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Interim report: Future carbon flows and their monitoring

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Kurzbeschreibung: Zirkuläre Kohlenstoffpfade und THG-Berichterstattung

Mit den Zielen des Übereinkommens von Paris (ÜvP) und den daraus abgeleiteten Treibhausgasneutralitätszielen für Deutschland (2045) und die EU (2050) sowie den teilweise schon bestehenden Zielen negativer Emissionen kommt dem Kohlenstoff zukünftig eine neue Rolle in unserem Wirtschaftssystem zu. Dabei steht die schnelle und möglichst vollumfängliche Vermeidung von Treibhausgasemissionen (THGs), allen voran Kohlendioxid (CO_2), im Zentrum klimapolitischer Überlegungen. Zum Umgang mit und Ausgleich von verbleibenden Restemissionen und zum Erreichen möglicher Negativemissionen bekommen Speicher und Senken eine neue Rolle, da sie es ermöglichen, dem Kreislauf Kohlendioxid zu entziehen. Gleichzeitig dient Kohlenstoff in einigen Bereichen derzeit als wichtiger Input, z. B. als Basis für Kunststoffe und andere chemische Produkte und als zentraler Bestandteil von flüssigen Kraftstoffen. Solche Kohlenstoffpools, die derzeit z. B. für in Wäldern oder in Holzprodukten gespeicherten Kohlenstoff bereits im Inventar erfasst werden, können zukünftig eine größere Rolle bekommen.

Dieser Bericht beleuchtet die möglichen Pfade einer zirkulären Kohlenstoffwirtschaft und die Herausforderungen, die sich für eine transparente Erfassung dieser Ströme unter den internationalen Berichtspflichten des ÜvP und dem Bundes-Klimaschutzgesetz ergeben. Das Vorgehen ist zweistufig: zunächst werden die denkbaren Kohlenstoffflüsse visualisiert, um damit ein Gesamtverständnis über die zukünftig relevanten Kohlenstoffflüsse zu schaffen. Die Visualisierung baut auf den aktuellen Berichtspflichten zu nationalen Treibhausgasinventaren auf und ergänzt diese um zukünftig mögliche Flüsse einschließlich Quellen für Kohlenstoff, ggf. neu entstehende Nutzungspfade sowie Speicher und Senken. Aufbauend auf den entwickelten Kohlenstoffpfaden werden Hindernisse identifiziert, die derzeit eine adäquate Erfassung in den nationalen Treibhausgasinventaren verhindern. Die Analyse charakterisiert diese Fehlstellen hinsichtlich ihrer Auswirkungen, aber auch hinsichtlich der Möglichkeiten sie zu adressieren.

Abstract: Circular carbon pathways and GHG accounting

In the future, carbon will play a new role in our economic system as a result of the goals of the Paris Agreement (PA) and the greenhouse gas neutrality targets derived from them for Germany (2045) and the EU (2050), as well as the already existing targets of negative emissions. The rapid and comprehensive avoidance of greenhouse gas emissions (GHGs), especially carbon dioxide (CO_2), is at the heart of climate policy thinking. Offsetting remaining residual emissions and achieving possible negative emissions, stores and sinks take on a new role, as they make it possible to remove carbon dioxide from the cycle. At the same time, carbon currently serves as an important input in some areas, for example as a basis for plastics and other chemical products and as a central component of liquid fuels. Such carbon pools, which are currently already included in the inventory of stored carbon, in forests or in harvested wood products, for example, may play a greater role in the future.

This report highlights the possible approaches to a circular carbon economy and the challenges that arise in terms of the transparent monitoring of these flows under the international accounting requirements of the PA and the Federal Climate Action Act. The approach is two-fold: first, the potential carbon flows are visualized in order to create an overall understanding of the carbon flows that will be relevant in the future. The visualization is based on the current accounting requirements for national greenhouse gas inventories and supplements these with possible future flows, including sources of carbon, newly emerging uses, storage and sinks. Zoom-ins are used to highlight individual aspects of these carbon flows, while an overview map attempts to provide a broader view of future relevant carbon flows. The visualization is done using Sankey diagrams to enable quantitative data to be added to the individual flows in the future.

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List of abbreviations

Abbreviation	Explanatory notes
BECCS	Bioenergy Carbon Capture and Storage
CC	Carbon Capture
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Usage
CDR	Carbon Dioxide Removals
CO_2	Carbon Dioxide
CRCF	Carbon Removal Certification Framework
CRT	Common Reporting Tables
DAC	Direct Air Capture
DOC	Direct Ocean Capture
ETF	Enhanced Transparency Framework
EU	European Union
HWP	Harvested Wood Products
HFCs	Hydrofluorocarbons
IPCC	Intergovernmental Panel on Climate Change
IPPU	Industrial Processes and Product Use
LULUCF	Land Use, Land Use Change and Forestry
MPGs	Modalities, Procedures and Guidelines
OCC	Onboard Carbon Capture
PFCs	Perfluorocarbons
RFNBO	Renewable Fuels of Non-Biological Origin
GHG	Greenhouse Gases
UNFCCC	United Nations Framework Convention on Climate Change
PA	Paris Agreement

Summary

In the future, carbon will play a new role in our economic system as a result of the goals of the Paris Agreement (PA) and the greenhouse gas neutrality targets derived from them for Germany (2045) and the EU (2050), as well as the already existing targets of negative emissions. The rapid and comprehensive avoidance of greenhouse gas emissions (GHGs), especially carbon dioxide (CO2), is at the heart of climate policy thinking. In areas where avoidance is not possible, the use of carbon capture from the exhaust gas stream and the storage (carbon capture and storage, CCS) or reuse (carbon capture and usage – CCU) of the captured carbon dioxide are ways to prevent the emission of carbon dioxide into the atmosphere. Offsetting remaining residual emissions and achieving possible negative emissions, stores and sinks take on a new role, as they make it possible to remove carbon dioxide from the cycle. At the same time, carbon currently serves as an important source material in some areas, for example as a basis for plastics and other chemical products and as a central component of liquid fuels. Such carbon pools, which are currently already included in the inventory of stored carbon, in forests or in harvested wood products, for example, may play a greater role in the future.

This report highlights the possible approaches to a circular carbon economy and the challenges that arise in terms of the transparent monitoring of these flows under the international accounting requirements of the PA and the Federal Climate Action Act. The approach is two-fold: first, the potential carbon flows are visualized in order to create an overall understanding of the carbon flows that will be relevant in the future. The visualization is based on the current accounting requirements for national greenhouse gas inventories and supplements these with possible future flows, including sources of carbon, newly emerging uses, storage and sinks. Zoom-ins are used to highlight individual aspects of these carbon flows, while an overview map attempts to provide a broader view of future relevant carbon flows. The visualization is done using Sankey diagrams to enable quantitative data to be added to the individual flows in the future.

Based on the carbon pathways developed, obstacles are identified that currently prevent adequate monitoring in national greenhouse gas inventories. The analysis classifies these gaps in terms of their implications, but also in terms of the options for addressing them.

Zusammenfassung

Mit den Zielen des Übereinkommens von Paris (ÜvP) und den daraus abgeleiteten Treibhausgasneutralitätszielen für Deutschland (2045) und die EU (2050) sowie den teilweise schon bestehenden Zielen negativer Emissionen kommt dem Kohlenstoff zukünftig eine neue Rolle in unserem Wirtschaftssystem zu. Dabei steht die schnelle und möglichst vollumfängliche Vermeidung von Treibhausgasemissionen (THGs), allen voran Kohlendioxid (CO_2), im Zentrum klimapolitischer Überlegungen. In Bereichen, in denen eine Vermeidung nicht möglich ist, stellen der Einsatz von CO_2-Abscheidung aus dem Abgasstrom oder eine andere Form der Separierung von Kohlenstoff z. B. durch Pyrolyse und die Einspeicherung (Carbon Capture and Storage, CCS) oder erneute Nutzung (Carbon Capture and Usage – CCU) des abgeschiedenen Kohlenstoffs Möglichkeiten dar, eine Emission des CO_2 in die Atmosphäre zu verhindern. Zum Ausgleich verbleibender Restemissionen und zum Erreichen möglicher Negativemissionen bekommen Speicher und Senken eine neue Rolle, da sie es ermöglichen, dem Kreislauf Kohlendioxid zu entziehen. Gleichzeitig dient Kohlenstoff in einigen Bereichen derzeit als wichtiger Input, z. B. als Basis für Kunststoffe und andere chemische Produkte und als zentraler Bestandteil von flüssigen Kraftstoffen. Solche Kohlenstoffpools, die derzeit z. B. für in Wäldern oder in Holzprodukten gespeicherten Kohlenstoff bereits im Inventar erfasst werden, können zukünftig eine größere Rolle bekommen.

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Aufbauend auf den entwickelten Kohlenstoffpfaden werden Hindernisse identifiziert, die derzeit eine adäquate Erfassung in den nationalen Treibhausgasinventaren verhindern. Die Analyse charakterisiert diese Fehlstellen hinsichtlich ihrer Auswirkungen, aber auch hinsichtlich der Möglichkeiten sie zu adressieren.

1 Introduction

In the future, carbon will play a new role in our economic system as a result of the goals of the Paris Agreement (PA) and the greenhouse gas neutrality targets derived from them for Germany (2045) and the EU (2050), as well as the already existing targets of negative emissions. The rapid and comprehensive avoidance of greenhouse gas emissions (GHGs), especially carbon dioxide (CO2), is at the heart of climate policy thinking. This applies across all sectors. A central element is the avoidance of the formation of greenhouse gases, e.g. by changes in the use of energy sources, products and production processes. In areas where avoidance is not possible, the use of carbon capture from the exhaust gas stream and the storage (carbon capture and storage, CCS) or reuse (carbon capture and usage – CCU) of the captured carbon dioxide are ways to prevent the emission of carbon dioxide into the atmosphere. Offsetting remaining residual emissions and achieving possible negative emissions, stores and sinks take on a new role, as they make it possible to remove carbon dioxide from the cycle. Both natural processes, such as the binding of carbon dioxide in biomass, and technical approaches, such as the separation of carbon dioxide from the air (direct air capture – DAC) or from the ocean (direct ocean capture – DOC), can play a role here. Furthermore, storage in geological formations or in the ocean, in the form of bound carbon in biochar and in soils, or in the form of permanent forest, are relevant.

At the same time, carbon currently serves as an important source material in some areas, for example as a basis for plastics and other chemical products and as a central component of liquid fuels. Most of this carbon is derived from fossil sources. Although there are biomass-based alternatives, the use of biomass is not without its own challenges. The use (and release) of carbon is at odds with long-term storage in biogenic material. Sustainable biomass is a limited resource, high demand for it puts compliance with strict sustainability criteria at risk. Last but not least, there is also competition with food production for the use of agricultural land.

Currently, carbon-based products (especially plastics) are not recycled to any significant extent in Germany and the EU. 89% of all plastic packaging consists of virgin material, while more than 50% of packaging waste is incinerated (WWF 2021). The recycling of CO2 bound in products, but also of captured CO_2, are essential elements of a future climate-neutral carbon economy.

The creation of national greenhouse gas inventories is a central instrument for monitoring greenhouse gas emissions. Under the PA and the transparency framework associated with it, the guidelines for calculating and reporting greenhouse gas emissions have been revised and adapted. However, CCS and carbon cycles in particular have only been given limited consideration in the revisions of the greenhouse gas reporting rules to date. In 2027, the IPCC is planning to present a methodology report that will address how negative emissions should be reflected in inventories (but without any binding requirements).

This report highlights the possible approaches to a circular carbon economy and the challenges that arise in terms of transparent monitoring of these flows under the international accounting requirements of the PA and the Federal Climate Action Act. The approach is two-fold: first, the possible carbon flows are visualized in order to create an overall understanding of the carbon flows that will be relevant in the future. The visualization is based on the current accounting requirements for national greenhouse gas inventories and supplements these with possible future flows, including sources of carbon, newly emerging uses, storage and sinks. Zoom-ins are used to highlight individual aspects of these carbon flows, while an overview map attempts to provide a broader view of future relevant carbon flows. The visualization is done using Sankey diagrams to enable quantitative data to be added to the individual flows in the future.

Based on the carbon pathways developed, obstacles are identified that currently prevent clear monitoring in national greenhouse gas inventories. The analysis classifies these gaps in terms of their implications, but also in terms of the options for addressing them.

2 Concept

2.1 Background

As outlined in the introduction, the role of carbon in the future will have to change significantly in order to achieve the goals of the PA: emissions must be significantly reduced, carbon sequestration and sinks (removal of carbon from the atmosphere) must be significantly expanded, while non-fossil carbon will play a new role as a raw material, particularly in the chemical industry and possibly in the production of energy sources.

International GHG reporting is the main instrument for monitoring the development of national emissions. In addition to fulfilling international reporting obligations, the German GHG inventory also serves as a basis for setting targets and monitoring target achievement under the German Federal Climate Action Act. It is therefore a central element of national climate policy. The basis for this is a complete monitoring of all anthropogenic territorial greenhouse gas emissions that avoids double counting. This is achieved using the transparency framework established in the PA and related guidelines as well as the corresponding IPCC guidelines on GHG accounting. For this reason, we use the regulations for GHG accounting that are currently in use as a basis for developing and visualizing possible future carbon pathways (chapter 3) and for identifying gaps (chapter 4)

In this chapter, we explain the basic principles and structures of today's GHG inventories and present the various elements of the visualization.

2.2 Principles and structure of current GHG inventories

Emissions reporting in accordance with the Paris Agreement

The ‘Modalities, Procedures and Guidelines’ (MPGs) of the ‘Enhanced Transparency Framework’ (ETF) under the Paris Agreement provide the basis for emissions accounting.

The MPGs define how the signatories have to report their greenhouse gas emissions, climate protection measures and support payments. The aim is to provide a clear understanding of the progress being made towards achieving the climate targets and increase transparency. The MPGs refer to the IPCC guidelines, which describe standardized methods for calculating and reporting emissions.

IPCC guidelines

Under the United Nations Framework Convention on Climate Change (UNFCCC), countries have committed to submitting national greenhouse gas inventories. The IPCC Guidelines for National Greenhouse Gas Inventories are detailed guidelines that describe the methodology for preparing greenhouse gas inventories. The guidelines date from 2006 and many sections were revised in 2013 and 2019[1]. In terms of the accuracy of the data collection methods, a distinction is made between different ‘tiers’, which take into account the available data and resources for compiling the inventories (IPCC, 2006):

- Tier 1 is the easiest to apply and uses aggregated standard parameters (partly country-specific). This tier has the highest level of uncertainty.
- Tier 2 requires that the parameters be more strongly disaggregated, ideally with country-specific data (AR / EF).

1 However, the 2013 and 2019 revisions are not being consistently applied.

- Tier 3 requires the best available methods, such as models and inventory measurement systems, that are tailored to national circumstances and use the best possible input data (plant-specific data (AR / EF)).

2.2.1 CRT Table

Common Reporting Tables (CRTs) are a key tool of the greenhouse gas inventory. These tables are used by individual countries to report their greenhouse gas emissions and sinks in a standardized way, thus enabling consistent and comparable monitoring of greenhouse gas emissions and sinks worldwide. (UNFCCC, 2021)

CRT are divided into the five sectors and their sub-sectors described below. The tables show emissions and sequestration of greenhouse gases, including CO_2, CH_4, N_2O and F-gases (e.g. HFCs, PFCs, SF_6 and NF_3). They are arranged by year (from 1990 onwards), so that the development of emissions/sinks over the years can be tracked. The tables for each sub-sector contain detailed activity data (e.g. the amount of fuel consumed) and show implicit emission factors that are calculated for each greenhouse gas. This ensures transparent and comprehensible accounting of emissions and enables international comparability.

2.2.2 CRT Sectors

The structure of the greenhouse gas inventory is defined in the modalities, procedures and guidelines (MPGs), which in turn define five sectors. The IPCC Guidelines are divided into these five sectors. They are outlined in brief below with regard to their relevance for carbon capture (CC) processes.

CRT Sector 1: Energy

The energy sector is described in Volume 2 of the guidelines. In Germany (and in most other countries), this is by far the most greenhouse gas-intensive sector and accounts for around 85% of GHG emissions (excluding LULUCF). It includes the energy industry, trade, transport and combustion plants. The following are particularly relevant for the accounting of CC:

- Volume 2, Chapter 2.3.4: Stationary combustion systems (mainly electric power and heat production plants)
- Volume 2, Chapter 4.2.1. Natural gas and Hydrogen Processing Plants

In addition, Volume 2, Chapter 5, explicitly deals with CCS. However, this does not cover CO_2 capture (to avoid double counting), but only emissions from transport, injection and storage:

- Volume 2, Chapter 5.4: Emissions related to the transport system (Category 1.C.1), i.e. CO_2 transport via pipelines, ships and others (e.g. temporary storage)
- Volume 2, Chapter 5.5: Emissions related to injection (Category 1.C.1). With no Tier 1 method available (no default parameters), only specific estimates are allowed
- Volume 2, Chapter 5.6 Emissions related to geological storage. With no Tier 1 method available (no default parameters), only specific estimates are allowed

CRT Sector 2: Industrial processes

The process-related emissions of the industrial sector are described in Volume 3 of the guidelines. Process-related emissions include, for example, geogenic CO_2 emissions from the cement industry or CO_2 emissions from steel production or nitrous oxide emissions from the chemical industry. Combustion-related emissions are covered in CRT sector 1. CRT sector 2 covers around 7.5 per cent of GHG emissions in Germany (excluding LULUCF), primarily from emissions in the cement, steel and chemical industries. Volume 3 (IPPU) Chapter 1.2.2 Capture and abatement is particularly relevant for the monitoring of CC, for a general description and in more detail go to

- Volume 3, Chapter 2.2, Cement manufacture
- Volume 3, Chapter 3.2 Ammonia production
- Volume 3, Chapter 3.9, Methanol manufacture
- Volume 3, Chapter 4.2 Iron and steel manufacture

When hydrocarbons are used as source materials, the carbon bound in the product is factored in (deducted) via a mass-balance approach, e.g. in the production of methanol or soot. If emissions arise when these products are in use, they are accounted for in the use-related category.

CRT Sector 3: Agriculture

The agriculture sector is described in the first part of volume 4 of the guidelines. In Germany, it accounts for around 7.5% of GHG emissions (excluding LULUCF), these are mainly methane emissions from cattle farming and methane and nitrous oxide emissions from fertilizers.

In principle, agricultural processes are relevant carbon sources and sinks. However, CO_2 flows resulting from agricultural processes in soils are covered by the LULUCF sector (CRT 4.B, see below) and not by the agricultural sector (CRT 3). Therefore, the gap analysis of carbon flows in a circular carbon economy does not focus on the CRT 3 sector.

CRT Sector 4: LULUCF

The LULUCF sector includes sources and sinks from forests, agricultural land, grassland and wetland areas and settlements, as well as the storage of carbon in wood products and their subsequent release[2,3]. It takes into account emissions and sinks (i) in these categories and (ii) movements between them. Only CO_2 can act as a sink within one of these categories, while emissions of CO_2, CH_4, and N_2O can result in sources. CO_2 is the most important greenhouse gas in the LULUCF sector, but because sources and sinks partially cancel each other out, the net effect is roughly comparable to that of CH_4 emissions. N_2O emissions only play a minor role.

In particular, the LULUCF sector (in addition to agriculture) must be recorded correctly in relation to nature-based solutions.

In Germany, net emissions from the LULUCF sector fluctuate between slightly positive in some years and slightly negative in others. Emissions of CH_4 (and N_2O) act as sources, while the net CO_2 effect acts as a sink. In this context, grassland and cropland are CO_2 sources, whereas forests, in particular, act as CO_2 sinks. To a limited extent, built-in wood products also act as CO_2 sinks.

The LULUCF sector is thus a complex interaction of different categories and greenhouse gases. Furthermore, the level of uncertainty associated with almost all the components is much higher than in other sectors, where emissions can often be measured accurately. On the contrary, sources and sinks in the LULUCF sector are typically represented on the basis of a series of assumptions and uncertain parameters.

2 Forests, croplands, grasslands and wetlands, settlements and harvested wood products (HWP)

3 The 2019 Refinement to the 2006 IPCC Guidelines is particularly important for the HWP sector, as it provides updated methodological guidelines and emission factors. See: https://www.ipcc-nggip.iges.or.jp/public/2019rf/index.html (last checked on 31/10/2024)

CRT Sector 5 refuse

The waste sector is described in Volume 5 of the guidelines. In Germany, it accounts for less than 1% of GHG emissions (excluding LULUCF), mainly from methane emissions from waste landfilling and the treatment of wastewater and solid waste. Historically, emissions from landfill have been dominant. However, since the landfilling of organic material was banned in 2005, these have fallen sharply (partly replaced by treatment and waste incineration). Waste incineration in Germany is entirely linked to energy production. To avoid double counting, emissions from waste incineration are therefore reported in the energy section (CRT 1), especially in waste incinerators (CRT 1.A.1.a). Their use as alternative fuels in the cement industry is also included (CRT 1.A.2.f).

The waste sector is not currently a focus for the gap analysis in the context of a circular carbon economy because its role is fairly limited. However, its significance could increase in the future, if, for example, new inert carbon-enriched construction materials end up in the waste and long-term carbon storage becomes necessary.

2.2.3 Other relevant principles

The IPPC guidelines also have the following relevant principles.

Territorial principle and calculation based on fuel sold data

The territorial principle is a central concept in international emissions reporting and the IPPC guidelines. It forms the basis for calculating a country's greenhouse gas emissions (total national emissions). All emissions that occur within the country's geographical borders are taken into account. Emissions that occur outside the country's borders are not included (but are partially calculated and reported for information purposes, as in the case of international transport).

For fuel consumption, the amount of fuel that was sold in the country during the year is credited. Regardless of whether or not it is consumed domestically (e.g. in road traffic). Aviation and shipping are exceptions. In these cases, only the fuel consumption for the domestic shares is added to the national total emissions. The international share is reported separately as a memo item in the greenhouse gas inventory.

Biogenic CO_2 emissions

CO_2 emissions from the combustion of biomass in installations in sector 1 are recorded and reported in the greenhouse gas inventory, but these are not included in the total national emissions. If CO_2 capture also takes place in a biomass combustion plant (e.g. BECCS), negative values can be reported for CO_2 in accordance with the guidelines for the respective plant4. Assuming that the use of biomass is in equilibrium (Sector 3 Agriculture and Sector 4 LULUCF)5, this corresponds to a potential negative emission. The subsequent emissions from CO_2 transport, CO_2 injection and CO_2 storage should be recorded, regardless of whether the carbon is of fossil or biogenic origin.

4 See the following footnote from CRT Table 1A(a)s4: „(3) Although CO_2 emissions from biomass are reported in this table, they will not be included in the total CO_2 emissions from fuel combustion. The value for total CO_2 emissions from biomass is recorded in Table 1 under the memo items. If CO_2 is captured from biomass combustion and transferred to long-term storage, the recovered amounts should be reflected in the total emission for the sector, i.e. contribute with a negative emission. See the 2006 IPCC Guidelines (vol. 2, chap.2, p2.37; and chap. 5, p.5.8)."

5 Emissions from biomass production are taken into account in sector 3 or 4.

2.3 Visualization of possible carbon pathways

2.3.1 Scope of the analysis

The carbon circular economy that is expected to emerge in the future will pose challenges for the monitoring of data in the GHG inventory. The following analysis aims to capture and appropriately map the relevant flows of such an economy from an inventory perspective. The actual carbon flows within the individual manufacturing processes and procedural steps are diverse and fragmented. However, this level of detail is not necessary for the representation and evaluation of the flows with regard to their GHG impact and their inclusion in national inventories. Therefore, the individual process steps and routes are summarized in suitable pathways. The focus is on representing those conversion steps where emissions are (or could be) released. In addition, pools are required for the representation, i.e. intermediate storage facilities in which carbon is temporarily stored in biomass, energy sources, various products or residual and waste materials. These can serve as temporary carbon stores for the period of their use and become emission relevant as soon as the carbon is released again. Finally, the sector classification used, and the flows are based on the inventory specifications.

To assess the emissions impact of carbon pathways, it is necessary to record the origin of the carbon. Where possible, a distinction is made between atmospheric, biogenic, geogenic, fossil and recycled carbon. The origin of the carbon is shown separately in the flows. Currently, in many cases such traceability is already possible (e.g. with regard to biogenic fuel shares). In other cases, however, such as atmospheric carbon, no entry has been yet made in the inventory. In some areas, particularly in the pools, the traceability of the carbon origin is (currently) lost (e.g. in the production of plastics that are then used as waste in waste incineration). This point is taken up in the gap analysis in the following section 4.

The analysis focuses on those pathways that are relevant for accounting purposes. Uses that occur over the course of a year, such as carbon in beverages or greenhouses, are usually excluded. However, fuels (with biogenic, atmospheric or recycled carbon) remain within the scope of the study because they play a relevant role, particularly with regard to synthetic fuels and CCU, even though their use and emission effect could occur over the course of a year (see also section4).

Although every attempt has been made to include all relevant emission sources in the figures, emissions from leaks during the extraction of fossil energy sources and the transportation of energy sources (fossil or synthetic) and CO_2 (CRT 1.B) have been excluded in order to avoid making the figures less clear.

2.3.2 Methodology of graphical representation

Sankey diagrams are used to visualize the flows. The Sankey diagrams connect the carbon sources with the carbon sinks and storage sites via various intermediate steps. The atmosphere and the ocean play a special role: on the one hand, they are sources of carbon (e.g. biogenic carbon or CO_2 capture from the air or the ocean (direct air capture (DAC)/ direct ocean capture (DOC)), on the other hand, they are storage sites that absorb CO_2 emissions.

The Sankey diagrams in the current version are purely qualitative, i.e. they do not contain any information about the relevance (i.e. quantity) of the flows. The flow can be gaseous, liquid or solid, or it can contain carbon bound in products. In a later step, quantitative information could be added. Since the origin of the carbon is crucial to the assessment of the pathways GHG relevance, this information is included in the figures wherever possible (using different colours for the various flows). Emissions resulting from leaks during CO_2 storage must be recorded independently of the origin of the carbon and reported as emissions. Likewise, information about the origin of recycled CO_2 is not always known. To clarify the fact that the origin is partially unknown, a mixed pathway for carbon of unknown origin has been added. However, the figures do not distinguish between different subtypes of a source (e.g. cultivated vs. waste biomass) or the aggregate state of the carbon (gaseous or bound).

At the ends of the pathways, storage and sinks are shown separately in the visualization to show a clear differentiation between negative emissions and the storage of captured fossil and geogenic emissions ('sink' vs. 'storage').

Different levels of aggregation of the carbon economy are shown in the sankeys in order to provide sufficient detail on the one hand and to enable an overall picture on the other. The following detailed images ('zoom-ins') were created for this purpose:

- **Carbon sources**, entering the cycle. Possible sources include the atmosphere, the ocean, biomass, fossil fuels, rocks/minerals from the lithosphere or material flows from the capture of carbon from various processes.
- **Carbon sinks and storage sites**, where carbon is stored and leaves the cycle (temporarily or permanently).
- Carbon flows in **industry**, including captured carbon that re-enters the cycle as recycled carbon.
- **Chemical industry** carbon flows **including parts of the energy industry**.
- All sectors are shown in an **overview diagram**. For the sake of clarity, this illustration does not show all the details.

The freely available software R Studio and the R package Panta Rhei for the R programming language (https://www.r-project.org) were used to create the sankeys.

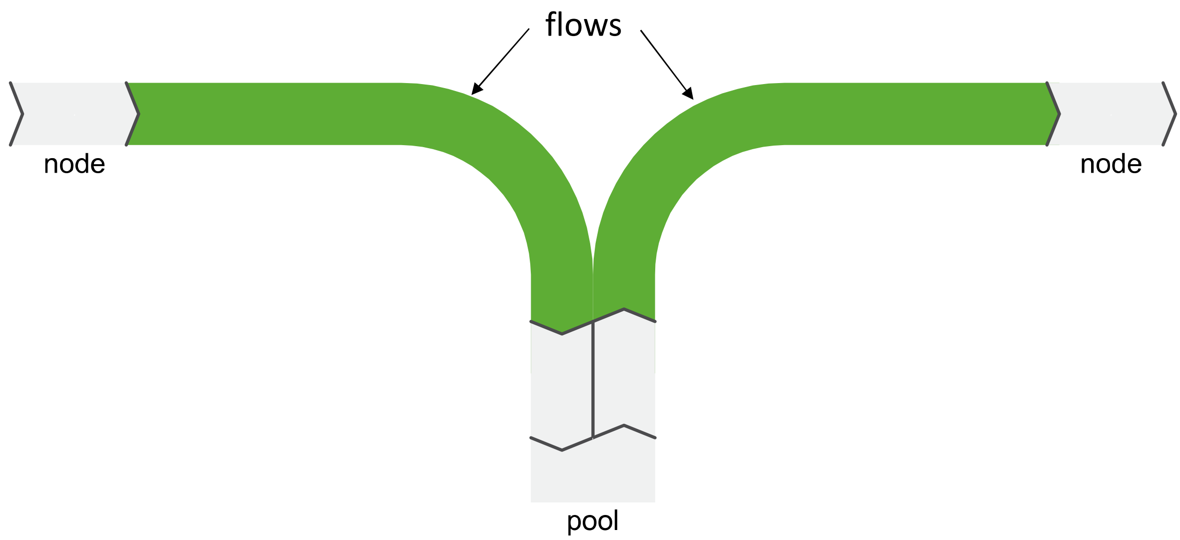
3 Carbon flows in a circular carbon economy

3.1 Diagram elements

The diagrams are made up of four graphical elements (see Figure 1):

- **Nodes** represent all the intermediate steps relevant for the illustration. The focus is on those intermediate steps where conversion processes take place that can result in emissions, as only these are relevant for monitoring in the inventory. In addition, there are auxiliary nodes that facilitate process understanding such as “recycling” in the zoom-in for the chemical industry. This path makes it clear that carbon bound in products is fed back into the process during recycling. Emissions from recycling are documented in the respective industrial sector.
- **Pools** illustrate how carbon is stored, e.g. bound in the form of a product such as wood, industrial products or fuels/energy carriers, and is then released again at a later point in time. These pools are especially relevant for the discussion about the traceability of carbon origin.
- **Flows** show how carbon moves between different nodes.
- The **colour of a flow** clearly indicates the carbon origin of this flow.

Figure 1: Elements of Sankey diagrams



Source: Own illustration, IREES

Starting from the sources, the flows map the different carbon paths to and between different nodes up to the sinks and storage sites. Paths are understood to be combined flows from source to sink/storage. Recirculating carbon (capture and recycling) results in carbon cycles.

The flow width in the diagrams does not convey any information. Information about the quantities involved could be added at a later stage if available.

3.2 Visualization of the flows within the carbon economy

In the following, the individual elements of the graphical representation are introduced step by step from the source to the use phase to permanent sinks and storage sites, before these are summarized in an overview chart. For greater comprehensibility, the possible sinks and sequestration in storage sites are presented after the sources to link the beginnings with the possible ends.

3.2.1 Zoom-in: Carbon sources

The carbon contained in the carbon cycle can be assigned to five sources:

- **Atmosphere**
  Carbon can be removed from the atmosphere in different ways. To avoid double counting, here, this only refers to the technology of direct air capture (DAC).
- **Oceans**
  Large quantities of atmospheric CO_2 have been absorbed by the oceans.6 Recent approaches are exploring the possibility of removing CO_2 from the ocean (analogous to DAC) (this approach is referred to as Direct Ocean Capture - DOC). Similar to removing CO_2 from the atmosphere, this category includes only the direct extraction of CO_2 from the ocean. In terms of color, the diagrams do not differentiate between carbon from the atmosphere and carbon from the ocean.
- **Biomass**
  Carbon that has been bound from the atmosphere or the ocean in organic material (especially plants, algae, but also, e.g. animal carcasses or phytoplankton) is shown in the diagrams as biogenic carbon.
- **Fossil energy sources**
  Fossil energy sources (hard coal and lignite, natural gas, crude oil) are currently the largest source of CO_2 emissions. In addition to using fossil energy sources to generate energy, they are also a source of carbon for material use. During these processes, carbon is bound in products.
- **Lithosphere/Minerals**
  Carbon is bound in rocks and minerals. During production of cement clinker and lime, in particular, this carbon is emitted in the form of CO_2 as the result of exposure to heat.

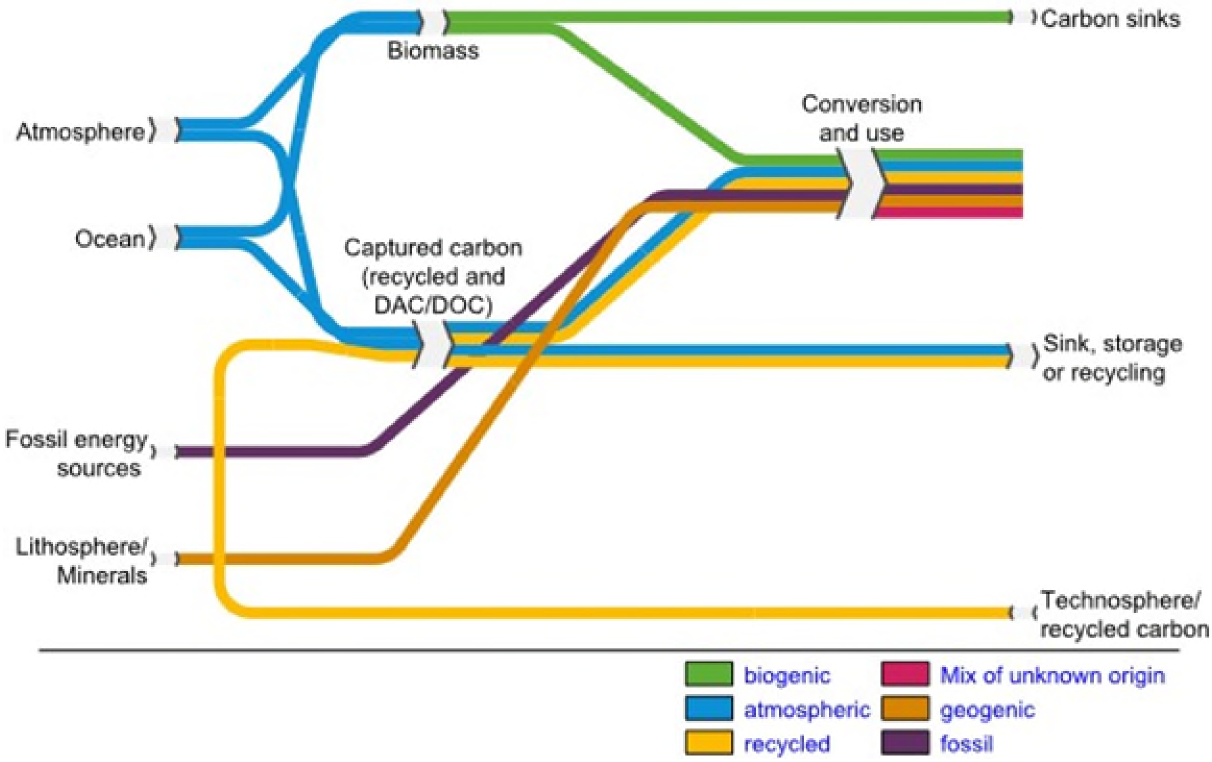
Besides these natural carbon sources, **recycled CO_2** occurs as a further source in a circular carbon economy. CO_2 can be captured at various points in the carbon economy: on the one hand, at large point sources, e.g. in the conversion sector, in industry or in public energy supply, including waste incineration. On the other hand, there are ideas for and technical approaches to capturing CO_2 at smaller emission sources, such as in the transport sector (maritime transport) or in buildings (ventilation or heating systems) We use the term recycled CO_2 to refer to this CO_2 returning to the carbon cycle. Recycled CO_2 can have different origins (atmospheric, biogenic, fossil or geogenic).

The following figure shows the visualization of carbon sources. Recycled CO_2 comes from sequestration and circulates within the technosphere without leaving it. In contrast, the other sources bring carbon into the pathways from outside. Due to the mixing of CO_2 from different origins during use (collected at the “conversion and utilization” nodes), the carbon source or at least the exact proportions of the different sources in the recycled flow cannot be determined and recorded. If information about the origin is lost, the flow is shown as a mix. Recycling flows

6 During this process, (bi-)carbonate ions react with CO_2 molecules from the air and are initially dissolved in surface waters. Ocean currents then carry the dissolved CO_2 into the depths as well. At the same time, this affects the ocean’s chemistry and seas become more acidic with increasing absorption of CO_2 from the air. (IPCC, 2022)

are illustrated separately. Recycling flows of known origin are possible (e.g. BECCS or capture from fossil sources) as are recycling flows of uncertain origin.

Figure 2: Zoom-in carbon sources



Source: Own illustration, IREES

“Conversion and utilization” in this diagram is the collective node for (all) uses: energetic (e.g. refinery underfiring) and material (e.g. refinery products). The biomass and (partly) recycled and captured CO_2 paths refer to directly feeding the captured CO_2 into sinks or storage sites without undergoing any conversion or use. In this case, traceability might be possible if necessary7

3.2.2 Zoom-in: Carbon storage sites and sinks

Carbon storage sites and sinks are only considered in the inventories if they include active human intervention. Natural storage processes remove carbon passively and are therefore not classified as inventory-relevant in this report; cp. the recent report on “The State of Carbon Dioxide Removal“ (Geden et al., 2024) and the definition by the UNFCCC (UNFCCC, 2022). In the following, therefore, only anthropogenic (“active”) sinks are addressed, while natural (“passive”) sinks are not examined in more detail.

Carbon stores differ greatly depending on how long the carbon is bound. Both the IPCC’s sixth assessment report and the report mentioned above divide the available stores into three time periods (Geden et al., 2024; IPCC et al., 2022):

- Decades to centuries

7 It might be possible to document this at the accounting level, since transporting CO_2 flows from different origins in the same network unavoidably leads to the molecules mixing. However, assigning the removed CO_2 quantities to the corresponding sources might be conceivable at the level of balances.

- Centuries to millennia
- Tens of thousands of years and longer

In the framework developed by the EU Commission for the certification of negative emissions, permanent CO_2 storage is defined as storage over several centuries and in practice assumed to be at least 200 years. Accordingly, we will now look at carbon sinks and storage sites based on the IPCC classification, which divides them into two groups:

- Group 1: Carbon storage sites with storage periods of decades to centuries
- Group 2: Carbon storage sites with storage periods of centuries to millennia and beyond

The second group in particular can be considered permanently stored according to the definition of the EU Carbon Removal Certification Framework (CRCF) and are eligible to receive permanent sink credits. In contrast, sinks in group 1, according to the CRCF, may be recognized as permanent sinks, but this is not mandatory. (EU parliament & EU council, 2024).

Carbon storage sites with storage periods of decades to centuries (temporary carbon storage sites)

According to the IPCC, temporary carbon stores include the natural elements such as vegetation, soil and sediments. These stores are activated by the following anthropogenic activities:

- Afforestation
- Improved forest management
- Agroforestry
- Carbon storage in cropland and grassland
- Biochar/solid biomass (storage duration and net emission effect are case dependent, so classification is controversial)
- Rewetting and management of peatland and coastal wetlands
- Blue carbon in coastal zones (illustrated in the visualization as the coastal wetlands sink).

Carbon stores with a storage period of at least two centuries and up to millennia and beyond (permanent carbon storage sites)

According to the IPCC, permanent carbon storage sites include geological formations, mineralization and marine sediments. These are used in the following man-made activities:

- Burying biomass on land (e.g. harvesting and the airtight burying of trees) or sinking biomass into the ocean
- Biochar (storage duration and net emission effect are case dependent, so classification is controversial)
- Marine fertilization
- Storage in geological formations (including saline aquifers, basalt rock or former oil and gas storage sites)
- Mineral products (including cement or concrete enriched with CO_2 or carbon, asphalt containing bitumen)

- Accelerated weathering
- Increase in ocean alkalinity.

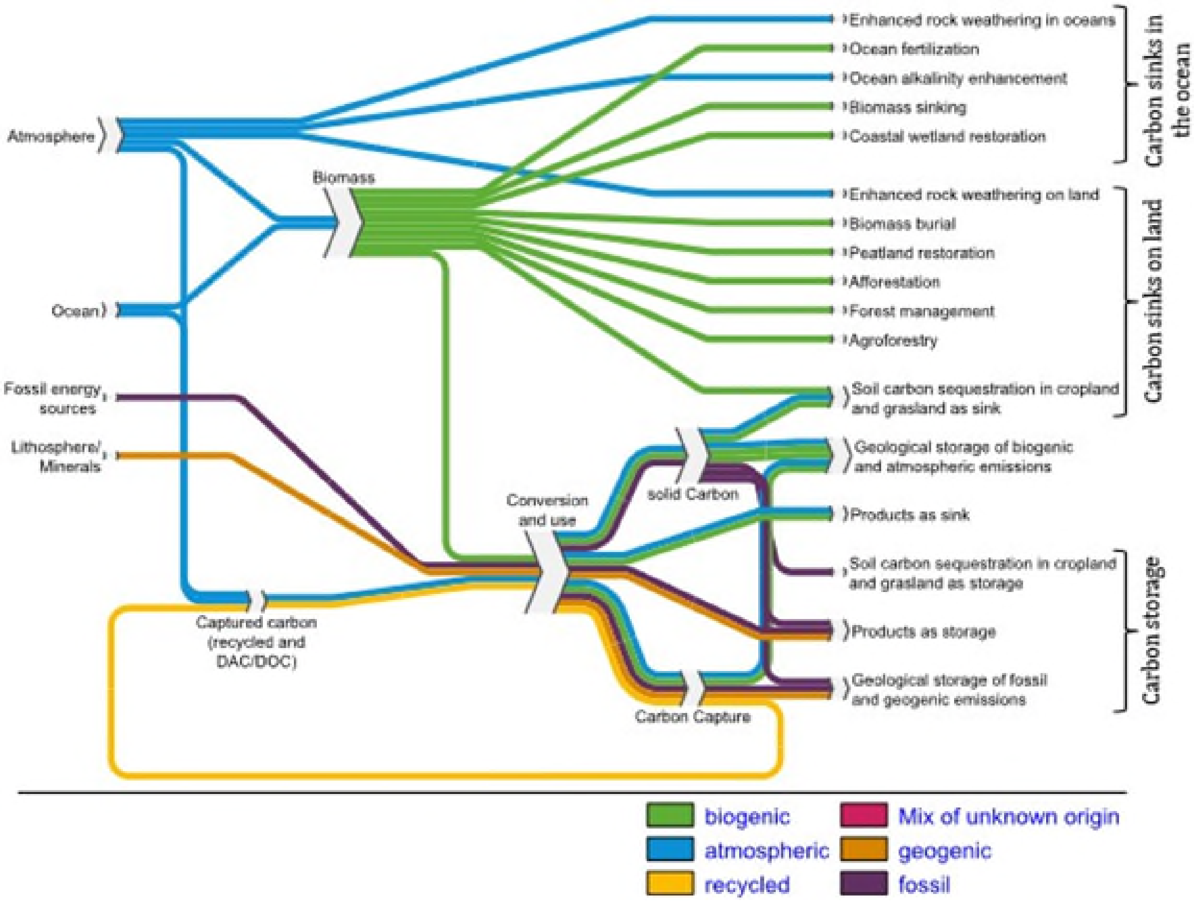
The various storage options are subject to different levels of uncertainty regarding the permanence of storage (e.g. leakage of gaseous CO_2 from underground storage sites or forest fires). Furthermore, the various storage methods have varying consequences for the respective systems (e.g. the marine ecosystem in the case of CO_2 storage in the ocean fertilization or increased alkalinity). The methods listed have not all been researched to the same extent, and there is a lack of knowledge about the uncertainties, impacts and, in some cases, the actual effort required to (permanently) store 1t CO_2. These aspects are not taken into account in the visualization.

The following figure classifies the carbon storage sites in terms of their storage duration and storage medium (land, ocean, geological storage). Sinks that arise from the removal and permanent storage of atmospheric or biogenic CO_2 are labelled separately to storage sites. Sinks and thus negative emissions can only arise where atmospheric or biogenic carbon is permanently stored. The storage of fossil or geogenic CO_2 only ever represents the avoidance of emissions and cannot lead to negative emissions.

The inventory takes into account the **territorial principle**, so that storage sites in the ocean that are difficult or impossible to assign to a territory have a different significance than storage sites that can be unequivocally assigned to a state's territory. Ocean fertilization and increased ocean alkalinity clearly cannot be allocated to any territory. However, such an allocation could be possible for ocean biomass sinks and accelerated weathering in the ocean. So far, it has not been possible to include such ocean-based sinks in the GHG inventory, in a similar way to the treatment of extra-territorial emission sources. Since this may change in the future, oceanic sinks (both territorially difficult and those that cannot be allocated) are included in the visualizations. The mechanisms of these sinks and their uncertainties require considerable research before they can be included in the GHG inventory.

Based on the system of classification outlined in Figure 3 the carbon storage sites and sinks in a carbon economy show the inflows and origin of carbon.

Figure 3: Zoom-in carbon storage and sinks



Source: Own illustration, IREES

Sinks are roughly divided into oceans and land. This rarely involves the direct removal of atmospheric carbon; instead, it is usually incorporated into biomass and then stored as biogenic carbon. Blue carbon as a sink is not listed separately but is included in “coastal wetlands” and “bogs and wetlands”.

“Conversion and use” and “carbon capture” refer to the energy sector, industry, trade and the building sector and also include refineries. The traceability of the origin of the carbon is partially lost at this point. However, the traceability of the biogenic and geogenic proportions is usually possible (e.g. for BECCS or CCS in cement plants). As a rule, not all emissions from the processes can be captured, so that some of the CO_2 is released into the atmosphere. Such leakages are not shown in the figure.

The use of atmospheric carbon with the help of DAC & DOC is shown as “captured CO_2” and then enters “conversion and use” as an atmospheric flow. It then either enters a sink directly as solid or bound carbon or, after the carbon has been used as a material, is recycled through carbon capture (in the mixed flow “recycled CO_2”) or is also introduced into a sink.

On the one hand, emissions can be released during the “conversion and use” process. On the other hand, carbon can be captured and stored (flows into carbon sinks and storage sites) or utilized (circular flow). The flow to the “solid carbon” node refers to pyrolysis. This can be done with fossil, biogenic or, in the future, synthetic natural gas using recycled or atmospheric carbon. This process produces hydrogen and solid carbon. The solid carbon can be introduced as a powder or granulate, or as coal in sinks and stores. In “cropland and grassland”, biomass can also be introduced directly, and biochar can be produced from biogenic carbon. This path also includes humus formation. In ‘geological sinks’, gaseous CO_2 from CO_2 capture can also be stored. Both types of sink have equivalents for the storage of carbon of fossil and geogenic origin. In addition, carbon can be bound in products (e.g. “solid carbon” as a concrete aggregate in “products as storage sites”).

The **captured CO_2** from conversion and utilization processes can be recycled for reuse; see the yellow flow. This flow can include all carbon sources. This creates carbon cycles that keep the carbon in the utilization phase for longer and thus delay or reduce emissions. At the same time, different carbon sources are mixed in the long term (CO_2 captured from waste incinerators will also have fossil components from plastic products and biogenic components from wood products in the future), so that it is difficult to count any subsequent storage as a pure sink. **Traceability** of the carbon origin is therefore an important factor in the evaluation. Particularly in the case of recycled carbon, it can be assumed that the information about the origin is difficult to trace and may be partially lost. Approaches for tracking and evaluation need to be developed for this in the future. The key here is to know how much of the carbon in an emission or sink is biogenic or atmospheric in origin and how much is fossil or geogenic in origin.

Biomass is included in various pathways. Biomass from the node itself is understood to be cultivated biomass, while biogenic flows from “conversion and use” also include biomass from waste and residues. The reporting has not previously been broken down into biogenic flows in this way. However, the information is taken into account when calculating emissions using the emission factors applied to biomass.

3.2.3 Zoom-in: Carbon pathways and carbon pools in industry

Carbon is used for a variety of industrial purposes, both as an energy source and as a raw material. The latter is particularly relevant in the chemical industry. In addition, there are processes in which emissions arise: During cement production, carbon is released from limestone. In metal production and processing, carbon is needed to adjust the material properties and is (currently still) used as a reducing agent. In both cases, CO_2 is released.

A particular challenge in the carbon accounting is that carbon can be temporarily bound in products. We therefore speak of a **product pool**, for example the **harvested wood products** (HWP) pool. If the product is recycled (either materially or chemically) at the end of its useful life, the carbon remains in the cycle. Landfill is one of the possible methods of disposal for these products allowing the carbon in the product to be stored. When the product is incinerated, the bound carbon is released again. Usually this happens at the end of its life, when it is disposed of as waste. Then, as a rule, it is recycled as energy, either in the public energy supply or as a substitute fuel in industry. In both cases, CO_2 can be captured, and the carbon can either be reused or stored.

Biomass plays a special role in its function as a pool, in that it can act either as intermediate storage or as a sink (see chapter 3.2.2). Removing biomass from the system in any way creates a conflict with its potential sink function.

Furthermore, there is an **energy source pool**. In the future, it will be important to track the origin of the sequestered carbon in this pool. This is already possible for biofuels, and the requirements for renewable fuels of non-biological origin (RFNBO) will make it necessary in the future. If the CO_2 from biogenic fuels or possibly RFNBO is captured, this results in negative emissions. Subsequent emissions during transport and storage (leakage) reduce the negative emissions and can therefore not be recorded as GHG-neutral in accounting terms. Atmospheric or recycled carbon is currently not traceable (see gap analysis in section 4). This also applies to recycled carbon of biogenic origin.

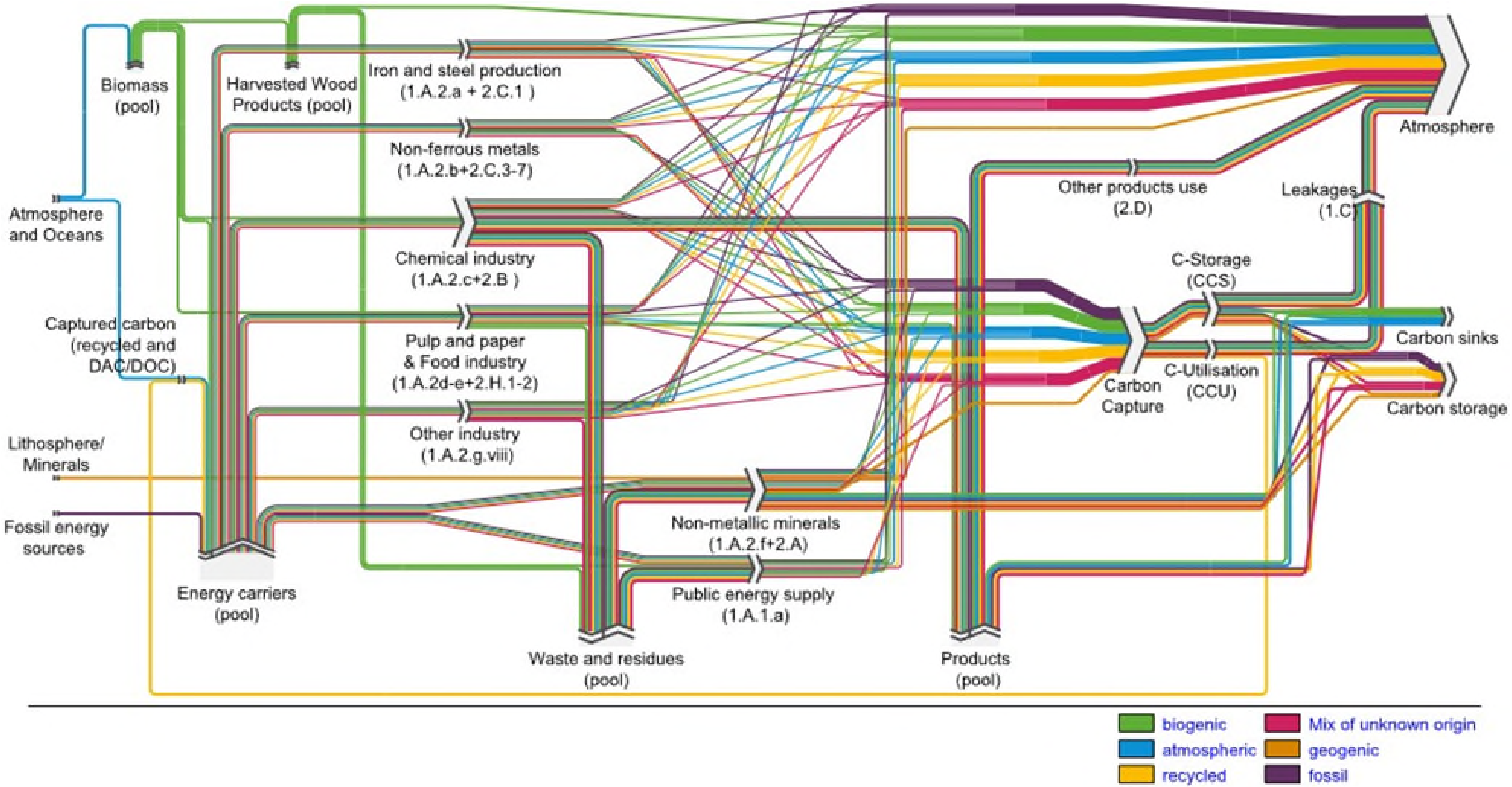
In the future, it may be possible to trace atmospheric and recycled carbon. Approaches are emerging from the existing regulatory and certification approaches for biogenic fuels, RFNBO and recycled carbon fuels. These allow at least a partial identification of the origin of the carbon. In the case of recycled carbon-containing fuels, according to RED II, it is not only the origin of the carbon that is relevant, but also the fact that the capture of the CO_2 that would otherwise be released takes place as part of well-defined EU ETS processes and that these CO_2 emissions have already been subject to a CO_2 tax and have therefore been officially recorded and are considered GHG-neutral when they are reused. A special feature of the pool of energy sources is the time limitation of the carbon sequestration in those energy sources destined for combustion and thus the release of carbon.

For product pools in which carbon is bound in a product for several decades and then, at the end of its service life, is either (i) recycled directly, (ii) used for energy generation, possibly with CO_2 capture, or (iii) is moved to the waste pool or (iv) acts as a form of storage when deposited in a landfill site, tracking the changing proportions of C sources is a major challenge. Physical traceability is not possible in many cases, because, for example, when used as a raw material in the chemical industry or transported in pipelines, the mixing already occurs at the molecular level.8 However, it is certainly conceivable that traceability could be ensured in accounting terms at the systemic level on the basis of quantity proportions. In the chemical industry, for example, an approach based on accounting for mass flows is being promoted for the certification of biogenic or recycled product components. The production of chemical products is already recorded in the CRT using activity data and could be used in conjunction with statistical data to determine carbon pools. Tracking the proportions of carbon sources in the product pool is further complicated by annually varying influences on the pool, which generally cannot be recorded precisely or exhaustively.

Figure 4 shows the carbon flows associated with industry. Carbon flows, in particular, are differentiated according to their origin, even if this is not yet the case in some areas of current reporting. In the future, these will have to be traceable in order to evaluate the actual capacity for mitigation or removal. This issue will be discussed in more detail later in the project. See the gap analysis in section 4 for the current traceability.

8 Carbon dating in exhaust fumes makes it possible to determine biogenic proportions, since fossil energy sources do not have any 14C content. However, such measurements are only carried out on a random sample basis and not constantly. (Lorenz et al., 2022)

Figure 4: Zoom-in Carbon pathways and pools in industry with differentiated Carbon flows



Notes: For reasons of simplicity, the diagram does not show the flow of CO_2 captured from the atmosphere and the ocean and stored directly. The use of captured atmospheric CO_2 is represented by the flow "CO_2 captured in energy carriers". Use as a material is also possible. This is not shown separately as a node in the diagram.

Source: Own illustration, IREES

3.2.4 Zoom-in: The carbon flows of the chemical industry

The chemical industry is one of the largest consumers of fossil energy carriers. It uses these not only as an energy source, but also as a carbon source for a wide range of hydrocarbon chains (plastics). The chemical industry is therefore shown as a separate zoom-in in figure Figure 5. The exact tracking of non-fossil carbon sources is a particularly challenging task in the chemical industry and will be discussed in more detail during the project.

In the chemical industry, a distinction is made between the “energy sector” (CRT 1) and “industrial processes and product use” (CRT 2) with regard to the CRT codes. Thus, refineries are also differentiated in their function of fractionating and processing fossil energy sources according to whether the carbon is used for energy in the energy industry (1.A.1) or for materials in chemical plants. On the one hand, refineries produce fuels such as diesel and petrol for use in a wide range of industrial sectors (1.A.2), in transport (1.A.3) and in public energy supply (1.A.1.a). On the other hand, refineries for chemical plants9 (2.B.8) play a key role because they produce the raw materials for the basic chemicals such as methanol and ethylene, which the chemical industry (1.A.2.c + 2.B.) uses to manufacture its products. (UNFCCC, 2021)

In the Sankey diagram and in the subsequent discussion in this report, refineries in the energy sector and chemical plants are grouped together under “fuel and raw material production”. Both the “energy sources and basic chemicals” and the “products” of the chemical industry, as well as the resulting “waste and residual materials”, form pools that store carbon temporarily until the corresponding components of a pool are reused. Fuels and raw materials can be used directly in the “chemical industry” to manufacture products. After a period in the product pool, these products enter the “other product use” (2.D), which refers to the use phase of non-energy products made from fuels and raw materials. For example, for bitumen/asphalt, there is a path from the refineries of fuel and raw material production to another product use via the product pool.

Fuels can be used not only in the chemical industry but also in the public energy supply and in the non-metallic minerals sector (1.A.2.f + 2.A) after a period in the pool of “energy sources”. For technical and economic reasons, not all emissions can be captured in any of the processes mentioned, so that even with the most efficient carbon capture, there will always be a certain residual flow into the atmosphere (see Sankey node Leakage).

The massive use of fossil energy sources and the resulting large-scale emission of GHGs must be changed in a climate-neutral future. Biomass as well as carbon from the atmosphere and the ocean (DAC and DOC) can be used as alternative carbon sources. The carbon contained in biogenic raw and residual materials as well as in wood products can be technically unlocked via pyrolysis in order to convert potentially renewable raw materials into chemical (precursor) products10. Hydrogen and carbon dioxide can be converted into renewable base chemicals (hydrocarbon chains) using electricity. In addition, the recycling of products and plastic waste will play an increasingly important role in the reuse of the carbon they contain. (Geres, R. et al., 2023)

Another source of carbon is carbon capture with utilization (CCU) in chemical plants. In this process, CO_2 emitted in various industrial sectors, in energy supply and in waste incineration can be captured and converted into basic chemicals or energy sources. This is particularly

9 Chemical plants for processing petrochemical base chemicals (CRT 2.B.8.a-e) play a key role in the production of a wide range of fine and specialist chemicals. (a) methanol, (b) ethylene, (c) ethylene dichloride and vinyl chloride, (d) ethylene oxide and (e) acrylonitrile are each considered as basic chemicals due to their potential CO_2 and methane emissions. (UNFCCC, 2021)

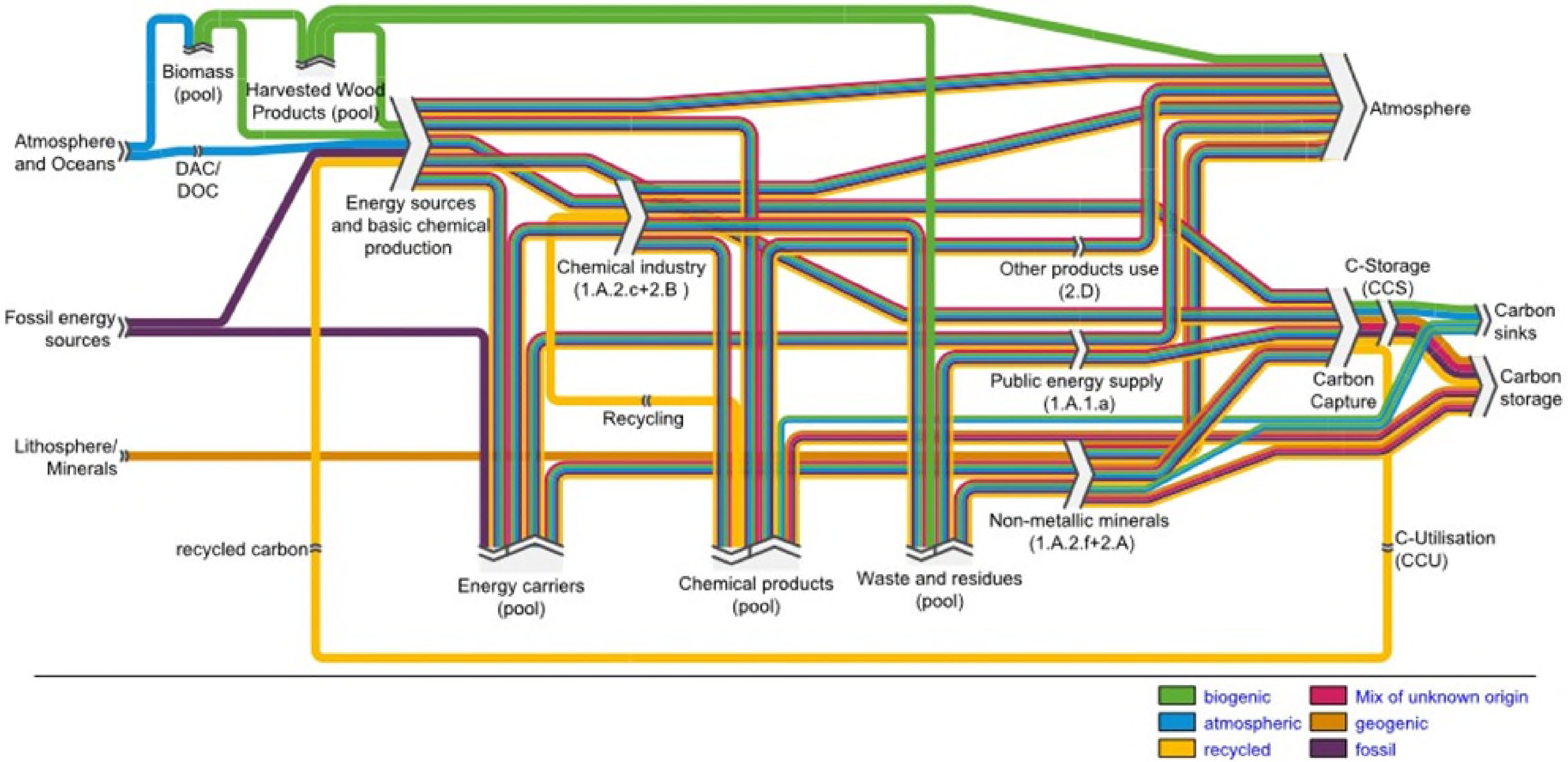
10 https://www.thuenen.de/de/themenfelder/nachwachsende-rohstoffe-und-holz/bioraffinerieprozesse-und-biobasierte-produkte/biomasseaufschluss-und-pyrolyseverfahren (last updated 31.10.2024)

relevant for the non-metallic minerals industry, as it will continue to emit process-related geogenic CO_2 that needs to be captured. (acatech, 2018)

Therefore, the flow of recycled carbon from CO_2 capture will play an increasingly important role and potentially include not only carbon in the form of CO_2, but also in the form of carbon chains from recycling processes and biomass from waste and residual materials. However, not all emissions can be captured for technical and economic reasons, so that a certain residual stream from the previously mentioned sectors will remain in the atmosphere even if capture is in place. Simultaneously, carbon will be kept in circulation for longer, meaning that, on the one hand, fossil fuel emissions will decrease but, on the other hand, they will simply be shifted into the future. After the transformation is complete, these fossil shares will gradually disappear.

Consequently, in a net-GHG-neutral carbon economy, fossil and geogenic carbons must be captured and stored or reused after their conversion and use. Emissions that continue to be released during this use and conversion (partly unavoidable due to emissions from extraction, slippage and leakage, as well as from capture) must be offset using CDR measures. At the same time, the potential for both storage and CDR is limited.

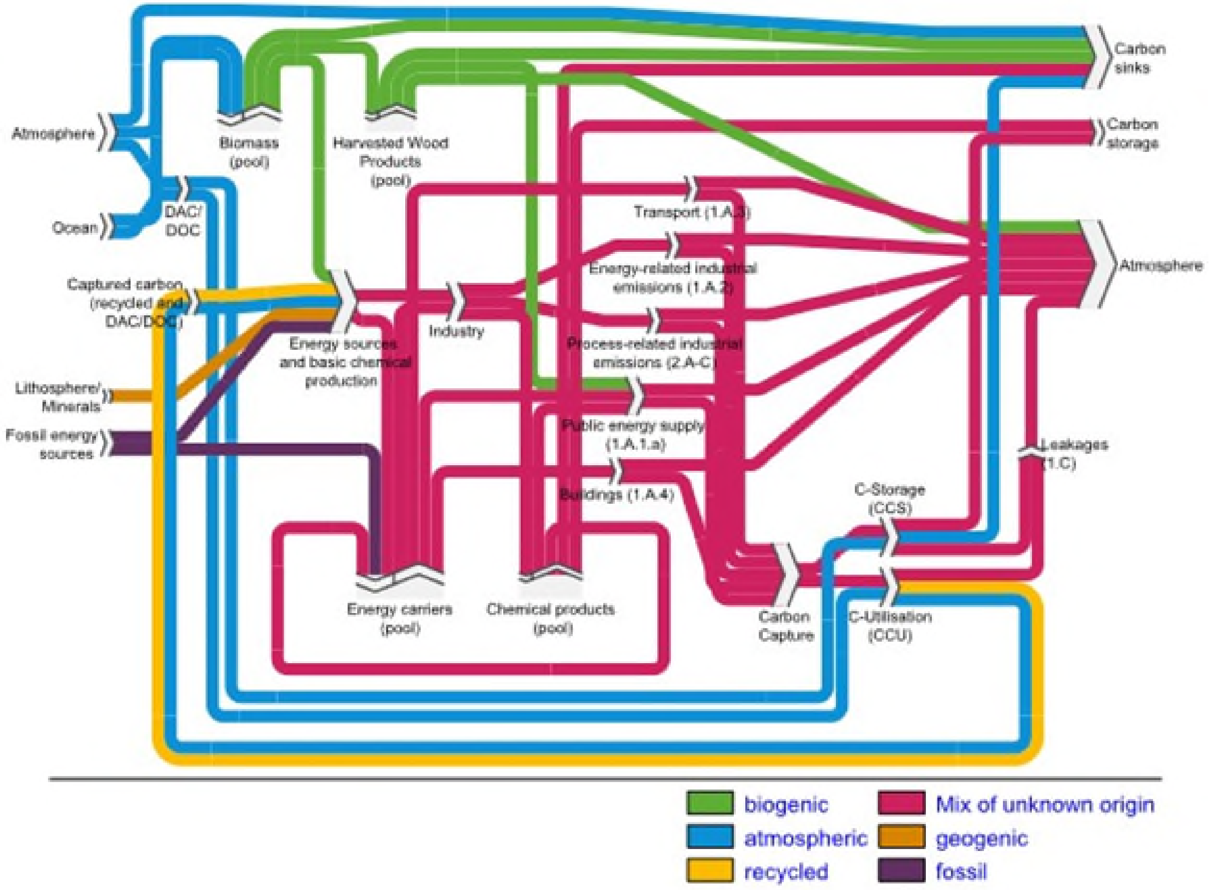
Figure 5: Zoom-in Carbon flows of the chemical industry with parts of the energy industry



Source: Own illustration, IREES

3.2.5 Overview diagram

Figure 6: Carbon flows in the transformation to a circular carbon economy – overview



Note: For clarity, the "Mix" category here represents all the remaining categories.
Source: Own illustration, IREES

Even if the fossil content of sources, especially in the energy sector, declines in the future, the use of raw materials with bound carbon from geogenic sources (e.g. limestone in the cement industry) and possibly from fossil sources (e.g. for organic basic chemicals or as anodes in metal production) will continue to cause emissions relevant to GHGs. These fossil and geogenic carbons must be captured and stored or used (CCS/CCU) after their use. Unavoidable emissions and leaks must also be offset.

The energy conversion includes the production of turquoise hydrogen in high-temperature reactors via methane pyrolysis. The resulting carbon from fossil natural gas can be stored geologically in the form of solid carbon as granules, for example. The path also exists with biogenic, atmospheric or recycled CO_2 via bio-methane or synthetic methane.

CO_2 capture is also being discussed for use in buildings, e.g. by DAC at the ventilation system (part of the atmospheric path "atmosphere" – "CO_2 capture") or by carbon capture in heating systems (part of the fossil path "conversion and use" – "CO_2 capture"). Carbon capture for international shipping is also being discussed (OCC – Onboard Carbon Capture) (Transport – CO_2 capture).

Emissions from the industrial sector are categorized as energy-related emissions and process-related emissions (for details on the sectors, see the Zoom-in Industry section 3.2.3). Carbon also leaves the industrial sector in the form of products. These products form a temporary store. This presents a challenge for the traceability of the C source. If, for example, products are used as waste and used as fuel for public energy supply (waste incineration plant), the origin of the carbon cannot (currently) be traced except for the biogenic portion (see Zoom-in industry). The same applies when waste materials are used for energy in industry (shown in the figure by the flow of chemical products into the energy source pool) or when plastics declared as waste materials are stored (shown as a flow of chemical products into storage in the case of mitigation or a sink).

4 Gap analysis

In the previous chapter, the carbon flows of a circular carbon economy were outlined. Now, we will analyse which of these carbon flows cannot be represented in today's GHG inventories (based on the IPCC Guidelines and the CRT tables, see chapter 2.2). Inconsistencies between a circular carbon economy and today's GHG inventories are referred to as 'gaps' in the following.

4.1 Procedure for identifying and assessing gaps

The carbon flows from the overarching Sankey diagram (Figure 6) were recorded in a table and the source and store or sink were documented for each flow, along with a process description. Where possible, each flow is assigned to the corresponding categories of the CRT. Finally, the possible origin of the carbon contained in each flow is recorded, subdivided into fossil, geogenic, biogenic, atmospheric and recycled.

On this basis, the gap analysis is carried out for each flow using the following key criteria:

1. Is the flow defined in the IPCC Guidelines (Yes/No)?
   Is the monitoring of the flow in the CRT clearly and specifically defined in the IPCC guidelines? Can the flow be represented in the structure of the CRT?
2. Are the necessary data (in particular, stock levels) available (Yes/No)?
   Is there statistical data (e.g. stock levels) that is important for the flow? Is this data represented in the CRT? Are they sufficiently detailed?

If the answer to any of these questions is no, then there is a gap.

In addition, the following criteria are evaluated for each flow:

- Can the flow be represented with sufficient accuracy using the calculation methods from the IPCC guidelines? (Yes/No)

  Do all the proposed IPCC calculation methods (all tiers) model the flow with sufficient accuracy? *Are the calculation methods sufficiently detailed to reflect the flow? Yes = sufficiently accurately covered by all tiers*

- Is the origin of the carbon shown in the CRT (Yes/No)?
  Is it possible to derive the origin of the carbon from the information contained in the CRT? If not, is it possible to determine the origin of the biogenic carbon and/or atmospheric/recycled carbon?

- Is the flow affected by other gaps?
  Qualitative description of the influence of other flows with gaps.

If the answer to one or more of the following criteria is 'No' for a flow, a decision must be made on a case-by-case basis whether a gap exists.

Based on the criteria described above, the carbon flows are divided into the following three categories:

- Representable, already existing: 'Classic' carbon flows that can be recorded/represented in today's GHG inventories (e.g. energy-related emissions from fossil fuels, industrial process emissions, agriculture)

- Representable, new developments: 'new' carbon flows that will become relevant in a circular carbon economy and that can already be recorded in today's GHG inventories (e.g. HWP pool[11] recovery of MSWI emissions)
- Gaps: 'new' carbon flows that will become relevant in a circular carbon economy but that cannot be recorded in today's GHG inventories (e.g. e-fuels, DAC, CCU; carbon pools)

Most of the leaks can be identified and analysed on the basis of the overarching Sankey diagram (Figure 6). The zoom-in Sankey diagrams for individual sectors (Figure 2 to Figure 5) do not provide any additional information for the gaps in most cases and are therefore not considered in more detail for the gap analysis. Exceptions are the flows around biochar/solid biomass, which are not visible on their own in the overarching Sankey diagram but are explicitly included in the gap analysis.

The IPCC-Guidelines (IPCC, 2006)and the templates for the UNFCCC Common Reporting Tables (CRT) formed the basis for the gap analysis(UNFCCC, 2021). The results of the analysis were also checked for plausibility using a working paper by the Oeko-Institut (Challenges for the accounting of emerging negative and zero/low emission technologies) (Jörß et al., 2022).

4.2 Results of the gap analysis

This chapter summarizes the results of the gap analysis. Detailed information on the individual flows and their assessment can be found in the attached Excel file.

4.2.1 Overview

The Sankey diagram of the overview of the circular carbon economy (see chapter3.2.5, Figure 6) contains 39 overarching flows. Most of the flows can be well represented in the CRT tables of today's GHG inventories, especially when it comes to calculating emissions (which is the main purpose of the inventories). 9 flows exhibit gaps. Something that all these flows have in common is that the IPCC guidelines do not specify how they are to be taken into account in the GHG inventories. Furthermore, the data basis for correctly modelling most of these flows in the CRT tables is missing.

The gaps in one flow also have an impact on other (subsequent) flows. For example, the IPCC guidelines do not specify how to deal with DAC and CCU. This means that the origin of atmospheric (DAC) or recycled (CCU) carbon cannot be identified in the CRT tables. The following table shows the possible origin of a carbon atom (fossil, geogenic, biogenic, atmospheric, recycled) and whether there is a gap for each flow. Only flows where a gap occurs for the first time are marked as gaps – subsequent flows affected by this are not marked as gaps (see example in Figure 8).

Table 1: Carbon pools and possible sources of carbon in the circular carbon economy

Legend: fos. = fossil, geo. = geogen, bio. = biogen, atm. = atmospheric, rec. = recycled

No.	Pathway	CRT category(ies)	Possible source of carbon					Gaps
			fos.	geo.	bio.	atm.	rec.	
1	Long-term (natural) CO_2 storage in the atmosphere (not as biomass; e.g. enhanced weathering)	-						

11 Harvested Wood Products

No.	Pathway	CRT category(ies)	Possible source of carbon					Gaps
			fos.	geo.	bio.	atm.	rec.	
2	CO_2 is bound in biomass from the atmosphere	4 (without 4G)						
3	Co₂ from Biomass in the atmosphere	4 (without 4G)						
4	CO_2 capture from the atmosphere using DAC	-						
5	CO_2 capture from the ocean using DOC	-						
6	Manufacture of wood products (furniture, paper, buildings, etc.)	4G						
7	Biomass (wood, etc.) as a raw material (not as an energy source) in industry	2H						
8	Import and production of biogenic fuels	Energy statistics						
9	CO_2 is bound in biomass from the ocean	-						
10	Import and production of fossil energy carriers	Energy statistics						
11	Use of energy sources in industry	1A2a to 1A2gvii						
12	Use of captured CO2 (DAC/DOC/CCU) as a raw material for industry (material use) or as an energy source (synthetic fuel)	-						
13	Uncaptured emissions from fuel storage and transport into the atmosphere	1B						
14	Production of synthetic fuels with CO_2 from DAC/CCU	Energy statistics						
15	C in chemical products (e.g. plastic)	2B						
16	Use of energy sources for transport (incl. international transport)	1A3, 1A4cii, 1A2gvii, 1D						
17	Use of energy sources for heating buildings	1A4						
18	Emissions from heating buildings	1A4						
19	CO_2 capture from buildings	1A4						

No.	Pathway	CRT category(ies)	Possible source of carbon					Gaps
			fos.	geo.	bio.	atm.	rec.	
20	Emissions from transport into the atmosphere (including international transport)	1A3, 1A4cii, 1A2gvii, 1D	■		■	■	■	
21	Emissions from public energy supply into the atmosphere	1A1, 1A4a to 1A4cii	■		■	■	■	
22	Use of energy sources for public energy supply (electricity/heat supply, etc.) and in buildings, as well as for the production of energy sources	1A1, 1A4a to 1A4cii	■		■	■	■	
23	Use of waste/materials for public energy supply (electricity/heat supply, etc.)	1A1a	■		■	■	■	
24	Long-term storage of CO2 from CCS	1C	■		■	■	■	
25	CO_2 capture from public power supply	1A1	■		■	■	■	
26	Wood as an energy source (part of waste) in energy supply	1A1a			■			
27	Energy-related industrial emissions into the atmosphere	1A2	■		■	■	■	
28	CO_2 capture in industry (energy-related emissions)	1A2	■		■	■	■	
29	Process-related industrial emissions into the atmosphere	2	■	■	■	■	■	
30	CO_2 capture in industry (process-related emissions)	2	■	■	■	■	■	
31	Production of biochar from biomass	1B1bi			■			
32	Application of biochar to cropland and grassland	4			■			
33	Storage of biochar in geological storage sites	-			■			■
34	Uncaptured emissions from transport and storage of CO2 in the atmosphere	1C	■		■	■	■	
35	Net emissions/sinks from HWP	4G			■			
36	Reuse of captured CO2	-					■	■
37	Uncaptured emissions from CO_2 transport and processing for reuse in the atmosphere	1C					■	

No.	Pathway	CRT category(ies)	Possible source of carbon					Gaps
			fos.	geo.	bio.	atm.	rec.	
38	C from geological sources for industrial processes (e.g. concrete)	2A						
39	CO2 capture from international transport	Bunker fuels						

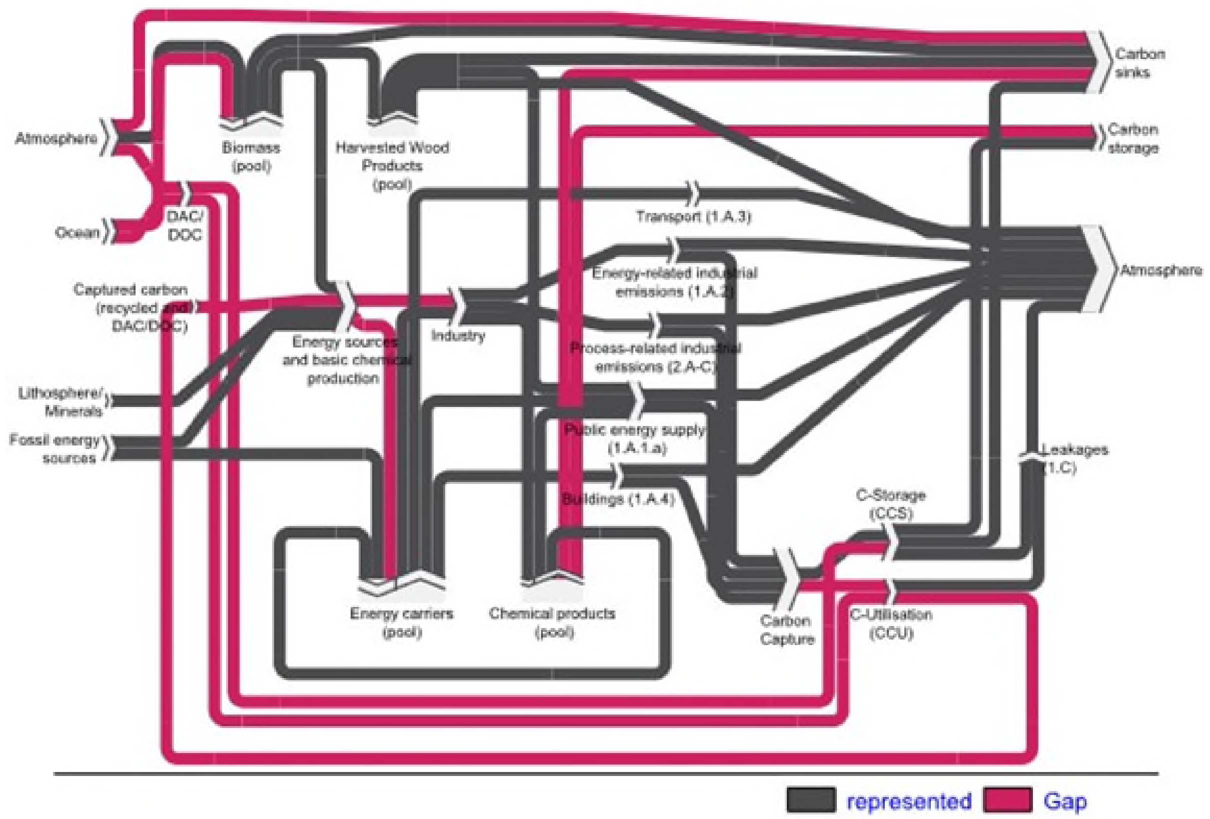
Source: Own illustration, INFRAS

Generally speaking, the calculation methods in the IPCC guidelines are sufficient for most pathways. In a few cases, however, such as the storage of biochar/solid biomass in geological storage sites or the use of captured CO_2 (for energy or material purposes), the calculation methods available in the IPCC guidelines are still insufficient.

Likewise, the CRT tables can in most cases indicate whether the origin of the carbon is biogenic or geogenic. An important exception is carbon stored in chemical products (e.g. plastic) – in this case, the CRT tables cannot show whether the carbon is biogenic or not. It is not possible to distinguish between atmospheric and recycled origin.

The gaps in the table above are illustrated in the following figure (exception: the gap when storing biochar/solid biomass into geological storage sites).

Figure 7: Graphical representation of the gaps in a circular carbon economy



Source: Own illustration, IREES

4.2.2 Carbon pathways that can be represented in the GHG inventories (CRT)

The main purpose of the GHG inventories is to report on annual emissions. Accordingly, carbon pathways associated with emissions can usually be well represented in the CRT tables (especially fossil sources). These include energy-related and process-related emissions into the atmosphere (from buildings, industry, transport and public energy supply, including waste incineration). Additional information on emissions can also be provided:

- Fuels of biogenic origin: It is possible to distinguish between different energy sources. These can also include biomass, which leads to biogenic emissions. However, it is not possible to break this down by type of biomass. The proportion of biomass in waste incineration can also be indicated.
- CO_2 capture: CO_2 capture can be reported individually for each energy carrier. For other processes (e.g. waste incineration, wastewater treatment or industrial processes), partially recovered GHG emissions ('recovery') can be reported (e.g. methane).
- The transport of CO2 and any associated leakages can be represented in the CRT (Sector 1C).

In some cases, carbon pools can be represented in the GHG inventories (usually in combination with statistical data from the countries, which are recorded in the National Inventory Document NID). For example, the CRT contains data on the consumption of various energy sources and the production of chemical products (activity data in the CRT). Supplemented with statistical data from the NID, carbon pools can also be determined from this. In the LULUCF sector, the pool of harvested wood products (HWP) is also shown.

In addition, the CRT tables provide an option for most processes to specify further (country-specific) categories (category 'Other' in the tables). These 'Other' categories can be used to report, for example, additional energy sources, other industrial processes or different types of land use.

4.2.3 Gaps

A key gap in the GHG inventories is that the capture of CO_2 from the atmosphere or oceans and the use of recycled CO_2 cannot be represented.

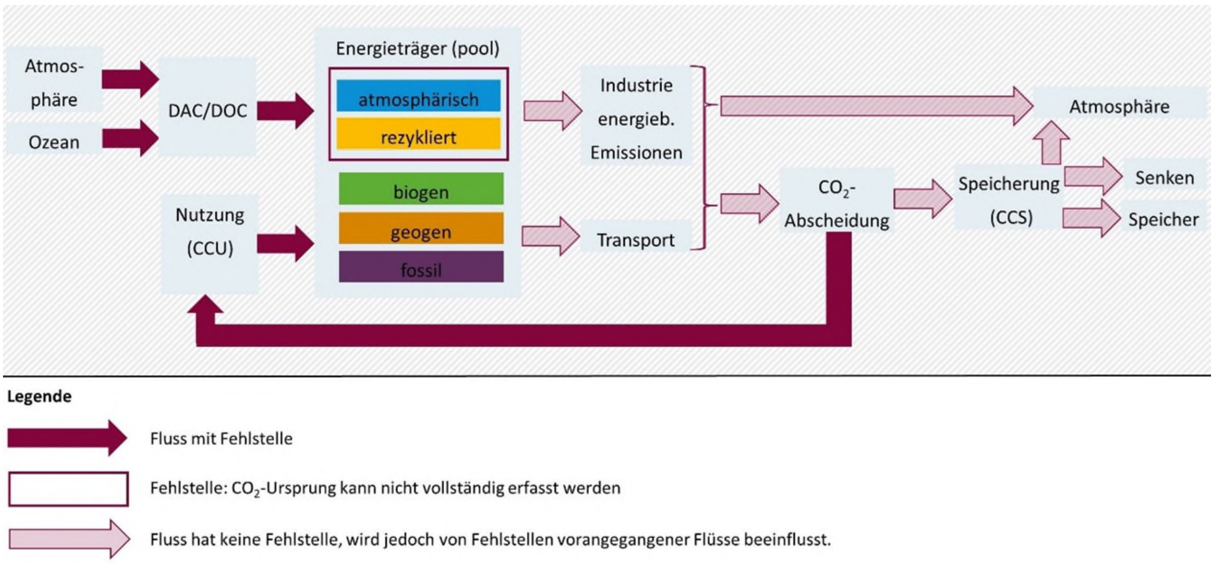
- DAC/DOC: The IPCC guidelines do not provide any guidance on how to report CO_2 that is captured directly from the atmosphere using DAC or directly from the oceans using DOC. It is conceivable that DAC/DOC could be reported in CRT categories 4 (LULUCF) or 6 (Others), but there is no formal requirement to do so.
- CCU: Only CO_2 that has been captured for long-term storage can be reported. If the CO_2 is only stored for a short period or reused at a later date, it may not be deducted from the reported emissions – unless the captured CO_2 emissions are taken into account elsewhere in the inventory when they are reused.
  This also applies to <u>synthetic fuels</u>. As yet there is no category for these in the CRT tables. It would be possible to report them under the liquid fuels category. To do so, the emission factor for liquid fuels would have to be adjusted accordingly and there is no formal requirement to do this.
  The <u>material use</u> of recycled CO_2 in industry (e.g. for chemical products) cannot be represented.

The fact that DAC, DOC and CCU cannot be represented in today's GHG inventories has consequences for the subsequent flows (see Figure 8). For example, the origin of CO_2 cannot be defined with sufficient accuracy. Although a distinction can be made between biogenic and fossil or geogenic CO_2, it is not possible to identify atmospheric or recycled CO_2 (which is only stored for a short time).

In subsequent flows, such as CO_2 emissions into the atmosphere or CO_2 capture and storage or reuse, it is therefore not possible to determine which proportion of the CO_2 comes from fossil, geogenic, biogenic, atmospheric or recycled sources.

However, the origin of CO_2 plays a central role for the GHG accounting in a circular economy: For example, the storage of atmospheric CO_2 is considered a 'negative' emission because it contributes to the reduction of the CO_2 concentration in the atmosphere. The storage of biogenic CO_2 can also be considered a negative emission if the use of biomass is in equilibrium. By contrast, the storage of fossil or geogenic CO_2 is considered neutral because it neither adds to nor removes from the concentration in the atmosphere. GHG accounting is therefore not useful without a complete record of the origin of the CO_2.

Figure 8: Graphical representation of the effects of defects on other flows



Source: Own illustration, INFRAS

Some long-term sinks also have gaps. For example, negative emissions technologies that do not directly involve biomass cannot be reflected in the inventories (e.g. CO_2 storage through enhanced weathering). The storage of biochar/solid biomass in geological storage sites cannot be reflected either.

Other gaps concern pathways which are not compatible with the territorial principle. These include CO_2 captured from the ocean in biomass and CO_2 capture from international transport. While there is a lack of data on the oceans in the GHG inventories, fuels for international transport are documented (but not included). In principle, CO_2 capture could be included in the GHG inventories on the basis of the bunker fuels used for international transport, but there are no guidelines for doing so.

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