ship applications. *Renew. Sustain. Energy Rev.* **2023**, *183*, 113459. [CrossRef]
13. He, M.; Sun, Y.; Han, B. Green Carbon Science: Efficient Carbon Resource Processing, Utilization, and Recycling towards Carbon Neutrality. *Angew. Chem.* **2022**, *134*, 15. [CrossRef]
14. Wang, F.; Harindintwali, J.D.; Yuan, Z.; Wang, M.; Wang, F.; Li, S.; Yin, Z.; Huang, L.; Fu, Y.; Li, L.; et al. Technologies and perspectives for achieving carbon neutrality. *Innovation* **2021**, *2*, 100180. [CrossRef] [PubMed]
15. Zhou, Y. Worldwide carbon neutrality transition? Energy efficiency, renewable, carbon trading and advanced energy policies. *Energy Rev.* **2023**, *2*, 100026. [CrossRef]
16. Carus, M.; Dammer, L.; Raschka, A.; Skoczinski, P. Renewable carbon: Key to a sustainable and future-oriented chemical and plastic industry: Definition, strategy, measures and potential. *Greenh. Gases* **2020**, *10*, 488–505. [CrossRef]
17. Archer, D. *The Global Carbon Cycle*; Princeton University Press: Princeton, NJ, USA, 2011.
18. *The Global Carbon Cycle and Climate Change*; Elsevier: Amsterdam, The Netherlands, 2023.
19. Riebeek, H. The Carbon Cycle. Available online: https://www.earthobservatory.nasa.gov/features/CarbonCycle (accessed on 24 January 2023).
20. Berner, R.A. The long-term carbon cycle, fossil fuels and atmospheric composition. *Nature* **2003**, *426*, 323–326. [CrossRef]
21. Houghton, R.A. Balancing the Global Carbon Budget. *Annu. Rev. Earth Planet. Sci.* **2007**, *35*, 313–347. [CrossRef]
22. Canadell, J.G.; Le Quéré, C.; Raupach, M.R.; Field, C.B.; Buitenhuis, E.T.; Ciais, P.; Conway, T.J.; Gillett, N.P.; Houghton, R.A.; Marland, G. Contributions to accelerating atmospheric CO2 growth from economic activity, carbon intensity, and efficiency of natural sinks. *Proc. Natl. Acad. Sci. USA* **2007**, *104*, 18866–18870. [CrossRef] [PubMed]
23. Intergovernmental Panel on Climate Change 2007 (Ed.) *The Physical Science Basis: Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK, 2007.
24. Kähler, F.; Carus, M.; Porc, O.; vom Berg, C. Turning off the tap for fossil carbon: Future Prospects for a Global Chemical and Derived Material Sector Based on Renewable Carbon. April 2021. Available online: https://renewable-carbon.eu/publications/product/turning-off-the-tap-for-fossil-carbon-future-prospects-for-a-global-chemical-and-derived-material-sector-based-on-renewable-carbon/ (accessed on 18 March 2024).
25. Pales, A.F.; Levi, P. The Future of Petrochemicals: Towards a More Sustainable Chemical Industry. Paris, France. October 2018. Available online: https://www.iea.org/reports/the-future-of-petrochemicals#overview (accessed on 18 March 2024).
26. Aguilar, P.; Groß, B. Battery electric vehicles and fuel cell electric vehicles, an analysis of alternative powertrains as a mean to decarbonise the transport sector. *Sustain. Energy Technol. Assess.* **2022**, *53*, 102624. [CrossRef]
27. Peng, R.; Tang, J.H.C.G.; Yang, X.; Meng, M.; Zhang, J.; Zhuge, C. Investigating the factors influencing the electric vehicle market share: A comparative study of the European Union and United States. *Appl. Energy* **2024**, *355*, 122327. [CrossRef]
28. Bringezu, S.; Kaiser, S.; Turnau, S. Zukünftige Nutzung von CO2 als Rohstoffbasis der deutschen Chemie- und Kunststoffindustrie. 2020. Available online: https://kobra.uni-kassel.de/bitstream/handle/123456789/11483/ZukuenftigeNutzungVonCO2AlsRohstoffbasis.pdf;jsessionid=BE40A417B043E88C3820EF39DF618840?sequence=4 (accessed on 27 March 2023).
29. International Energy Agency (IEA). *Putting CO2 to Use: Creating Value from Emissions*; IEA: Paris, France, 2019.
30. Huo, J.; Wang, Z.; Oberschelp, C.; Guillén-Gosálbez, G.; Hellweg, S. Net-zero transition of the global chemical industry with CO2-feedstock by 2050: Feasible yet challenging. *Green Chem. Int. J. Green Chem. Resour. GC* **2023**, *25*, 415–430. [CrossRef]
31. Hepburn, C.; Adlen, E.; Beddington, J.; Carter, E.A.; Fuss, S.; Mac Dowell, N.; Minx, J.C.; Smith, P.; Williams, C.K. The technological and economic prospects for CO2 utilization and removal. *Nature* **2019**, *575*, 87–97. [CrossRef]
32. Schmid, C.; Hahn, A. Potential CO2 utilisation in Germany: An analysis of theoretical CO2 demand by 2030. *J. CO2 Util.* **2021**, *50*, 101580. [CrossRef]
33. Viebahn, P.; Horst, J.; Scholz, A.; Zelt, O. Technologiebericht 4.4 Verfahren der CO2-Abtrennung aus Faulgasen und Umgebungsluft innerhalb des Forschungsprojekts TF_Energiewende. Wuppertal. 2018. Available online: https://nbn-resolving.org/urn:nbn:de:bsz:wup4-opus-70624 (accessed on 27 March 2023).
34. Fröhlich, T.; Blömer, S.; Münter, D.; Brischke, L.-A. *CO2-Quellen für die PtX-Herstellung in Deutschland—Technologien, Umweltwirkung, Verfügbarkeit*; Institut für Energie- und Umweltforschung Heidelberg (IFEU): Heidelberg, Germany, 2019.
35. Hobohm, J.; der Maur, A.A.; Dambeck, H.; Kemmler, A.; Koziel, S.; Kreidelmeyer, S.; Piégsa, A.; Wendring, P.; Meyer, B.; Apfelbacher, A.; et al. *Status und Perspektiven flüssiger Energieträger in der Energiewende*; Endbericht: Basel, Switzerland, 2018.

36. Geres, R.; Kohn, A.; Lenz, S.; Ausfelder, F.; Bazzanella, A.M.; Möller, A. *Roadmap Chemie 2050: Auf dem Weg zu einer Treibhausgasneutralen Chemischen Industrie in Deutschland*; DECHEMA e.V.: München, Germany, 2019.
37. DIRECTIVE (EU) 2018/2001 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 11 December 2018 on the Promotion of The Use of Energy from Renewable Sources (Recast). 2018. Available online: https://eur-lex.europa.eu/eli/dir/2018/2001/oj (accessed on 2 April 2024).
38. DIRECTIVE (EU) 2023/2413 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 18 October 2023 Amending Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as Regards the Promotion of Energy from Renewable Sources, and Repealing Council Directive (EU) 2015/652. 18th 2023. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32023L2413&qid=1699364355105 (accessed on 2 April 2024).
39. Andrew, R.M.; Peters, G.P. The Global Carbon Project's Fossil CO2 Emissions Dataset. 2023. Available online: https://zenodo.org/records/10562476 (accessed on 2 April 2024).
40. Ritchie, H.; Rosado, P.; Roser, M. Emissions by sector: Where do greenhouse gases come from? *Our World in Data*. 2020. Available online: https://ourworldindata.org/emissions-by-sector (accessed on 5 April 2024).
41. Kost, C.; Shammugam, S.; Fluri, V.; Peper, D.; Memar, A.D.; Schlegl, T. Studie: Stromgestehungskosten erneuerbare Energien: Juni 2021. Freiburg. *June 2021*. Available online: https://www.ise.fraunhofer.de/de/veroeffentlichungen/studien/studie-stromgestehungskosten-erneuerbare-energien.html (accessed on 15 April 2023).
42. IEA—International Energy Agency (Ed.) Renewable Energy Market Update: Outlook for 2023 and 2024. *June 2023*. Available online: https://iea.blob.core.windows.net/assets/63c14514-6833-4cd8-ac53-f9918c2e4cd9/RenewableEnergyMarketUpdate_June2023.pdf (accessed on 23 July 2024).
43. Taylor, M.; Al-Zoghoul, S.; Ralon, P.; Sorokina, O. Renewable Power Generation: Costs in 2022. Abu Dhabi. 2023. Available online: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2023/Aug/IRENA_Renewable_power_generation_costs_in_2022.pdf?rev=cccb713bf8294cc5bec3f870e1fa15c2 (accessed on 10 April 2024).
44. Bazzanella, A.; Krämer, D. (Eds.) *Technologies for Sustainability and Climate Protection—Chemical Processes and Use of CO2: Results of the BMBF Funding Measure*; DECHEMA Gesellschaft für Chemische Technik und Biotechnologie e.V.: Frankfurt/Main, Germany, 2019. Available online: https://dechema.de/en/energyandclimate/_/CO2_Buch_engl.pdf (accessed on 20 February 2023).
45. Kähler, F.; Carus, M.; vom Berg, C.; Stratmann, M. CO2 Reduction Potential of the Chemical Industry through CCU: A Simplified Exploratory Scenario for Ccu-Based Supply of Embedded Carbon for the Global Chemicals and Derived Materials Sector. 2022. Available online: https://renewable-carbon-initiative.com/wp-content/uploads/2022/05/22-05-03-CO2_Reduction_Potential_of_the_Chemical_Industry_Through_CCU.pdf (accessed on 18 March 2024).
46. Del Rio, D.D.F.; Sovacool, B.K.; Foley, A.M.; Griffiths, S.; Bazilian, M.; Kim, J.; Rooney, D. Decarbonizing the ceramics industry: A systematic and critical review of policy options, developments and sociotechnical systems. *Renew. Sustain. Energy Rev.* **2022**, *157*, 112081. [CrossRef]
47. Korczak, K.; Kochański, M.; Skoczkowski, T. Mitigation options for decarbonization of the non-metallic minerals industry and their impacts on costs, energy consumption and GHG emissions in the EU—Systematic literature review. *J. Clean. Prod.* **2022**, *358*, 132006. [CrossRef]
48. Zhang, C.-Y.; Han, R.; Yu, B.; Wei, Y.-M. Accounting process-related CO2 emissions from global cement production under Shared Socioeconomic Pathways. *J. Clean. Prod.* **2018**, *184*, 451–465. [CrossRef]
49. Alassali, A.; Picuno, C.; Chong, Z.K.; Guo, J.; Maletz, R.; Kuchta, K. Towards Higher Quality of Recycled Plastics: Limitations from the Material's Perspective. *Sustainability* **2021**, *13*, 13266. [CrossRef]
50. Huang, K.; Peng, X.; Kong, L.; Wu, W.; Chen, Y.; Maravelias, C.T. Greenhouse Gas Emission Mitigation Potential of Chemicals Produced from Biomass. *ACS Sustain. Chem. Eng.* **2021**, *9*, 14480–14487. [CrossRef]
51. Wiśniewski, P.; Kistowski, M. Greenhouse Gas Emissions from Cultivation of Plants Used for Biofuel Production in Poland. *Atmosphere* **2020**, *11*, 394. [CrossRef]
52. Hiloidhari, M.; Sharno, M.A.; Baruah, D.C.; Bezbaruah, A.N. Green and sustainable biomass supply chain for environmental, social and economic benefits. *Biomass Bioenergy* **2023**, *175*, 106893. [CrossRef]
53. Gasparatos, A.; Stromberg, P.; Takeuchi, K. Sustainability impacts of first-generation biofuels. *Anim. Front.* **2013**, *3*, 12–26. [CrossRef]
54. Mohn, J.; Szidat, S.; Fellner, J.; Rechberger, H.; Quartier, R.; Buchmann, B.; Emmenegger, L. Determination of biogenic and fossil CO(2) emitted by waste incineration based on (14)CO(2) and mass balances. *Bioresour. Technol.* **2008**, *99*, 6471–6479. [CrossRef] [PubMed]
55. Lan, X.; Tans, P.; Thoning, K.; NOAA Global Monitoring Laboratory. Trends in Globally-Averaged CO2 Determined from NOAA Global Monitoring Laboratory Measurements. 2023. Available online: https://gml.noaa.gov/ccgg/trends/global.html?doi=10.15138/9n0h-zh07 (accessed on 10 February 2023).
56. IEAGHG (Ed.) *CO2 as a Feedstock: Comparison of CCU Pathways. 2021-02*; IEAGHG: Cheltenham, UK, November 2021.
57. Lehtonen, J.; Järnefelt, V.; Alakurtti, S.; Arasto, A.; Hannula, I.; Harlin, A.; Koljonen, T.; Lantto, R.; Lienemann, M.; Onarheim, K.; et al. *The Carbon Reuse Economy: Transforming CO2 from a Pollutant into a Resource*; VTT Technical Research Centre of Finland: Espoo, Finland, 2019.

58. Bradke, H.; Büdicker, K.; Deister, U.K.; Krämer, D.; Rinschede, A.; Zapp, P. Industrielle CO2-Kreisläufe. May 2021. Available online: https://www.vdi.de/ueber-uns/presse/publikationen/details/industrielle-co2-kreislaeufe (accessed on 8 March 2023).
59. *Gaseous Carbon Waste Streams Utilization*; National Academies Press: Washington, DC, USA, 2019.
60. Kasten, P.; Heinemann, C.; Seebach, D.; Sutter, J. Not to Be Taken for Granted: Climate Protection and Sustainability Through PtX: Discussion of Requirements for and First Approaches to Developing Verification Criteria for a Climate-Friendly and Sustainable Production of PtX. Impulse Paper on Behalf of BUND as Part of the Copernicus Project P2X, Berlin. September 2019. Available online: https://www.oeko.de/fileadmin/oekodoc/Impulse_paper_criteria_for_e-fuel_production.pdf (accessed on 10 February 2023).
61. Terlouw, T.; Bauer, C.; Rosa, L.; Mazzotti, M. Life cycle assessment of carbon dioxide removal technologies: A critical review. *Energy Environ. Sci.* **2021**, *14*, 1701–1721. [CrossRef]
62. Galán-Martín, Á.; Tulus, V.; Díaz, I.; Pozo, C.; Pérez-Ramírez, J.; Guillén-Gosálbez, G. Sustainability footprints of a renewable carbon transition for the petrochemical sector within planetary boundaries. *One Earth* **2021**, *4*, 565–583. [CrossRef]
63. NASA. Definition of Technology Readiness Levels. Available online: https://esto.nasa.gov/files/trl_definitions.pdf (accessed on 10 February 2023).
64. Fischedick, M.; Görner, K.; Thomeczek, M. *CO2: Abtrennung, Speicherung, Nutzung*; Springer: Berlin/Heidelberg, Germany, 2015.
65. Bisotti, F.; Hoff, K.A.; Mathisen, A.; Hovland, J. Direct Air capture (DAC) deployment: A review of the industrial deployment. *Chem. Eng. Sci.* **2024**, *283*, 119416. [CrossRef]
66. Budinis, S.; McCulloch, S.; Bains, P.; Bennet, S.; Briens, F.; Fajardy, M.; Fernandez Pales, A.; Greenfield, C.; Hannula, I.; Kochhar, K.; et al. Direct Air Capture: A Key Technology for Net Zero. April 2022. Available online: https://www.iea.org/reports/direct-air-capture-2022 (accessed on 10 February 2023).
67. Vaz, S.; de Souza, A.P.R.; Baeta, B.E.L. Technologies for carbon dioxide capture: A review applied to energy sectors. *Clean. Eng. Technol.* **2022**, *8*, 100456. [CrossRef]
68. Leeson, D.; Dowell, N.M.; Shah, N.; Petit, C.; Fennell, P.S. A Techno-economic analysis and systematic review of carbon capture and storage (CCS) applied to the iron and steel, cement, oil refining and pulp and paper industries, as well as other high purity sources. *Int. J. Greenh. Gas Control.* **2017**, *61*, 71–84. [CrossRef]
69. Psarras, P.C.; Comello, S.; Bains, P.; Charoensawadpong, P.; Reichelstein, S.; Wilcox, J. Carbon Capture and Utilization in the Industrial Sector. *Environ. Sci. Technol.* **2017**, *51*, 11440–11449. [CrossRef] [PubMed]
70. Bains, P.; Psarras, P.; Wilcox, J. CO2 capture from the industry sector. *Prog. Energy Combust. Sci.* **2017**, *63*, 146–172. [CrossRef]
71. Rodin, V.; Lindorfer, J.; Böhm, H.; Vieira, L. Assessing the potential of carbon dioxide valorisation in Europe with focus on biogenic CO2. *J. CO2 Util.* **2020**, *41*, 101219. [CrossRef]
72. Madhu, K.; Pauliuk, S.; Dhathri, S.; Creutzig, F. Understanding environmental trade-offs and resource demand of direct air capture technologies through comparative life-cycle assessment. *Nat. Energy* **2021**, *6*, 1035–1044. [CrossRef]
73. IEA—International Energy Agency. CO2 Emissions in 2023: A New Record High, But Is There Light at the End of the Tunnel? Paris, France. February 2024. Available online: https://www.iea.org/reports/co2-emissions-in-2023 (accessed on 4 April 2024).
74. Bentsen, N.S.; Felby, C.; Thorsen, B.J. Agricultural residue production and potentials for energy and materials services. *Prog. Energy Combust. Sci.* **2014**, *40*, 59–73. [CrossRef]
75. Syed-Hassan, S.S.A.; Wang, Y.; Hu, S.; Su, S.; Xiang, J. Thermochemical processing of sewage sludge to energy and fuel: Fundamentals, challenges and considerations. *Renew. Sustain. Energy Rev.* **2017**, *80*, 888–913. [CrossRef]
76. Gao, N.; Kamran, K.; Quan, C.; Williams, P.T. Thermochemical conversion of sewage sludge: A critical review. *Prog. Energy Combust. Sci.* **2020**, *79*, 100843. [CrossRef]
77. European Commission. A New Circular Economy Action Plan: For a Cleaner and More Competitive Europe. March 2020. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1583933814386&uri=COM:2020:98:FIN (accessed on 27 March 2023).
78. Singh, N.; Ogunseitan, O.A.; Tang, Y. Medical waste: Current challenges and future opportunities for sustainable management. *Crit. Rev. Environ. Sci. Technol.* **2022**, *52*, 2000–2022. [CrossRef]
79. National Oceanic and Atmospheric Administration. Carbon Dioxide Now More Than 50% Higher than Pre-Industrial Levels. Available online: https://www.noaa.gov/news-release/carbon-dioxide-now-more-than-50-higher-than-pre-industrial-levels (accessed on 27 March 2023).
80. Friedlingstein, P.; O'Sullivan, M.; Jones, M.W.; Andrew, R.M.; Gregor, L.; Hauck, J.; Le Quéré, C.; Luijkx, I.T.; Olsen, A.; Peters, G.P.; et al. Global Carbon Budget 2022. *Earth Syst. Sci. Data* **2022**, *14*, 4811–4900. [CrossRef]
81. European Commission. Sustainable Carbon Cycles. December 2021. Available online: https://climate.ec.europa.eu/system/files/2021-12/com_2021_800_en_0.pdf (accessed on 27 March 2023).
82. REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL Establishing a Union Certification Framework for Permanent Carbon Removals, Carbon Farming and Carbon Storage in Products. 20th 2024. Available online: https://www.europarl.europa.eu/meetdocs/2014_2019/plmrep/COMMITTEES/ENVI/DV/2024/03-11/Item9-Provisionalagreement-CFCR_2022-0394COD_EN.pdf (accessed on 4 April 2024).

83. COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS—Towards an Ambitious Industrial Carbon MANAGEMENT for the EU. 6th 2024. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2024:62:FIN&qid=1707312980822 (accessed on 4 April 2024).
84. COMMISSION DELEGATED REGULATION (EU) 2023/1185 of 10 February 2023 Supplementing Directive (EU) 2018/2001 of the European Parliament and of the Council by Establishing a Minimum Threshold for Greenhouse Gas Emissions Savings of recycled Carbon Fuels and by Specifying a Methodology for Assessing Greenhouse Gas Emissions Savings from Renewable Liquid and Gaseous Transport Fuels of Non-Biological Origin and from Recycled Carbon Fuels. 2023. Available online: http://data.europa.eu/eli/reg_del/2023/1185/oj (accessed on 4 April 2024).