Carbon accounting in Bio-CCUS supply chains – identifying key issues for science and policy

IEA Bioenergy Task 45

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Carbon accounting across Bio-CCUS supply chains

– identifying key issues for science and policy

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Summary

Having just a few years ago been a topic primarily featured in future-oriented energy system and climate models, Bio-CCUS (bioenergy with carbon capture and utilization or storage), is increasingly becoming a matter of on-the-ground deployment. However, while the technological aspects of capture, utilization and storage of biogenic CO_2 are rather well-understood and have in many cases already been used in commercial settings, there are still substantial gaps on the policy and governance side. Particularly important aspects here are carbon accounting, how to quantify the climate impact of Bio-CCUS systems and how to include these elements in policy frameworks. In this report, we review key issues to focus on and discuss different options for how these could be addressed from a scientific as well as from a policy perspective. Importantly though, while upstream feedstock supply chains are a key factor in total life cycle emissions accounting, there is already a large literature on carbon accounting in biomass supply chains in general. As we do not expect feedstock supply chains for bio-CCUS differ from biomass supply chains in general, this report only briefly touches upon upstream aspects.

While it is common for CCU and CCS systems – be they based on biogenic or fossil CO_2 - to be jointly discussed as (bio-) CCUS, there are important differences between the two. This pertains to post-capture CO_2 accounting, as well as policy systems and business models. For Bio-CCS, analysis of post-capture CO_2 flows should be fairly straightforward, as the CO_2 is to be permanently stored and immobilized in geological formations. This is assuming avoidance of e.g., leakages in transport and storage as well as the minimization of use of fossil energy for CO_2 transport. The major policy challenge around Bio-CCS concerns how to design policy frameworks to incentivize carbon dioxide removal (CDR), also referred to as negative emissions. A key question is if, or to what extent, policy frameworks for carbon dioxide removal should be integrated into existing systems for emission reductions – such as the EU emissions trading system – or whether there should be specific ring-fenced systems for CDR.

Analysis of the post-capture CO_2 flows for Bio-CCU is more complicated than for Bio-CCS. CO_2 can be utilized for a wide range of purposes, including as feedstock for many different products, which means that there are great many cases to analyze to understand the net climate impact in detail. This concerns aspects such as the process efficiency, the kinds of energy used and what existing product the Bio-CCU product could be replacing. In addition, a very important issue that has thus far not received sufficient attention is how to factor in the variation in CO_2 storage permanence between different CCU products, i.e., for how long time CO_2 used in a product stays away from the atmosphere. This can vary from less than a year for a fuel or a chemical, via decades for non-packaging plastics and up to possibly centuries in the case of some building materials. Given the growing interest in (bio-)CCU projects, it is essential to find approaches to *a)* quantify how the climate impact of CCU products depends on CO_2 storage permanence and *b)* how these aspects can be integrated into policy frameworks. To this end, we suggest to draw inspiration from similar frameworks, such as the UNFCCC accounting framework for Harvested Wood Products. However, there is a clear and urgent need for more research into this. To ensure that Bio-CCUS systems can fulfil their potential to mitigate climate change, it is key to strike a balance between properly understanding the full picture of their climate impacts and finding reasonably straightforward means how to include these aspects in policy frameworks.

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Abbreviations

AFOLU	Agriculture, Forestry and Other Land Use
Bio-CCUS/BECCYS	Capture and storage or utilization of biogenic CO_2
CCS/CCU	Carbon capture and storage/carbon capture and utilization
CDM	Clean Development Mechanism
CDR	Carbon Dioxide Removal
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
DAC	Direct Air Capture
ETS	Emissions Trading System
EOR/EGR	Enhanced Oil/Gas Recovery
GWP	Global Warming Potential
HWP	Harvested Wood Products
LCA	Life Cycle Assessment
NDC	Nationally Determined Contribution
NET	Negative Emissions Technology
NIR	National Inventory Report
P2X/PtX	Power-to-X
PV	Photovoltaics
R&DDD	Research and development, demonstration & deployment
RED	Renewable Energy Directive

1 Introduction

In order to realize the ambition of the 2015 Paris agreement to limit global warming to 1.5°C, global CO_2 emissions need to reach net-zero by around 2050 (IPCC 2018). This is clearly a highly ambitious and very challenging target despite rapid developments in deployment of key technologies like solar PV, wind power and electrification of road transport. Carbon dioxide removal (CDR) - sometimes also referred to as Negative Emissions Technologies or NETs - is an additional tool that can be drawn upon to enable the net-zero target even in the presence of residual greenhouse gas (GHG) emissions. Among the different solutions that can enable CDR, bioenergy with carbon capture and storage (Bio-CCS or BECCUS) has been one of those most discussed in the research literature (e.g., Anderson and Peters 2016; van Vuuren et al. 2017; Heck et al. 2018).

Much of the discussion in the literature has taken a very long-term perspective on the issue and has been dedicated to addressing the potential broader sustainability impacts from broad deployment of Bio-CCS (IPCC 2018; Hansson et al. 2021). However, in the light of the increasing interest in CDR from policy makers, it is high time to also investigate aspects pertaining to the practicalities of actual near-term deployment of Bio-CCS systems and value chains.

In parallel with the growing political and research interest in Bio-CCS, there has been a similar rise of interest in capture and *utilization* of biogenic CO_2 for different purposes, including as feedstock for production of materials, chemicals or fuels. This is commonly referred to as Bio-CCU or BECCU and the two are often jointly referred to as Bio-CCUS or BECCUS (Text box 1).

Bio-CCUS systems can be implemented in a broad range of contexts, including but not limited to sectors that already use substantial amounts of biomass as fuel or feedstock, such as heat & power generation, pulp & paper mills or biogas production (Olsson et al. 2020)[1]. However, even though there is substantial physical and technological potential, there are still plenty of questions remaining when it comes to operationalizing full Bio-CCUS value chains. While there are relatively mature CO_2 capture technologies, Bio-CCS transportation & storage infrastructures are still in early stages of development, and the same goes for Bio-CCU product markets. It is still not clear how business models should be designed to make for economically viable Bio-CCUS value chains.

Text box 1. On abbreviations related to capture of biogenic CO2

Note on abbreviations

Capture and storage or utilization of biogenic CO_2 is sometimes abbreviated as "BECCS/U", sometimes as "BECCUS" and sometimes as "Bio-CCUS". There is not yet real consensus as to which is preferred. However, the latter has the advantage that it does not exclude capture of biogenic CO_2 that originates from processes where energy generation is **not** the primary goal. Examples of this include fermentation in the production of bioethanol or upgrading of biogas to biomethane.

[1] While the potential volumes to be captured from existing biomass-using facilities are small relative to those envisioned in IAMs, they should not be dismissed. For example, adding CCS to biogenic CO_2 point sources in the global pulp & paper sector could enable more than 130 million tonnes of carbon dioxide removal (Kuparinen et al. 2019).

Further development and scaling of bio-CCUS will require policy support, which will logically be linked to potential contribution to climate change mitigation. However, developing and implementing such policies may turn out to be quite challenging, for several reasons. *Firstly*, quantification of biomass-based life cycle GHG emissions is already quite complicated, as has become clear over the recent decade as the merits of different biomass-based energy carriers have been discussed across a broad range of policy contexts (Searchinger et al. 2008; Berndes et al. 2013; Lamers and Junginger 2013) . To this already intricate analysis shall now also be incorporated an analysis of the climate impacts related to capture, utilization and/or storage of CO_2.

Secondly, even with comprehensive and transparent methods by which Bio-CCUS life cycle GHG balances can be developed, a key remaining question is how to implement these methods in policy frameworks. There will be a need to find a balance between *a)* acknowledging the heterogeneity across different value chains, and *b)* avoiding overly complicated legal specifications that are costly to administer. In addition, it will be crucial to find ways to allocate burdens and benefits appropriately in cases where captured carbon is transferred across Bio-CCUS supply chains, not only between sectors (e.g., agriculture/forestry>industry->air transport as might be the case with a Bio-CCU aviation fuel) but between jurisdictions as well.

In this report, we review the challenges around accounting for the climate effects of Bio-CCS and Bio-CCU supply chains and discuss key issues that need to be addressed to prepare a sound scientific and legally functional foundation for political governance of Bio-CCUS. It is important to emphasize that Bio-CCUS can be implemented in many different contexts and sectors. This means that there can be substantial variations in terms of the actual details of carbon accounting and climate impact, and we do not strive to provide detail analysis for each context. Rather, our ambition is to give a more principal overview of some particularly important general issues.

The report is structured as follows. In section 2, we provide an overview of key issues that need to be considered when quantifying GHG emissions across Bio-CCUS supply chains. In section 3, we discuss how to apply these scientific findings within a governance context. Section 4, finally, concludes with a discussion, some recommendations for policy makers and researchers, and suggestions for further research.

2 CO_2 flows in Bio-CCUS systems - an overview

This report takes as its starting point Bio-CCUS/BECCUS as a joint concept, acknowledging that the Bio-CCS and Bio-CCU value chains have many joint components and that innovation processes will likely cross-fertilize between them (Olsson et al. 2020). At the same time, Bio-CCS and Bio-CCU are quite distinct when it comes to their CO_2 flows (see Figure 1), their climate change mitigation potential and how this should be governed. For this reason, this section reviews the Bio-CCS and Bio-CCU perspectives in turn.

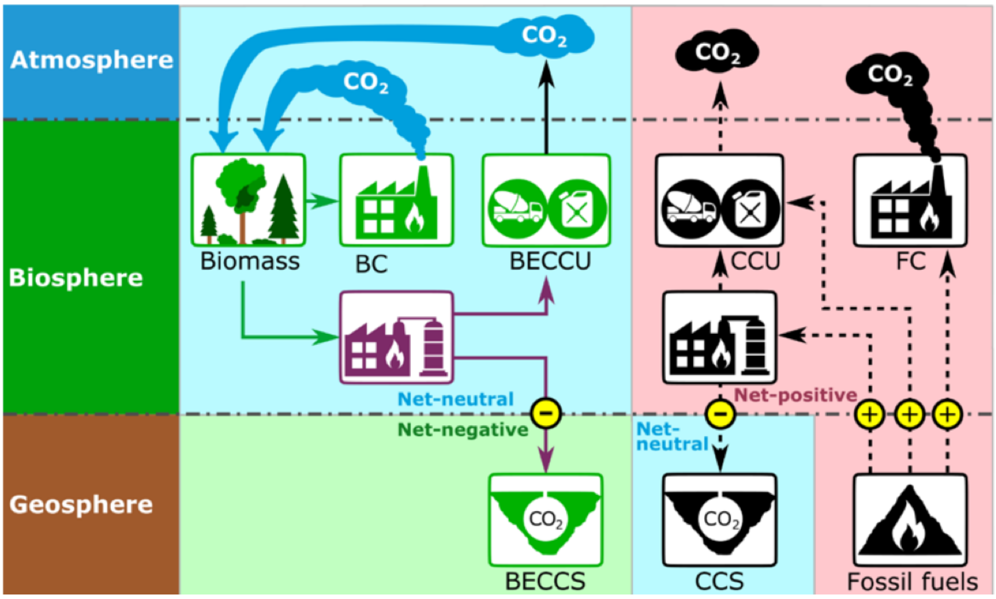

Figure 1. Conceptual illustration of the carbon flows related to Bio-CCS and Bio-CCU. BC=Biomass combustion & FC=Fossil fuel combustion. Figure by Lappeenranta University of Technology (Olsson et al. 2020)

Another key aspect that the reader should be aware of is that we do not dwell at any length on upstream feedstock supply chain emissions. While these are highly important for total life cycle emissions of Bio-CCUS systems (e.g., Terlouw et al. 2021), we assume that Bio-CCUS feedstock supply chains will not differ from bioenergy feedstock supply chains in general. As there is already a large body of literature on the greenhouse gas balances and climate change impacts of bioenergy supply chains in general (e.g, Creutzig et al. 2015; Cowie et al. 2021; IEA Bioenergy 2021), we will focus on the later stages of Bio-CCUS supply chain. In other words, one could frame our focus herein as a "gate-to-grave" (Bio-CCS) or possibly "gate-to-cradle" (Bio-CCU) analysis, as we center our discussion on flows of biogenic CO_2 either in different forms of products (Bio-CCU) or on the way to long-term storage (Bio-CCS).

2.1 CAPTURING BIOGENIC CO_2

A general aspect to keep in mind when discussing technological aspects of Bio-CCS and Bio-CCU is to see them as sub-categories of CCS and CCU in general. The CO_2 capture stage influences the overall climate impact of the Bio-CCUS supply chain predominantly through the capture rates and the energy needed for the process. The capture rates can vary substantially between processes and context, depending on e.g., the number of point sources at a specific facility. If most of the CO_2 emissions from a facility are concentrated at one source, this makes for lower costs of capture whereas if emissions are distributed across several different point sources, high capture rates can become prohibitively expensive (Olsson et al. 2020).

As for the energy needed for capture, the higher the energy efficiency – i.e., the lower the energy penalty of the process - and the lower the GHG footprint of the energy used for capture, the better the overall CO_2 balance of the capture stage. As is illustrated in Figure 2, there is great heterogeneity between different sectors and processes when it comes to the energy demands of CO_2 capture. An important aspect to emphasize here is that whether the CO_2 to be captured is biogenic or fossil is in itself typically not a primary factor in determining the energy demand.

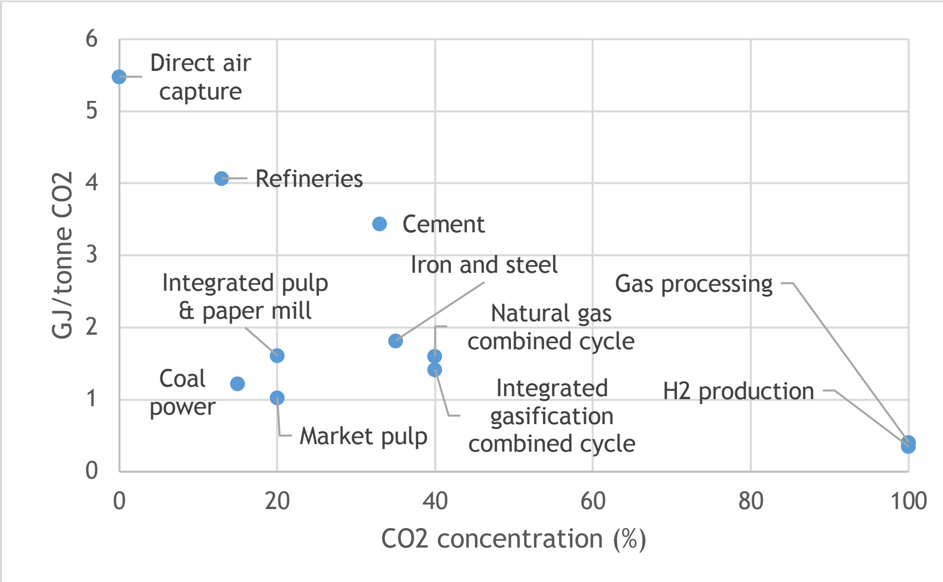

Figure 2. Overview of energy needs for CO_2 capture in different processes. Data from von der Assen et al (2016).

Some key aspects to be mentioned when it comes to things that determine the climate impact of the capture stage include CO_2 concentration in the gas stream in question, the availability of process heat on-site (e.g, Olsson et al. 2020) and if the heat used for the capture process can be recovered afterwards (Bisinella et al. 2021). For example, bioethanol production facilities typically have very highly concentrated CO_2 streams resulting from fermentation processes, and these can be captured at low energy expense. The same goes for biogas upgrading processes that already have CO_2 separation as one of its process stages. Pulp & paper mills have only modestly concentrated CO_2 streams but tend, on the other hand, to be very large facilities and with good on-site supply of process heat (von der Assen et al. 2016). For all these processes, however, it is important to emphasize that there is a lot of current R&D activity around developing more efficient capture processes with important analyses to be done around how best to integrate CO_2 capture as a component of overall plant operation and energy systems (Creutzig et al. 2019).

2.2 EMISSIONS FROM TRANSPORT & STORAGE OF CO_2

If the CO_2 captured is to be sequestered in geological formations for long-term storage, it will in many cases be transported a long distance. CO_2 can be transported by land in trucks or by railway, but for longer distances and larger volumes, pipelines and ship transport are the two most viable alternatives (Kjärstad et al. 2016). The emissions from the energy needed to transport CO_2 varies depending on the mode of transport used as well as the transport distance, but tend to be fairly small, amounting to 10-25 kg CO_2 per tonne CO_2 transported for distances up to 1000 km using pipeline or ship transport (Bisinella et al. 2021). Emissions from ship transport are mainly a function of the type of energy and the ship's fuel efficiency. Consequently, lower transport distances, more efficient engines and increased use of low-carbon fuels can help reduce emissions from this part of the supply chain. Note also that there are projects investigating the possibility of installing CCS equipment on ships, i.e., capturing CO_2 from the ship's engines for onboard storage (Roussanaly 2021).

There are also embedded emissions resulting from construction of transport & storage infrastructure. There has - to the best of our knowledge - not been any analyses done on how such emissions affect the overall balance of Bio-CCS projects, but Cuéllar-Franca & Azapagic (2015) analyze a fossil-based CCS supply chain and find that emissions arising from infrastructure construction play only a marginal role in the overall balance. This is a conclusion that reasonably should extend to Bio-CCS projects as well (Bennett et al. 2019).

As for the permanent storage stage of the CCS supply chain, an accident or some sort of failure could result in emissions. This means that careful site selection and construction of the storage facility is essential, as is reliable monitoring techniques (Gholami et al. 2021). Public concern around the safety of CO_2 storage is also a central issue and an important factor why e.g., key CO_2 storage sites in Europe are likely to be located offshore.

2.3 BIO-CCS AS A NEGATIVE EMISSIONS TECHNOLOGY

In section 2.1, we noted that from a technological perspective, Bio-CCS should be seen as a sub-category of CCS technologies more generally. Similarly, from a governance perspective, Bio-CCS should be seen as a sub-category of the portfolio of technologies used for carbon dioxide removal (CDR), also referred to as negative emissions technologies (NETs). CDR/NETs come in many forms and can be categorized as *a)* nature-based solutions like afforestation, reforestation, ocean fertilization and enhanced weathering, *b)* purely technology-based solutions, where direct air capture (DAC) is really the only available option, and *c)* technologies that straddle both the “nature” and “technology” spheres in the sense that their potential to remove CO_2 from the atmosphere is heavily reliant on management and process choices in the biosphere as well as in the “technosphere”. This latter category is where Bio-CCS resides, together with e.g., biochar systems.

CO_2 flows in nature as well as in human-engineered systems can be quite complicated and it is important to properly understand the kinds of demands that should be placed upon a specific solution to qualify as a negative emission or carbon dioxide removal technology. Tanzer & Ramírez (2019, p. 1216) argue that four key criteria need to be fulfilled in order to achieve carbon dioxide removal/negative emissions:

1. Greenhouse gases are physically removed from the atmosphere.
2. The removed gases are stored out of the atmosphere in a manner intended to be permanent[2].
3. Upstream and downstream greenhouse gas emissions associated with the removal and storage process, such as biomass origin, energy use, gas fate, and co-product fate, are comprehensively estimated and included in the emission balance.
4. The total quantity of atmospheric greenhouse gases removed and permanently stored is greater than the total quantity of greenhouse gases emitted to the atmosphere throughout the full supply chain.

For Bio-CCS systems, criterion 1 is fulfilled in the sense that photosynthesizing plants remove CO_2 from the atmosphere to produce plant biomass. In systems without human interference, the carbon would eventually return to the atmosphere in the form of CO_2 once the plant dies and decomposes.

Criterion 2 is fulfilled for Bio-CCS as CO_2 captured as part of Bio-CCS systems are destined for long-term/permanent geological storage.

Criteria 3 and 4 are related and should be fulfilled for Bio-CCS, considering the aspects that were discussed under section 2.1 and 2.2, i.e., high capture rates, low energy-related CO_2 footprint from capture and transport and sustainable feedstock.

[2] The question of how to define „permanent“ in this context is central. We discuss this in more detail in 2.4 and 3.2.

2.4 CLIMATE IMPACT OF BIO-CCU

In contrast to Bio-CCS, Bio-CCU value chains follow a different logic with the main purpose being to use carbon dioxide as input to generate value via the provision of products e.g., fuels, chemicals or plastics. However, in order to do this, there is need of additional valorization, following on the capture stage. This additional valorization might come with additional processes involved (such as the production of hydrogen for fuels), which subsequently lead to additional climate impacts. Therefore, an overview of the climate impact of Bio-CCU will be given here with particular focus on sources of emissions, supply chain processes and storage permanence.

2.4.1 Types of Emissions

Three key aspects are crucial when it comes to emissions related to Bio-CCU. Firstly, and as was discussed in section 2.1, CO_2 quality in terms of concentration, as this is key for energy demand for capture. Secondly, supply chain emissions including those that arise during the production of additional inputs needed for CCU valorization, such as hydrogen. Thirdly, emissions[3] arise when the CO_2-derived product reaches its end of life and is either energetically recovered or decomposed, i.e., provided that no additional cascading takes place[4].

2.4.1.1 Origin of CO_2

The energy demand and possible associated emission impacts from CO_2 capturing were covered in section 2.1 and are assumed to be the same for Bio-CCU value chains as for Bio-CCS. Having said this, the grade of purity of the captured CO_2, which depends on the process and technology involved, can be crucial for the subsequent utilization. Worth noting is that different grades of purity are required for different CCU applications. Mineralization, for example, can make use of low purity CO_2 (Zimmerman et al. 2018), whereas the food and beverage industry requires high purity CO_2 (Naims 2016).

2.4.1.2 Emissions within different utilization paths

There is a very wide range of CCU studies available and the general utilization routes are independent of the carbon origin – be it biogenic CO_2 or fossil CO_2. In terms of categorization of the different routes to make it easier to navigate the available options, a few different approaches have been suggested. For example, Bioenergy Europe (2019) distinguish between four main utilization paths: mineralization, chemical conversion, biological conversion and direct utilization (Figure 3). This overview is largely aligned with Al-Mamoori et al. (2017), who categorize the routes into *a)* enhanced oil/gas recovery (EOR/EGR), *b)* fuels production, *c)* chemicals production and *d)* non-geologic storage of CO_2 (mineralization). However, Al-Mamoori et al. (2017) also add desalination and potable water production as an additional CCU path by using CO_2 to transform brine to water.

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[3] Particular attention should be given to CH_4 emissions related to the end-of-life phase, as CH_4 contributes to climate change in other dimensions than CO_2.

[4] For example, through recycling of plastics produced via Bio-CCU.

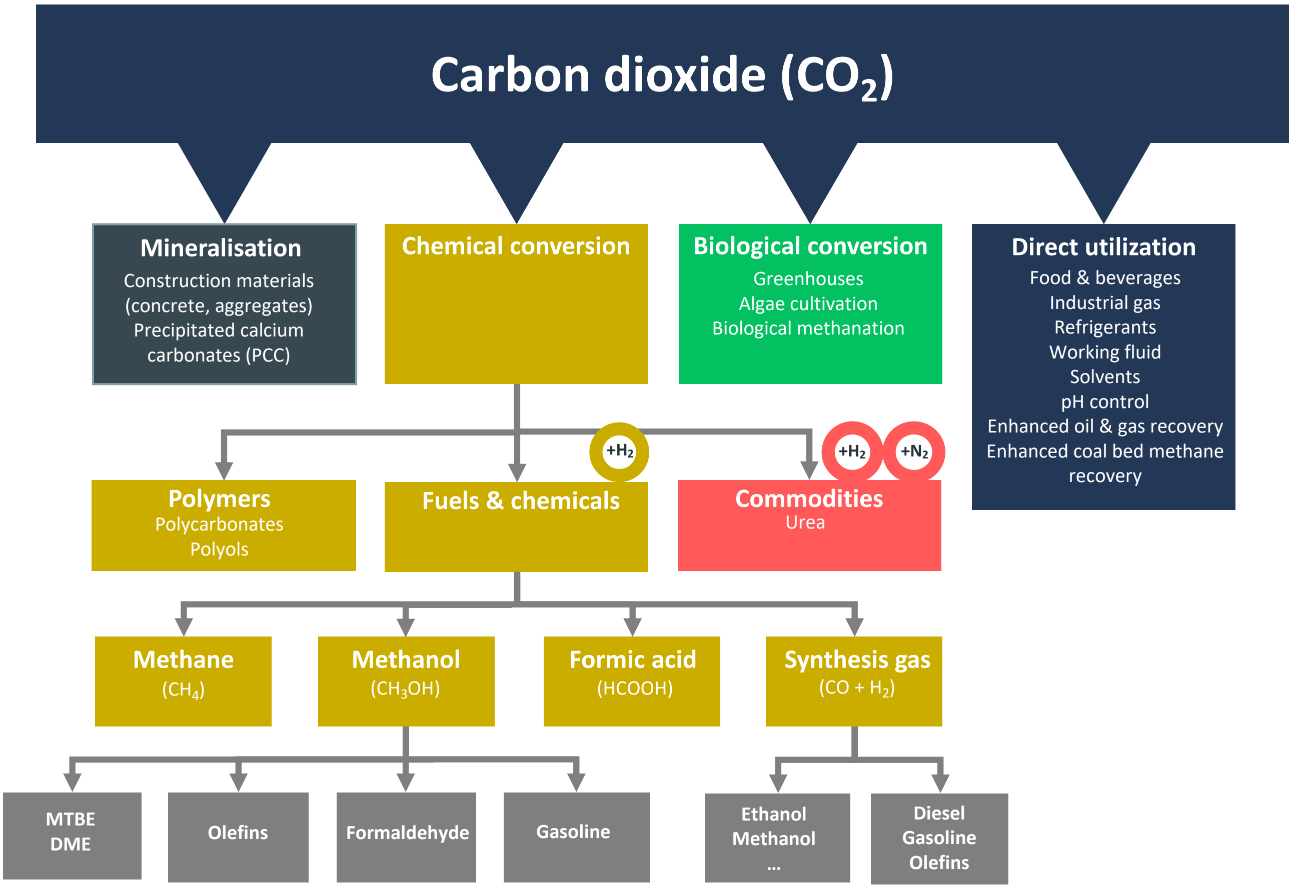

Figure 3. CO2 utilization pathways. Figure adapted from Bioenergy Europe (2018)

This broad variety of CCU options leads to different requirements in terms of feedstock - especially energy or hydrogen - which in turn are associated with emissions. Whereas direct utilization of CO_2 (in the case of e.g., enhanced oil recovery or carbonation of beverages) does not require additional inputs, the production of carbonates via mineralization requires calcium/magnesium-rich feedstock. Similarly, chemical conversion to fuel or chemicals requires energy and hydrogen. Consequently, each CO_2 utilization path has a different environmental impact, which needs to be analyzed in a life cycle assessment. Thereby, national or regional conditions in background systems and logistics need to be considered, as well as the time dimension (see section 2.4.3).

To assess the climate impacts of such Bio-CCU-products, their additional requirements in terms of feedstock, energy and hydrogen need to be considered thoroughly. Provision of these come with emissions, which, depending on the background system at hand, can either result in benefits or drawbacks, compared to conventional non-Bio-CCU product systems. Hence, such multi-inputs (e.g., several additional inputs) should be limited as much as possible, especially fossil-based inputs, and/or made available in a renewable way in order to reduce associated emissions. Considering the renewable energy system, particular attention should be given to alternative uses of the energy (conflict of use) and impacts of non-renewable components such as critical minerals.

2.4.1.3 Emissions within the production chain

Taking the entire production chain into account, emissions arise from CO_2 capture, CO_2 transportation and also from the provision of additional inputs, such as hydrogen. In the context of electrofuels, the origin of CO_2 and energy can be considered the main sustainability issues (Philibert 2018).

Consequently, a life cycle approach is required, as well as a comparison with an alternative (Bennett et al. 2014). Therefore, it is crucial to determine all emissions occurring within the production chain, but also take into account the contributing associated product systems, such as energy provision. Figure 4 from Bennet et al. (2014) provides a framework for assessing emissions for an LCA approach that will be described briefly.

Upstream emissions comprise the emissions associated with the capture of the CO_2 that will be further utilized. *Utilization emissions* originate from the process of utilizing CO_2, i.e., the valorization of the CO_2. Emissions occurring within the provision of additional material and energy input are included in this part. Further emissions associated with the manufacturing of products, transportation and distribution are part of the *downstream emissions*.

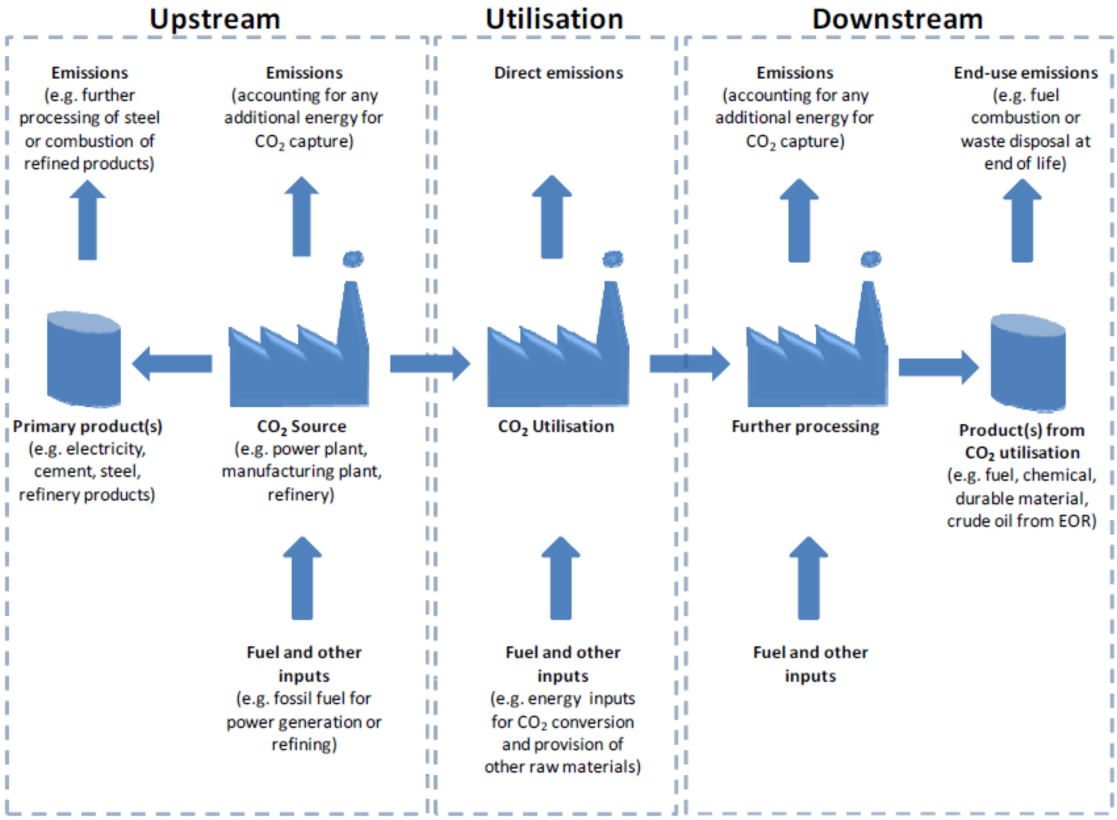

Figure 4: Emissions within CCU (Bennett et al. 2014)

Depending on the specific case, *upstream emissions* can vary from negligible to substantial. Excluding feedstock supply chain emissions, upstream emissions are mostly associated with the capture of the CO_2, collection and transportation. As mentioned in chapter 2.2, emissions related to transportation might vary and can have high impacts on the overall climate assessment. Similarly, high contributions to the overall climate impact can be related to the provision of CO_2 from low concentration CO_2 streams, as in this case high energy inputs are required.

Main emission sources typically occur within the utilization phase. Here, additional expenses in terms of, e.g., process energy - electricity as well as heat - are required to process the CO_2. As such, especially in terms of electricity-based paths such as PtX fuels and unless very low-emission electricity is used, *the utilization phase* contributes most to the overall climate impact (Liebich et al. 2020). Besides electricity, hydrogen and heat are often required in large amounts, especially in the case of fuel production. Both are currently based mainly on fossil sources, which means that decarbonization of these inputs is crucial to enable a CCU product with low life cycle emissions. Similarly to upstream emissions, *downstream emissions* play a rather minor role, as they are associated with transportation and distribution. However, end-of-life emissions can play a significant role in the context of carbon accounting if an energetic utilization or recovery takes place without subsequent CCS or cascading use (subsequent CCU). Whereas these emissions need to be accounted for in the case of fossil CO_2, they usually can be omitted in the case of CO_2 originating from biogenic sources, as these should have already been accounted for at the point of biomass harvest.

2.4.1.4 Hydrogen provision

Frequently, hydrogen is required as an additional input in order to manufacture CCU products. Currently, hydrogen originates mainly from natural gas steam reforming, but hydrogen can also be produced by water electrolysis, biomass or bioenergy carriers such as biomethane (IRENA 2020; Autenrieth et al. 2021). Electrolysis is a very energy-intense procedure, although there are ongoing R&D efforts aimed at reducing the energy demand. In hydrogen-based pathways, electricity for hydrogen production plays the main role regarding the global warming potential of the derived CCU product (Liebich et al. 2020). In order to minimize climate impacts of Bio-CCU, energy for electrolysis should thus only originate from sources with very low GHG emissions. Due to the intermittency of wind & solar and the fact that limited renewable energy needs to be available for other sectors as well, hydrogen production could take place when renewable energy generation exceeds demand or when remaining thermal production is underutilized (Bennett et al. 2014). This, however, would drastically increase the hydrogen generation costs, aggravating the fact that, besides energy availability, the high cost of hydrogen supply is a main economic challenge (Kärki et al. 2020)[5]. The role of hydrogen is thus crucial in the entire climate impact of CCU products. Hence, ideally, only so-called *green hydrogen*, generated by renewable energies (Horng and Kalis 2020), should be considered in the manufacture of any Bio-CCUS product. However, a question arises if there is enough hydrogen left for Bio-CCU, considering other competing demand of limited renewable electricity and H_2.

2.4.1.5 Energy provision

Besides the provision of electricity for hydrogen production, the general provision of energy in terms of electricity and heat plays a significant role. Liebich et al. (2020) investigated the environmental impact of the production of PtX fuels, such as Fischer-Tropsch fuels, methanol, synthetic natural gas, biomethane and hydrogen. They demonstrate that the provision of electricity contributes mostly to the overall GWP and that the use of renewable energies has positive climate impacts, compared to their conventional reference. Therefore, analogous to hydrogen, ideally, only renewable energies should be utilized in Bio-CCUS production chains.

2.4.2 Trends over time

For a holistic assessment of the climate impacts of CCU it is crucial to consider the impacts both now and in the future, taking into account trends in technological developments, including perspectives on future energy systems.

In the context of technological development, Dairanieh et al. (2016) conducted a market analysis and investigated key potentials and barriers of a large variety of CCU products over the coming decades[6]. The results demonstrate that progress has been made in the domain of CCU products and their scalability and that current market situation appears to be favorable for four primary markets: *a)* building materials, *b)* chemicals, *c)* fuels and *d)* polymers. Five CCU products are forecast to comprise a market with a total value of over US$800 billion by 2030, thereby utilizing 7 billion metric tons of CO_2 per annum. These products comprise aggregates, fuels, concrete, methanol and polymers. To maximize the market size as well as the CO_2 emission reduction potential, implementation of strategic action, such as political action, is central.

Additional scenario demonstration with an economic perspective can be found in Naims (2016). For example, in the long-term scenario, it is assumed that synthetic fuel production increases. The required CO_2 is expected to be available from a large variety of processes. However, taking the efficiency of synthetic fuels into account, SRU (2017) argues that synthetic fuels - including CCU fuels - should primarily be applied in aviation, shipping and other applications where electrification or other means of decarbonization will be

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[5] It should however be noted that many analysts expect electrolyser costs to decrease substantially as manufacturing scales up (Material Economics 2020), which is an important step towards reducing costs of green H_2. Having said this, electricity costs are the key parameter that needs to be addressed to lower the costs.

[6] Dairanieh et al. (2016) analyze conventional CCU, which means that the study does not explicitly focus on biogenic CO_2.

challenging or impossible[7].

Consequently, the future implementation of CCU depends on technological development, as well as overall political developments in this regard. Besides these trends in technologies, developing fuel prices need to be considered, as they might have an impact on the scale up and implementation of CCU technologies in general (Al-Mamoori et al. 2017). Furthermore, trends in energy systems play a significant role, as a lot of energy is required for many CCU options (chapter 2.4.1.3) and, as described in chapter **Error! Reference source not found.**, the climate impact is mostly a function of the type of energy provision.

With a particular view to Germany, Purr et al. (2019) developed six scenarios for new pathways towards resource-efficiency and GHG-neutrality. These scenarios describe different raw material consumption rates and energy systems, which make GHG-neutrality by 2050 possible. Highest GHG reduction and thus climate impacts can be achieved by substituting fossil electricity generation by renewable power generation. The so-called "supreme scenario" demonstrates such a possible pathway, focusing on the substitution of fossil electricity. Such a future development might be the basis for further CCU implementation. According to Bernath et al. (2017), renewable energy is considered the primary key in order to achieve decarbonization and that wind energy becomes the most important electricity provider in Germany and Europe. This trend might support CCU developments, as previously described.

On a European level, the future scenarios presented by the European Commission (2018) imply that by 2050, the large-scale electrification of the energy system will substitute the fossil-based energy system beyond just the electricity sector. Consequently, the renewable energy sector is considered to play a significant role, as it is crucial to achieve national and European-wide climate change mitigation goals. An important question for large scale Bio-CCU implementation (e.g., the provision of Bio-CCU fuel on large scale) is that it will require carbon sources that may be hard to come by in a world where comprehensive electrification takes place and limited sustainable biomass is required for material utilization rather than energy provision. In this context, direct air capture (DAC) might potentially play a significant role as a means of supplying carbon dioxide in the future.

Hence, the trends of CCU technology development and their efficiency as well as trends in energy systems are not the only aspects that need to be considered. An entire trend analysis of societal and economic change needs to be conducted to reveal systemic effects from how sectors may change.

2.4.3 CO_2 storage permanence

With respect to climate impacts of CCU as a whole, CO_2 storage permanence is of utmost importance. As previously described, CO_2 can be utilized and thereby stored in a large variety of products. However, the time carbon will be stored in these products varies substantially from days or weeks to centuries (Bruhn et al. 2016), as CO_2 can be re-emitted at the end of the product's lifetime. The characteristics of the storage solutions are crucial in the overall climate impacts of carbon removals, more so than the actual removal technology (Mitchell-Larson and Allen 2021).

From a systemic point of view, the issue of delayed emissions is paramount, as a temporal storage could provide some much-needed breathing room for the transformation of our society towards a more sustainable future. Several approaches have been developed in order to address delayed emissions in LCA's properly (Ramirez Ramirez et al. 2020; Zimmermann et al. 2018).

Bennet et al. (2014) distinguish between *utilizations with permanent storage* and *utilizations with subsequent emissions* of CO_2. The former comprises EOR and consequently any related utilization such as EGR, as well as the deployment of mineralization. These utilizations are considered to store carbon "permanently". Storage in cement can last from decades to centuries (Bruhn et al. 2016), whereas

[7] For example, much road transportation could be electrified directly without having to use synthetic fuels.

utilizations with subsequent near term emissions are products which are rather short lived, such as fuels or plastics (Bennett et al. 2014) that store carbon from days/weeks (fuels) to years (plastics) (Bruhn et al. 2016). However, to this day, there does not exist a general definition of permanence in the context of carbon storage. For example, when procuring carbon dioxide removal solutions, the software company Stripe defines permanent carbon storage to be 1000 years (Orbuch 2020). In the context of CCU and delayed emissions, Ramirez Ramirez et al. (2020) propose a 500-year horizon, meaning emissions within this time window should be accounted for, whereas emissions outside of this period should be ignored, under the assumption that climate change by this point in time either has been managed or has gone out of control completely. At the same time, the authors suggest that GWP20 and GWP100 should be used. In this light, intermediate storage can help mitigate climate change and could as such be considered, when discussing mid-term climate change mitigation policies. This could either entail a de-facto sink with view to the time frames 2050 and 2100, respectively, if carbon retention times exceed the aforementioned, or, on the other hand, be included with a proportionated share of its GWP, corresponding to the amount of radiative forcing carried out by the year 2050 / 2100. Whereas Ramirez Ramirez et al. (2020) present among others the 500-year horizon for delayed emissions, the IPCC uses 2100 as the timeframe for the reporting under the Paris Agreements (IPCC 2021). Consequently, further discussion is required in order to **define permanence** (i) and in order to decide how to **handle utilizations with a storage time of e.g. 40 years and subsequent crediting** (ii). Besides this, the question of **substitution and allocation** between sectors and across borders (iii) remains, which will be further discussed in chapter 3.2.1.

In principle, as long as CCU products do not store carbon physically on a very long time scale, these options cannot be considered to be negative emission technologies. Only CCU products with permanent storage can be considered as direct climate change mitigation measures in contrast to indirect effects, e.g. the displacement of fossil-based products via CCU, taking into account that the carbon storage will be monitored regularly, as it is the case for CCS (Bruhn et al. 2016). This implies that only Bio-CCS can be considered an option if negative emissions is the objective (Philibert 2018). However, in terms of carbon content of a product, Bio-CCU can be considered as a net-zero-CO_2 compatible option (Gabrielli et al. 2020) and could help face out fossil primary energy carriers or products. Provided these CCU routes achieve a reduction in GHG emissions, they could very well help bridge the gap to a fundamentally decarbonized economy.

Comparison of two products

	Cumulative CO_2-Storage (Mio. t CO_2)			Annual storage rate in Mio. t CO_2	Expected life-time[1)]
Scenario/year	until 2030	until 2040	until 2050	On average, consideration of the entire observation period	
CCU – plastics (long-lived)	158	316,80	473	16	Years
CCU - mineralization	26	51	77,8	2,6	Decades to centuries

Source: Fehrenbach et al. (2021); [1)] Bruhn et al. (2016)

Table 1 Potential cumulative CO_2 Storage in CCU of two exemplary cases in Germany

The comparison of two different CCU products demonstrates the importance of the consideration of the CO_2 storage permanence[8]. Taking an annual carbon storage rate of each CCU application (plastics and

[8] These storage rates originate from calculations of the Bio-CCU potential in Germany, unpublished.

mineralization) into account and modelling the storage potential for the next decades, the plastics CCU deployment appears to store more carbon than the CCU mineralization. Besides the fact that both CCU-products cannot be produced at the same quantity (due to limited additional calcium/magnesium-rich feedstock for mineralization), the storage permanence is not considered here, which brings the carbon storage of these products into a different light. Even long-lived plastics have a life-time shorter than mineralized building materials, whereas most of the theoretically stored carbon will practically be re-emitted subsequently. Following Bennet et al. (2014), such a mineralized building material can be considered a permanent storage, contrary to plastics. This example demonstrated that the factor storage permanence needs to be considered thoroughly in addition to production quantities of different CCU derived products. Furthermore, the substitution effects of fossil reference products need to be considered for both applications in order to derive a holistic estimation of the climate impact of CCU plastics and CCU mineralization.

2.4.4 Key determinants of overall climate impact

In summary, the key aspects that need to be taken into consideration and that contribute most significantly to the overall climate impact of Bio-CCU products are thus:

i. the concentration and purity of CO_2 to be further utilized,
ii. the nature of utilization, e.g., PtX with high energy demands vs. mineralization and respective low energy demands,
iii. the origin of hydrogen and energy, or – in other terms – the background energy system, and
iv. the storage permanence.

Additionally, the demand now and in the future for such CO_2-based products as well as the availability of CO_2 sources in a hypothetical decarbonized economy need to be taken into account. Bennet et al.(2014) analyze CCU options regarding their climate impact, compared to conventional product systems. Based on this, they propose three criteria that are crucial in determining the potential impact on limiting or reducing greenhouse gas emissions. These criteria extend the previously mentioned aspects and comprise:

- The extent of CO_2 emission reduction in comparison to conventional options: in order to fully assess the reduction potential, all emissions in the upstream, utilization and downstream system need to be considered and compared to an alternative scenario. Regarding the alternative scenario, particular attention should be driven to the fact that in a “Post-Paris-2015-World” a fossil reference scenario does not correspond to the current and future state anymore. Consequently, the comparison should be driven towards a scenario that – for example - includes current mitigation measures as well.
- Cover of costs by potential revenue: Ideally, the CCU product has a specific market price that entirely covers all costs during the production line. In order to lower costs, as well as energy requirements, especially utilization routes that do not require CO_2 purification should need to be considered.
- Scalability of the utilization path: The CCU product can only have significant (positive) climate impacts, when the production is scalable and thus the demand for CO_2 is high enough to be meaningful to mitigation overall. This aspect includes the demand from consumer side, as well as the supply of CO_2 for the production phase.

Finally, with regard to (i), Schwan et al. (2018) conclude that CCU can only be considered as an option, when a lot of renewable energy is available and when less energy is consumed than available. These circumstances could potentially be met in the MENA (Middle East & North Africa) region. In the context of renewable energy, the question about the most appropriate deployment of limited renewable energy resources remains (Bennett et al. 2014).

3 Integrating Bio-CCUS carbon accounting in policy frameworks

The rapid pace at which Bio-CCUS has gone from conceptual discussions to deployment considerations has meant that policy have not kept up and many regulatory frameworks currently in place do not include adequate governance provisions. However, challenges of integration into existing structure or developing new structures differ somewhat between Bio-CCU and Bio-CCS. For Bio-CCS, the challenge largely boils down to an absence of policy frameworks related to negative emissions more broadly, whereas the challenges related to Bio-CCU are more related to setting up accounting frameworks. Acknowledging the different characters of the challenges, we discuss the two separately below.

3.1 BIO-CCS CO_2 GOVERNANCE

In the last couple of years and following on the calls made by e.g., Anderson & Peters (2016) and van Vuuren et al. (2017) for intensified discussions around negative emissions policy, research around negative emissions governance has developed markedly. Having said that, this does not mean that all questions are resolved, quite the contrary. As it happens, the complicated nature of negative emissions conceptually as well as politically does not lend itself well to swift implementation in policy.

A first question to be discussed relates to the moral hazard problem highlighted by Anderson & Peters (2016) and concerns the extent to which negative emissions should be incentivized relative to emission reductions. It is important that negative emissions are not seen as an alternative to emission reductions, but rather as a complementary measure (Carton et al. 2021)[9]. Principal decisions around this question have important consequences for policy design. For example, Rickels et al. (2020) discuss how negative emissions could be integrated into the EU ETS through a system where companies are awarded free emission allowances (EUAs) amounting to the amount of CO_2 removed from the atmosphere. While this approach has advantages in being a relatively elegant way of integrating CDR in the EU ETS, it does entail an implicit recognition of the equivalence between emission reductions and carbon dioxide removal that is criticized by Carton et al. (2021).

Another question pertaining to incentivizing negative emissions is whether policy measures should be directed specifically at the carbon dioxide removal as such or towards stimulating demand for goods produced with negative emissions. For example, a facility that generates negative emissions through Bio-CCS will also produce other goods, be it electricity, heat, fuels or industrial products. Should, for example, policy incentives be tied strictly to the negative emissions as such, or should there be a system that incentivizes negative emission “products”, i.e. negative emission electricity/heat/etc. (Rickels et al. 2020; Harris 2021; Klement et al. 2021)?

In addition, there still exist some practical hurdles, which can prove quite challenging. CCS projects, regardless of the carbon origin, often lack social acceptance (Elkerbout & Bryhn, 2019) and are also feared to prolong the existing carbon-based energy system and thus hinder a transition to renewables[10]. Moreover, regulation in other places is slow to adapt. The 1996 London Protocol to the Convention on the Prevention of Marine Pollution by Dumping Wastes and Other Matter of 1972 (in the following referred to as the London Protocol) prohibited the transboundary transport of CO_2 for the specific injection into sub-seabed formations (Garrett & McCoy, 2013). Only as recently as October 2019, at the 41st London Convention, an amendment to article 6 of the London Protocol dating back to 2009 was adopted in order to allow for CO_2 exports for the above-mentioned purpose. Against the background of the vast availability of offshore storage sites (in contrast to the limited amount onshore), this development could prove quite significant (Elkerbout & Bryhn, 2019).

[9] A similar question pertains to whether or not negative emissions should be ring-fenced so that it would not be possible to use negative emissions generated in the LULUCF sector to compensate for residual emissions in the energy, industry or transport sectors.
[10] A concept referred to as „carbon lock-in“.

3.2 POLICY INTEGRATION OF BIO-CCU

3.2.1 Practical and Methodological Challenges of Bio-CCU Accounting

Historically, carbon dioxide as a process output has been treated like a waste without (by) product status or value. This is no longer is the case if said carbon dioxide gains value by using it in an adjacent process as an input for the purpose of, e.g., constituting the carbon source for a hydrocarbon-based fuel. Following this, a number of questions arise.

1) Who gets the credit for "carbon recycling", or: how to allocate the burden of the emitted carbon / carbon dioxide at the end of its lifecycle?
2) How to address carbon dioxide movement between different countries?
3) How to handle potential by-products?

Questions 1 and 2 are related, but vary in scope. The first question addresses the linking of multiple product systems on a company level (e.g., a power generation process and a subsequent production of PtX fuels or bio-methane production and subsequent carbonation of beverages). As a general rule, CO_2 of biogenic origin is considered to be a zero-sum-game, as the CO_2 was fixed by a plant. Its emission farther downstream thus does not contribute to climate change, as the amount of CO_2 emitted cannot exceed the amount of CO_2 fixed in the first place.[11] However, this only holds true for the lifecycle of the carbon in total. From the viewpoint of the carbon generating (first) process or product system, its product is no longer liable for the carbon emission, if a subsequent process (product system) can use this carbon as an input. This constitutes a "negative" emission, or removal of atmospheric carbon because up until this point in the value chain of the first product system, only carbon sequestration via biomass growth has taken place, but not a carbon release to the environment.

From the viewpoint of the subsequent, carbon utilizing process, the carbon would have entered the atmosphere anyway and is thus the responsibility of the first, CO_2 generating process. Hence, the first product system has to report the CO_2 emission in the end of the second product system's value chain. It is easy to see that, if there is no precaution taken, the result could be that this is accounted for as a negative emission and not the real zero-sum-game. As a solution, allocation of burdens (or credits) between both linked product systems is advised. As this constitutes a rather normative question, the authors refrain from advising on which allocation procedure is most suitable and refer to Fehrenbach et al. (2017) and Ramirez Ramirez et al. (2020) for a more in-detail discussion.

The following Figure 5 illustrates an example of two distinct product systems that are linked via CO_2. Here, the first product system is a biomass CHP plant which produces biogenic CO_2. The second product system is a generic process that valorizes this same CO_2. In the end, a permanent sequestration of the carbon takes place (arrow toward CCS). This constitutes a negative emission and thus a carbon credit. However, instead of a final CCS, a release to atmosphere is also applicable in this example (arrow towards CO_2 emission). Fehrenbach et al. (2017) find three possible solutions for the carbon crediting, as is reviewed below. If, however, no CCS at the end of the carbon value chain takes place, the above-mentioned precaution is needed, the "solutions" have to be expanded or modified:

Solutions 1a: If the biomass CHP plant credits itself as a carbon sink, the CO_2 valorization process has to account for the CO_2 emission in the end.

Solution 2a: The bioethanol plant does not consider itself a sink and accounts for / reports the CO_2 emission, then the subsequent CO_2 valorizing process has to be awarded the CO_2 credit or bonus in order for the zero-sum equation to be correct.

[11] Note that this holds only true for CO_2 or rather substances with equivalent GWP. If, for instance, the CO_2 is transferred to Methane with a different GWP, the delta of GWP x Amount for both species has to be accounted for.

Solution 3b: Both processes share the burdens and credits via an allocation mechanism, then in total, both credits and burdens have to add up to zero.

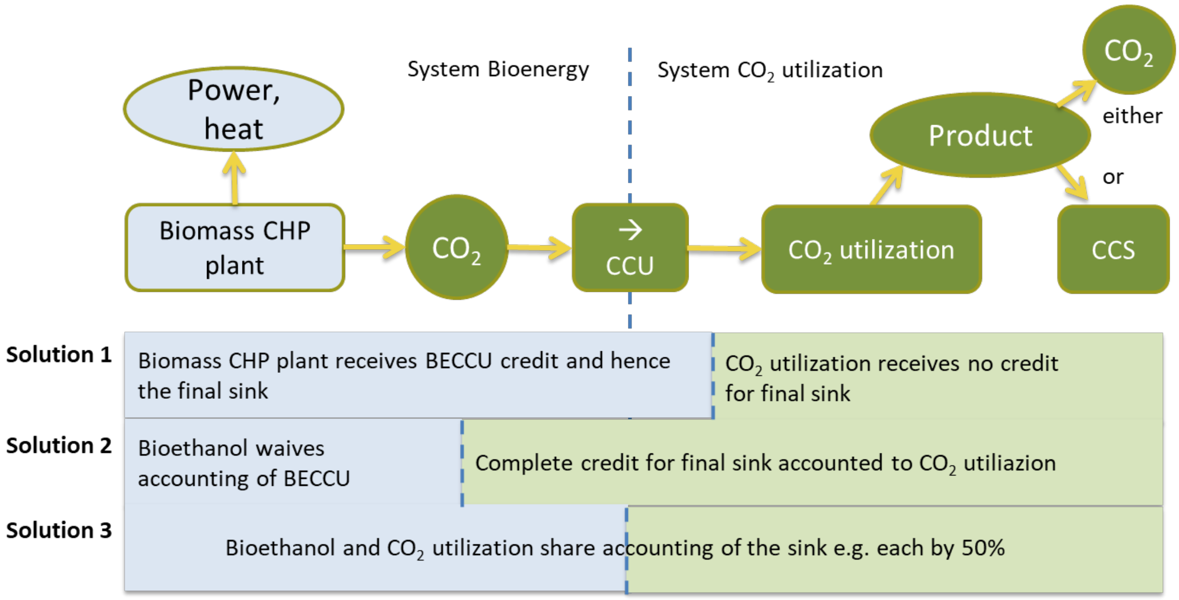

Figure 5 Multifunctional product systems linked via CO_2 (Fehrenbach, et al., 2017)

The second question focuses on carbon accounting among countries and reporting duties under climate change mitigation instruments such as the United Nations Framework Convention on Climate Change (UNFCCC). This follows a territorial principle, meaning that every ratifying state has to report the emissions that arise on its territory. If, however, a CO_2 transport or a Bio-CCUS value chain with subsequent export across borders are established, it is of utmost importance that no double counting (in form of a CO_2 credit or negative emission, double in the sense of the exporting country as well as the importing country both consider the amount of sequestered CO_2 within the product at hand for their respective carbon dioxide budget) occurs, if the carbon-based product is permanent. If, on the other hand, the CCU-based product is short-lived, it must be ensured that - with respect to the carbon content of the product - the zero-sum game still applies, i.e., it has to be avoided that the exporting country gains a negative emission, whereas the importing country treats the carbon content of the product as zero, following accounting practices for biogenic CO_2. As Bio-CCUS constitutes a technical parallel to 'natural' plant-based products, it should thus be treated as such (see section 3.2.2).

For a system integration of Bio-CCUS, both, for inland as well as cross-border transport of CO_2, there remains the question of transport infrastructure (Elkerbout & Bryhn, 2019). While the discussion of CO_2 transport for general CCS / CCU projects focuses on the benefits of concentrated industrial clusters, especially bioenergy plants to this date are decentralized and with regard to Germany - Europe's main consumer of bioenergy[12] - heavily so.[13] Although a gas network exists, the amount of CO_2 that could be transported is very limited, resulting in the need for either a separate additional pipeline network with corresponding expenditures or a large scale road transport, with accompanying emissions.

3.2.2 Existing examples of carbon accounting across borders and sectors

If Bio-CCS and Bio-CCUS systems should constitute a potential emission sink of any significance in the future, there have to be guidelines, methodologies, rules or conventions in place that are tailored especially for the handling of CO_2. With view to emerging CO_2 markets, one of the most important questions to be

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[12] Other notables are France, Italy and Sweden, on a per-capita basis, the Scandinavian countries, the Baltics and Austria (EUROSTAT 2018a, 2018b, https://publications.jrc.ec.europa.eu/repository/bitstream/JRC109354/biomass_4_energy_brief_online_1.pdf)

[13] This holds especially true for biogas plants.

addressed is how the movement of CO_2 between different sectors, industries and countries is regulated. To this date, an international comprehensive framework specifically for CO_2 does not exist. There is thus need for a development of such. However, for Bio-CCU, parallels to already existing frameworks can be drawn due to the apparent functional equivalency. Below, we discuss three frameworks that could provide guidance for the governance of Bio-CCU.

3.2.2.1 Reporting of HWP – Harvested Wood Products in the National Inventory Reports following the IPCC 2006 Guidelines and the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories

Reporting of HWP in the National Inventory Reports (NIR) follow the 2006 IPCC Guidelines for HWP. Generally, the guideline provides four different approaches[14] and addresses the question of how HWP contribute towards the AFOLU sector as sources or sinks of CO_2. Although the guideline in its' entirety focuses on many issues that are irrelevant for Bio-CCUS, some aspects, especially concerning the international trade and permanence of storage of CO_2 could provide a first basis for a corresponding regulation of Bio-CCUS.

In order to determine whether or not HWP constitute a carbon sink or source, both domestically used and exported HWP are considered[15] but only, if they stem from managed forests. However, here, the system boundary and thus the responsibility of carbon emissions or removals, respectively, is dependent on the approach chosen. The "production" and "simple-decay" approaches consider the HWP *producing country* as responsible for CO_2 emissions or removals, whereas the "stock-change" and "atmospheric-flow" approaches burden or credit the *consuming country*. While all approaches in themselves constitute viable options in assessing HWP as CO_2 source or sink only the former – "production" and "simple-decay" are really in line with the general idea of the *territorial principle* of the NIR. The country of origin is thus responsible for either the emissions or the carbon removals of the sector in total. In addition, it would hardly incentivize Bio-CCU (or other CCU projects, for that matter) to report the emissions related to the energy expenditures (and others) that are needed for CCS / CCU if related removals in the form of an exported product would be reported within the country of destiny (Umweltbundesamt, 2020). Moreover, the IPCC Guidelines on the one hand consider the decay of HWP and thus a change of the carbon storage over time. On the other hand, it distinguishes between different HWP categories with specific decay functions and HWP half-life. In this way, the changing carbon stock in HWP, and subsequently changing function as carbon sink, is done justice considering the differences in carbon retention of different product categories[16]. An implementation along the same lines for Bio-CCU products with distinct product categories and individual decay functions / CO_2 release in combination with territorial responsibility and reporting duty could constitute a first starting point for the regulatory framing of the accounting of international CO_2 trade.

3.2.2.2 CDM – Clean development mechanism and Paris Agreement Art. 6.4 – international carbon trading markets for emission offsetting.

Established in 2006, the CDM as part of the Kyoto Protocol was one of the first global carbon market / offset schemes for the purpose of climate change mitigation. The general idea could be described as follows: Industrialized countries (Annex B countries) invest in developing nations (non-Annex B countries) on a project basis in order to achieve *additional* emission reductions when compared to the pathway of the developing country without such an investment (baseline scenario). The quantities of achieved emission reductions are being assessed and a corresponding amount of "certified emission reductions" (CER) generated. These CERs can then be sold to Annex-B countries and count there towards the country's

[14] For reference and a detailed description, the authors refer to Chapter 12 and Annex 12A. of the 2019 refinement to the IPCC 2006 Guidelines

[15] In addition, the contribution of HWP in solid waste disposal sites (SWDP) is possible. As a parallel to Bio-CCUS, if Bio-CCUS derived products are being disposed of in SWDPs without oxidation to CO_2 or anaerobic degradation to CH_4 to a significant amount, this sink option could be included. The IPCC Guide includes this option for HWPs, too.

[16] For example, paper products on average have a shorter life span and thus carbon sequestration function when compared with solid wood products such as furniture.

respective emission reduction goals. The key aspect here is the concept of additionality, and it has to be indisputable that the emission reduction wouldn't have occurred without the CDM initiative. In reality though, additionality has proven to become a highly controversial issue. Similarly, correct estimation of the actual contribution of individual projects has been problematic because of an asymmetry in information between project participants on the one side and authorities on the other (Cames, et al., 2016)[17].

However disputed the CDM scheme in terms of real and measurable climate change mitigation may have been, it could prove a valuable basis for its' successor under the Paris Agreement (Cames et al. 2016). Lessons learned in terms of environmental integrity and general market design could thus be implemented. The above-mentioned successor of the CDM, Article 6.4 of the Paris Agreement, is still under negotiation and it remains to be seen how this carbon market will shape out. One key progression from the CDM, however, constitutes the fact that under the Paris Agreement, all participating countries have to fulfill Nationally Determined contributions (NDCs) (Cames, et al., 2016). This could lead to a fundamental reassessment of previous practices, as the host countries will now have to achieve emission reductions themselves, shrinking the opportunities / market for the generation of CERs[18]. Moreover, the countries' NDC will have to be considered as the new counterfactual scenario when determining emission reduction quantities in the form of CER, resulting in a more dynamic albeit potentially complex assessment, compared to the CDM's business as usual counterfactual scenario (Cames, et al., 2016).

3.2.2.3 CORSIA – Market-based initiative for the aviation sector

In addition to policy-based carbon markets, certain industries, especially the ones where a rapid decarbonization is not easily achievable could start their own carbon-offsetting in order to commit to climate mitigation. As a first, CORSIA (Carbon Offsetting and Reduction Scheme for International Aviation) is meant to stabilize the rapidly growing emissions in the international aviation sector (DEHST 2020)[19]. Whereas national- and international air travel within the EEA (the EU27 plus Iceland, Lichtenstein and Norway)[20] is covered by the ETS, international aviation is excluded thus far, resulting in a need of a scheme like CORSIA[21]. Starting in 2019, all aircraft operators monitor their emissions in order to determine the status-quo which functions as a baseline reference for future offsets. With the beginning of 2021, all participating airlines will have to compensate the CO_2 emissions[22] that exceed the baseline of the years 2019 and 2020 minus the usage of sustainable aviation fuels (DEHST 2020). The certificates to be purchased by the airlines have to fulfill a number of requirements in line with other carbon offset schemes, such as additionality (cf. section 3.2.2.2) no double-counting in other climate change mitigation initiatives or regulations and consideration of both, social and environmental aspects.

3.2.3 Possibilities of Policy Integration

Against the background of current climate change mitigation instruments, Bio-CCUS application and related recycling- and/or storage approaches for CO_2 only play a very subordinate role. Nevertheless, as outlined above, both the IEA and the EU envision Bio-CCU/S to contribute significantly towards a below 2°C goal as a key instrument in the toolbox of different approaches. In order to help Bio-CCUS technologies to gain the necessary momentum, the regulatory framework has to be in place first.

On an *international level*, countries achieving a net-increase in their carbon stock via Bio-CCUS should be eligible to account for this analogous to how HWP are represented as both, an emission sink and source,

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[17] The cited study concludes that the vast majority (85%) of investigated projects under the CDM would not fulfill the outlined criteria.

[18] On the other hand, this could also solve the problem of actual additionality as discussed in the context of the CDM.

[19] https://www.dehst.de/SharedDocs/downloads/DE/publikationen/Factsheet_CORSIA_EU_ETS.pdf?__blob=publicationFile&v=3

[20] Switzerland is part of the EEA, but does not participate in CORSIA.

[21] Covered are all companies that exceed 10.000 t CO_2 emissions on international flights with planes exceeding a maximum lift-off weight of 5.7 t.

[22] Other non-CO_2 related climate effects of aviation traffic are not yet included, but are subject to future considerations, as they pose a significant climate change risk.

within the *NIR*. This is only coherent with the logic of the report, as energy expenditures and the like needed within the Bio-CCU/S value chain already are included and have to be reported. If Bio-CCU-derived products, however, do not lead to an increased carbon stock, for instance, because the carbon storage duration is limited[23], the carbon content could be handled in analogy to other biogenic carbon within the NIR by assigning a GWP of 0. Moreover, as Bio-CCUS constitutes a promising option for both additionality and emission savings compared to the baseline, it could be considered an ideal project category for the CDM successor and other international carbon offsetting schemes.

With view to the more progressive and challenging climate change mitigation goals of *supranational institutions* such as the *EU,* a more regulative approach is thinkable with the *RED* and its' iterations as the key instrument. In its' current version, the RED with a time horizon until 2030 defines on the one hand overarching goals, such as the share of renewables in the different sectors, for example, but also defines quota for different technologies or raw materials. For instance, the share of first-generation biofuels is capped, while, on the other hand, there is a minimum quota for advanced biofuels that has to be achieved. A sub-quota for Bio-CCU-derived products in line with other sub-quotas constitutes a possible first step. In addition, multiplying factors[24] are permitted within the RED in order to increase the competitiveness of individual technologies or to help them to establish. Since Bio-CCU is a rather new approach far from large scale market penetration or competition with the status quo, multiplying factors could be considered.

Another, more indirect approach would be the implementation of emission reduction goals for different sectors, with the idea of the combination of challenging emission reduction criteria and (possible) high specific emission reduction potential (within to even negative emissions if carbon storage is of permanence) of Bio-CCU products resulting in a rapid development of a Bio-CCU economy. Both approaches are viable and could be included in order to reflect on the different pathways of EU countries in the past. In any case, it is paramount to all Bio-CCUS approaches that a) sustainable biomass feedstock is utilized, resulting in b) real emission reductions, and that c) double counting is avoided.

[23] See sections 2.4 and 4.

[24] Every kWh of electricity consumed in the transport sector can be multiplied by 3. If, say, the goal is to achieve at least 100 kWh electricity consumption in year 202X, in reality one would only require 33 kWh physically to fulfill the requirements.

4 Discussion

While both Bio-CCU and Bio-CCS can be important pieces in the puzzle of getting the world to net-zero GHG emissions by 2050, their roles are bound to be quite different. Bio-CCS is clearly a means to generate negative emissions, but whether or not this is the case for Bio-CCU is a more difficult question where the answer will vary between contexts and where there may be a substantial grey area depending on the carbon storage permanence. Regardless, Bio-CCU can provide society with fuels, chemicals and materials with a very low GHG footprint - one that will also tend towards zero as electricity generation is increasingly decarbonized. For both Bio-CCU and Bio-CCS however, it will be crucial to develop mechanisms and practices for how to track CO_2 flows across the respective supply chains as well as set up governance frameworks for how to address these issues in policy. In this report, we have outlined some of the concepts that will be particularly important to this end, with key issues summarized in Table 2 on the next page.

4.1 BIO-CCU AND NEGATIVE EMISSIONS - A QUESTION OF TIME

The key difference between Bio-CCU and Bio-CCS in terms of climate change impact is time, as is illustrated in Figure 6. For Bio-CCS, the CO_2 captured is stored permanently which should entail a reduction of atmospheric CO_2 provided that capture rates are high, a small GHG footprint of the energy used for capture and transport and low upstream feedstock emissions.

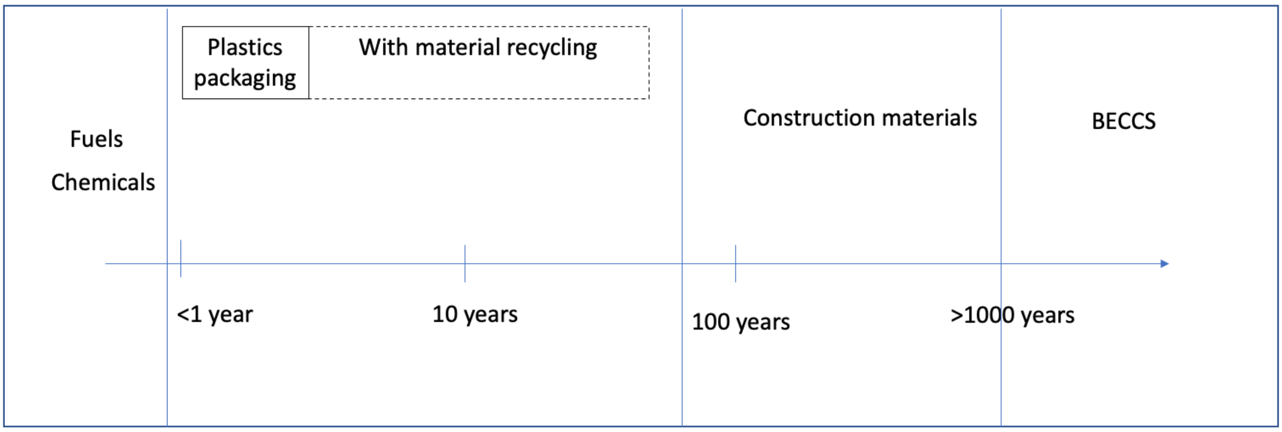

Figure 6. Timeline to illustrate indicative CO2 storage times for some Bio-CCUS examples.

For Bio-CCU, many applications currently under discussion entail CO_2 being re-released into the atmosphere fairly soon, in most cases too rapidly to be effective in terms of effectively **reducing** the warming effect in the way that is the case if the CO_2 is permanently stored. Whether one chooses the 500-year limit chosen as the cut-off point for permanence by Ramirez Ramirez et al. (2020) or the 1000-year limit set by Stripe (Orbuch 2020) both may be criticized for arbitrariness, it can still be argued that most Bio-CCU applications fail to meet criterion 2 – permanent storage – according to the framework developed by Tanzer & Ramirez (2019).

	All Bio-CCUS	Bio-CCS	All Bio-CCU	Short-lived Bio-CCU (e.g., fuels)	Mid-long lived Bio-CCU (e.g., plastics)	Long-lived Bio-CCU (e.g., construction materials)
Key aspects for CO2 counting	Energy input, Upstream feedstock emissions	Distance between biomass plant and geological storage?	Carbon retention over time (e.g. decay); potential second life stage / handling; Accounting principles (e.g. avoidance of double counting); LC performance in comparison to conventional products (systems); ILUC / aLUC and sustainability of the supply chain;	Movement between sectors, tracking across supply chains; LC performance in comparison to conventional products (systems); accounting principles (e.g. avoidance of double counting)	Second life; Carbon retention over time Decay function	Carbon retention over time (e.g. decay)
Key aspects for policy	Consideration of concentration and purity of CO2 in recommendations (avoid further purification steps where possible for environmental and economic reasons); consideration of energy and upstream feedstock in recommendations	Moral hazard problem? Emission reductions vs negative emissions: equivalence or ring-fencing?	Accounting principles; LC performance; Sustainability of the whole supply chain; ILUC / aLUC;	Consideration of end-use emissions	Adaptation to recyclability	Incentivise long-lived Bio-CCU rather than short-lived
Key open questions	Type of biomass involved	Storage permanence/geological security	Cut-off point(s) for long-lived vs. short-lived (HWP vs 0/500); Accounting principles in specific cases, e.g. sector coupling, CO2 as a resource	Type of hydrogen provided	Type of hydrogen provided supply of additional feedstock?	Market situation/access; supply of additional feedstock (calcium-rich minerals …)

Table 2. Summary of key issues for research on, and governance of, CO_2 flows in Bio-CCUS supply chains.

4.2 PARALLELS AS A GUIDE TO BIO-CCU GOVERNANCE?

Tracking CO_2 flows in Bio-CCS is – at least if we restrict ourselves to the post-capture parts of the value chain - conceptually fairly straightforward, as it is essentially a one-direction process from capture via transport to long-term storage. For Bio-CCU, however, keeping track of CO_2 can seem a bit daunting at first glance. One approach that can help structure thinking around this question is to view the Bio-CCU value chain as a parallel to the natural system, i.e., where CO_2 is captured not using technology but through photosynthesis. In other words, then, one could view the CO_2 capture facility as a really fast-working tree and with ensuing downstream processes, be they fuels or materials, as variants of bio-products. A fuel produced from biogenic CO_2 can be seen as form of biofuel and a plastic produced from biogenic CO_2 can be seen as a form of bioplastic. The key difference from the perspective of life cycle assessment is that the biofeedstock (i.e., the CO_2) can be assumed to be a pure waste product, in the sense that its upstream process supply chain emissions are assumed to be zero (Fagerström et al. 2021). Building on this parallel could facilitate the use of existing frameworks such as the accounting rules set up around harvested wood products as was discussed in section 3.2.2, although it would then be necessary to adapt specifics around e.g., assumed half-lives of products.

Another useful parallel when it comes to governance structures is the recently proposed *Proset* – Progressive Offset - concept (Mitchell-Larson and Allen 2021). This is an approach that would allow joint incentivization of different carbon dioxide removal solutions across a wide range of characteristics when it comes to cost, technological maturity and carbon storage permanence. As noted in section 2.3, CDR solutions can come in many varieties. Some – like afforestation – are commercially available and inexpensive but come with substantial uncertainties in that it is a process that takes place over many years and where natural disturbances like wildfires quickly can undo decades of carbon sequestration. On the opposite side of the spectrum, direct air capture and storage (DACCS) can enable almost instantaneous removal and low-risk permanent geological storage of atmospheric CO_2, but is still in early stages of commercialization and orders of magnitude more expensive. Under the Proset concept, companies wanting to offset their emissions can do so using all CDR solutions of different variations, but for every year that passes, the mandated share of emissions offset using permanent storage (e.g., DACCS) solutions will have to increase at the expense of sub-permanent solutions characterized by high risks of reversal (i.e., re-release of captured CO_2 into the atmosphere). Applying this thinking to Bio-CCU would mean that policy incentives for products with short-term CO_2 storage could be high in an initial stage but then gradually phased out, as focus increasingly shifts to longer-term storage solutions.

It is important to note though that the analogue is not perfect and more research is needed to analyze exactly if and how the Proset concept could be applied to (BE)CCU contexts. As it turns out, even though the issue of carbon storage permanence is common to the two concepts, there are also important differences. This includes the need to take into account the need to monitor and allocate responsibilities as Bio-CCU products move geographically as well as between actors.

4.3 NEXT STEPS AND FURTHER RESEARCH

This report should primarily be seen as a scoping study of some of the emerging issues that will have to be addressed, discussed and resolved to make sure that Bio-CCU and Bio-CCS can live up to their potential as climate change mitigation solutions. There are several issues that need to be addressed in the near-term to ensure that the policy and regulatory work keeps in pace with technological developments and demands for prompt on-the-ground deployment. Key remaining questions include:

- Is there a need for specific Bio-CCU LCA guidelines in addition to those developed for CCU by the LCA4CCU initiative? This could be especially important for B2B or cross-border trade & transport of CO_2 as a resource per se or embedded within products, e.g. a Bio-CCU derived PtX fuel.

- How to address cases that include negative emissions through Bio-CCS but where total process emissions still are above zero because of unavoidable fossil emissions? An important case here is cement, where half of the CO_2 emissions can come not from fuel burning but from calcination of limestone. This means so that even with CCS and use of biomass for process heat, it may not be possible to reach zero or below-zero emissions.

- How to address storage permanence of CO_2 in products with a carbon retention time of decades or years? How to address the contribution of delayed emissions from cascading use of CO_2 against climate goals, e.g. an intermediate storage of – say – 15 years? Is there need for a two-fold approach, e.g. one robust approach for the purpose of practical policy integration and a more distinguished approach to be used in – say – LCA?

- How to fix the conundrum of biomass-to-energy-CCS and inverse relationship of process efficiency and negative GWP (in short: a worse efficiency requires more biomass per kWh and with subsequent CCS, achieves respective 'better' negative GWPs per kWh)?

Finally, it is important to emphasize that a holistic approach for the utilization of biomass resources in different sectors is needed. This includes the consideration of limited renewables availability and transformation efficiencies on a supra-national scale. In order to properly assess the climate change mitigation potentials of Bio-CCUS, it is paramount to reflect on the availability of sustainably sourced biomass across all sectors.

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