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# Managing the Anthropogenic Carbon Cycle - Technologies, Pathways, Emissions

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## Abstract

Effective decarbonization and carbon removal require tools that facilitate holistic yet detailed decisionmaking across interconnected carbon pathways; however, existing research often isolates technologies and focuses on linear process chains. To bridge this gap, we present a systemic framework for the anthropogenic carbon cycle encompassing capture, conversion, utilization, and storage. Through an iterative synthesis and multi-level abstraction process, we decompose the cycle into 46 technological building blocks. These blocks can be assembled into diverse pathway configurations (Carbon Capture and Storage, CCS; Carbon Capture and Utilization, CCU; Carbon Capture Utilization and Storage, CCUS) and categorized by their resulting emission balances (net-negative, net-zero, netpositive). This modular representation enables flexible navigation between emerging technologies and established circular value chains, revealing synergies and emission trade-offs. The framework equips decision-makers with a practical tool to design and assess systemic circular carbon strategies.

## Keywords

Carbon Capture, Utilization and Storage (CCUS), Carbon Dioxide Removal (CDR), Negative Emission Technology, Hydrogen, Circular Carbon Economy

# MANAGING THE ANTHROPOGENIC CARBON CYCLE - TECHNOLOGIES, PATHWAYS, EMISSIONS

PREPRINT

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**ABSTRACT**

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## 1 Introduction

Over the past two centuries, human-driven carbon extraction has established a parallel anthropogenic carbon cycle [1] that increasingly perturbs the natural one [2–4], disrupting the equilibrium between the atmosphere, biosphere, oceans, and Earth's crust. Initially sourced from biomass and later predominantly from fossil reserves, carbon-based fuels have powered the modern economy. However, continued transfer of carbon from the lithosphere to the atmosphere must be halted to slow global warming [5, 6]. At the same time, natural sinks provide insufficient absorption capacity [3], making artificial carbon sequestration and removal necessary [7, 8] to compensate unavoidable emissions, counter rising atmospheric $CO_2$, and eventually restore climate equilibrium.

To phase out fossil fuels, energy systems must prioritize renewable operation to decarbonize electrifiable sectors [6]. However, a rapid and complete transition to decarbonized energy systems and electrification is unlikely, and several hard-to-abate sectors [9], such as aviation, will remain reliant on carbon-based molecules for the foreseeable future. Beyond energy supply, the economy also depends on carbon-based products and process chains [10]. In these sectors, achieving climate neutrality requires substituting fossil carbon with biogenic or atmospheric sources, or recirculating anthropogenic carbon, e.g., through point-source capture [9, 11–13]. In parallel, efforts to counteract or partially reverse anthropogenic $CO_2$ accumulation by "mining the atmosphere" [14] have accelerated the development of carbon capture, utilization, and storage technologies [12, 15].

These parallel efforts have generated a broad portfolio of technological solutions aimed at reducing fossil dependence within the anthropogenic carbon cycle. Yet, without coordinated system-level management, their combined impact remains fragmented. Most existing analyses still examine individual pathways in isolation, leading to narrow, linear perspectives. In practice, carbon can and will cycle through intersecting systems. Concepts such as the methanol [1],

hydrogen [16], and ammonia economies [17] stress the need for more systemic attempts to reduce fossil dependence. However, achieving rapid and comprehensive transitions requires coordinating multiple pathways in parallel while maintaining oversight of their interactions. What remains missing is a holistic, customizable framework that maps available pathways and associated emissions to support decision-making across interconnected anthropogenic carbon pathways.

To address this gap, we develop a modular conceptual framework that systematizes the anthropogenic carbon cycle into four quadrants: (1) Capture, (2) Conversion, (3) Utilization, and (4) Storage. Based on an extensive literature synthesis, pathways are decomposed into building blocks that can be flexibly combined and evaluated regarding their emission balances. This structure links high-level policy objectives, such as emission characteristics, with the specific technologies required to achieve them.

The primary novelty of this work lies in its departure from linear, technology- or pathway-specific analyses. Rather than evaluating isolated solutions, the modular framework treats the anthropogenic carbon cycle as an interconnected system, enabling holistic analysis and comparison of diverse process chains. By visualizing pathways as combinations of fundamental building blocks, it helps to highlight intersections, circular loops, and system-wide dependencies. This systemic perspective supports a more integrated assessment of carbon management strategies and enables decision-makers to evaluate not only individual technologies but also how their combination impacts overall carbon flows.

## 2 Proposed Conceptualization of the Anthropogenic Carbon Cycle

The core contribution of our work is a new conceptualization of the anthropogenic carbon cycle, which is visually represented in Fig. 1 and offers a holistic and systemic view of the complex web of carbon pathways that is currently missing from the literature. The carbon cycle is organized into four key quadrants: Q1 – Capture (Sec. 2.1), Q2 – Conversion (Sec. 2.2), Q3 – Utilization (Sec. 2.3), and Q4 – Storage (Sec. 2.4). Streams are categorized into eight types, indicated by the color code in the figure's legend, and correspond to the building blocks described later in Sec. 4–7. The gray inner circle represents carbon-based pathways, while carbon-free pathways such as hydrogen and ammonia are shown outside the circle.

### 2.1 Quadrant 1: Capture

Quadrant Q1 serves as the entry point for carbon into the anthropogenic carbon cycle. It encompasses pathways that source carbon from two main origins: the natural environment and primary recycling loops[1]. Environmental sources include atmospheric $CO_2$ captured via technologies such as Direct Air Capture (DAC) and Direct Ocean Capture (DOC) (Fig. 1, dark blue), as well as biogenic carbon fixed through photosynthesis in biomass (Fig. 1, green). Both pathways aim to substitute fossil carbon sources (Fig. 1, black dotted line). Internally, point-source capture recovers carbon from the thermochemical or biological treatment of fuels and waste, thereby recycling carbon from flue-gas streams within the system rather than releasing it to the atmosphere (Fig. 1, light blue).

### 2.2 Quadrant 2: Conversion

Quadrant Q2 encompasses the conversion of raw carbon inputs from Q1 into versatile, energy-dense chemical intermediates, commonly referred to as platform chemicals. These molecules, such as methane ($CH_4$), methanol ($CH_3OH$), and syngas ($CO + H_2$), as well as derived olefins and aromatics, serve as fundamental building blocks for fuels and materials and can act as renewable substitutes for fossil feedstocks such as natural gas and naphtha [10]. Conversion in Q2 proceeds via two primary routes: direct processing of biomass, or chemical reduction of captured $CO_2$, either electrochemically or using hydrogen ($H_2$). The latter routes, often associated with Power-to-X processes, employ renewable electricity to produce carbon-based derivatives (Fig. 1, red) or carbon-free energy carriers such as hydrogen and ammonia (Fig. 1, orange). The "Transport" arrow indicates that pathways may involve multiple conversion steps with intermediate transport. For example, $CO_2$ and/or $H_2$ can be converted into a platform chemical for transport via existing infrastructure, then converted into other materials or reformed after transport to recover $H_2$ and $CO_2$ for further use or storage.

### 2.3 Quadrant 3: Utilization

Quadrant Q3 represents the transformation of platform chemicals from Q2 into final products and their utilization in various sectors. This includes upgrading intermediates into market-ready fuels (Fig. 1, pink), chemicals, and materials

[1] In this work, carbon is viewed as a resource, and therefore we distinguish between 'recycling', which refers specifically to material recovery (e.g., plastics), and 'circular value chains', which encompass the broader industrial carbon cycle.

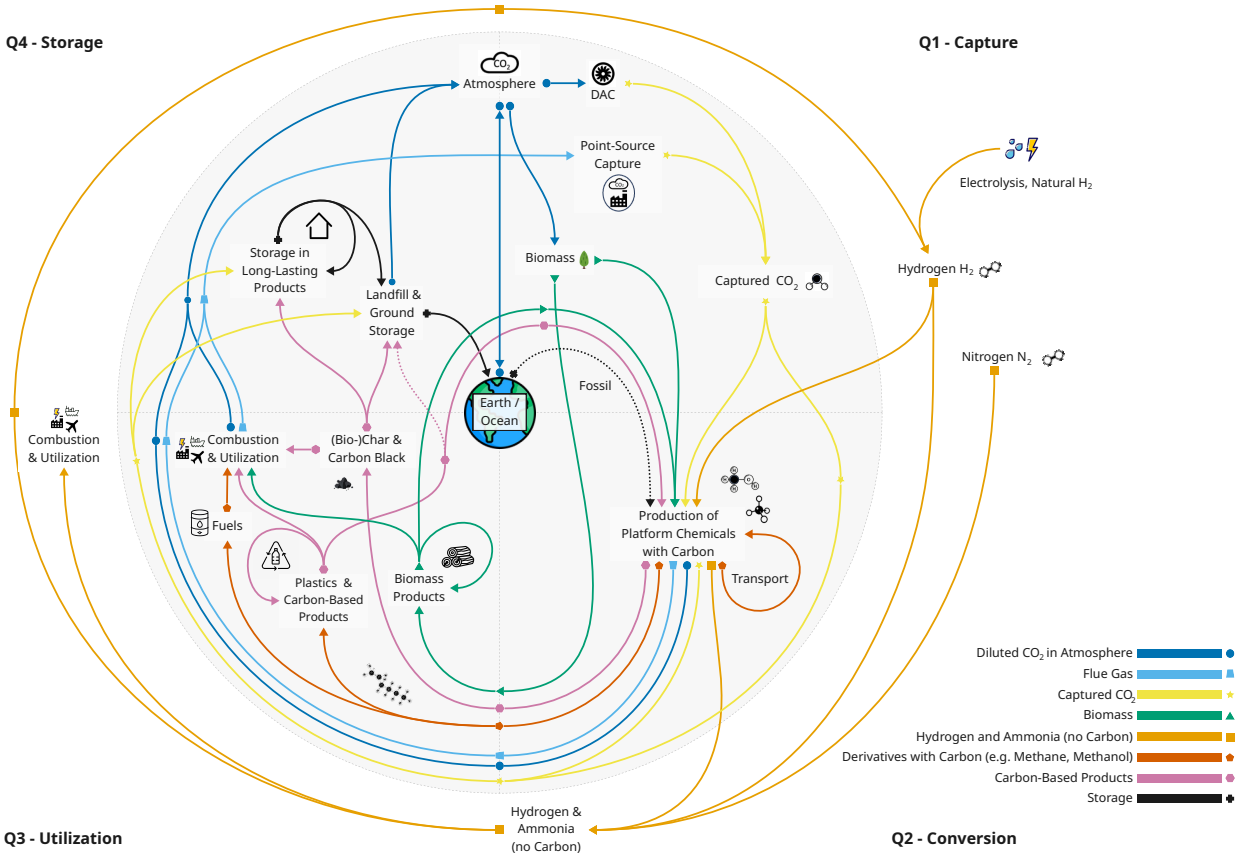



Figure 1: Anthropogenic carbon cycle with four quadrants (Q1–Q4) and color-coded pathways. The gray inner circle represents carbon-based pathways, while the outer areas correspond to carbon-free pathways.

such as plastics, char, and carbon black (Fig. 1, pink), as well as their direct use for power generation or transport. Q3 also defines the end-of-use pathways for carbon. Following utilization, carbon may be re-captured and re-enter the cycle at Q1, be recovered for conversion into platform chemicals in Q2, be permanently removed in Q4, or be released to the atmosphere. Extending carbon residence times within Q3 through material recycling is therefore a key strategy for enhancing circularity and delaying emissions [18, 19].

### 2.4 Quadrant 4: Storage

The final quadrant, Q4, serves as the carbon sink of the cycle and represents the permanent removal of carbon from anthropogenic and atmospheric circulation on timescales relevant to climate change (i.e., hundreds to thousands of years[2]). This removal is achieved through two principal strategies: long-term geological sequestration of captured $CO_2$, or stabilization of carbon in solid forms. Examples of the latter include fixation through carbonation reactions, production of char for soil amendment, or embedding carbon within durable products such as concrete and building materials, provided they do not release $CO_2$ at their end-of-life [14] (Fig. 1, black).

## 3 Methodology and Abstraction Framework

We conducted a comprehensive synthesis and systematization of carbon pathways to develop the conceptual framework (Fig.1) and its abstraction levels. Rather than relying on a rigid keyword-based search, the review began with well-established pathways and expanded iteratively to capture a broad spectrum of emerging technologies. We decomposed identified *pathway* configurations into constituent steps, isolating recurring elements as *building blocks* and specifying

[2]For storage to be relevant with respect to climate change mitigation, the final deposit must ensure that carbon is not released for at least several thousand years [20].

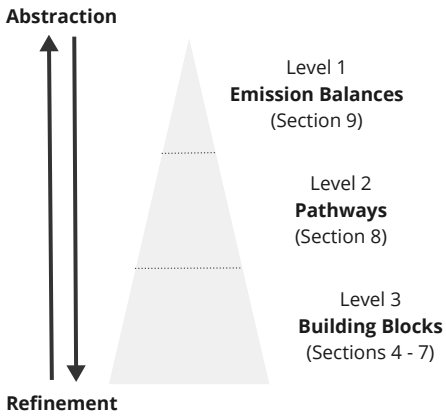



Figure 2: Three abstraction levels of carbon pathways enable alignment of emission policies with technology (refinement) and qualitative evaluation of emissions across technological options (abstraction).

their input and output streams to assemble pathways and evaluate *emission balances*. This bottom-up systematization yielded: (I) a holistic conceptualization of the carbon cycle with intersecting, color-coded flows (Sec. 2, Fig. 1); (II) a library of technological building blocks organized by quadrant (Sec. 4 to 7); and (III) a multi-level abstraction framework linking building blocks, pathways, and emission balances (Sec. 3. Methodological saturation was reached when further review ceased to yield new recurring elements, ensuring the framework provides a comprehensive template for both current and future carbon strategies.

### 3.1 Navigating the levels of abstraction

To navigate the solution space of carbon pathway configurations (Fig.1), we developed a framework comprising three levels of abstraction (Fig.2). While not a strict implementation of platform-based design [21, 22], the framework adopts key concepts from this theory to provide a structured design foundation. In platform-based design, a "platform" is a library of components that can be assembled to generate system designs at a specific abstraction level. Accordingly, our framework provides a platform-like library of technological building blocks at the most detailed level (Level 3), which can be assembled into pathway configurations (Level 2) and generalized into emission balance categories (Level 1).

This hierarchical structure supports bidirectional analysis. Top-down, it aids policy analysis by linking high-level emission goals (Level 1) to the specific pathway configurations (Level 2) and technologies (Level 3) required to achieve them. Bottom-up, it enables abstraction, allowing individual technologies (Level 3) to be evaluated within the context of their broader system pathways (Level 2) and resulting emission impacts (Level 1).

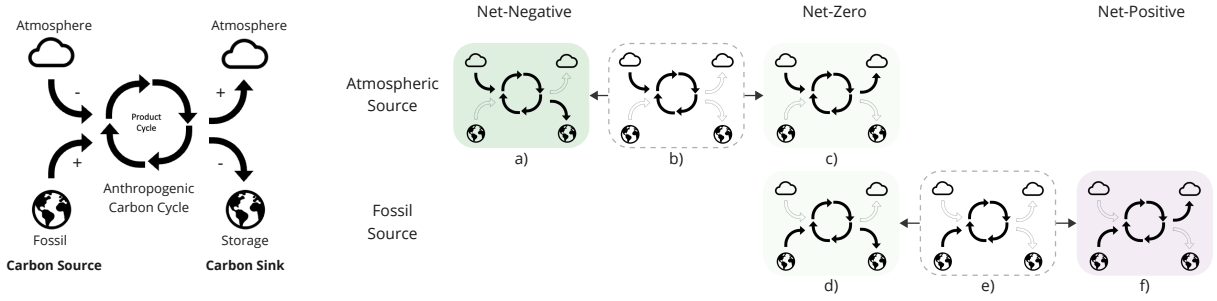



Figure 3: Emissions are defined as the net output of the carbon balance of pathways: net-negative [a), net = negative + negative], net-zero [c), net = negative + positive; d), net = positive + negative], and net-positive [f), net = positive + positive]. For pathways ending in utilization [b) or e)], the final balance remains undetermined.

### 3.2 Level 1: Emission balances

At the highest level of abstraction, pathways are classified according to their net emission balances - a metric primarily relevant for policymaking. Note that this conceptualization strictly addresses the carbon mass balance of the pathway and does not account for secondary greenhouse gas (GHG) emissions (e.g., energy consumption or leakage), though the framework is compatible with Life Cycle Analysis (LCA) for more comprehensive accounting (see Sec. 10.2).

Fig. 3 illustrates the emission balances based on the pathway's Source (Q1) and Sink (Q3/Q4). We define the sign convention relative to the atmosphere: removal or storage is "negative," while fossil extraction or release is "positive," in line with IPCC conventions [23].

- **Net-Negative:** The pathway sources atmospheric carbon and permanently stores it (Fig.3a). The net balance is negative, effectively reducing atmospheric $CO_2$.
- **Net-Zero:** The overall carbon balance is neutral. This occurs in two scenarios: (1) Circular pathways that capture atmospheric carbon and subsequently release it (Fig.3c); or (2) Fossil-based pathways where the carbon is captured and permanently stored (Fig.3d).
- **Net-Positive:** The pathway sources fossil carbon and releases it to the atmosphere (Fig.3f), resulting in a net increase in atmospheric $CO_2$.

Pathways ending in products (e.g., plastics) represent a temporary state. If the source is atmospheric, the temporary balance is net-negative (stored in product) or net-zero (circular use) (Fig.3b). If the source is fossil, the temporary balance is net-zero (stored in product) or net-positive (delayed release) (Fig.3e). The final classification depends on the product's end-of-life fate.

### 3.3 Level 2: Pathways

The mid-level of abstraction focuses on pathways, representing configurations connecting carbon capture (Q1) to final storage (Q4) or release. Pathways are constructed by assembling specific technological building blocks, following the color-coding scheme presented in Fig.1 and detailed in Sec.3.4.

Fig. 4 illustrates two representative configurations. Although both pathways start with Direct Air Capture (DAC), their trajectories diverge significantly. Pathway (a), representing the Climeworks Mammoth project [24], moves directly from capture to storage (CCS). In contrast, Pathway (b), representing the "Mining the Atmosphere" concept [14], includes conversion and utilization steps (CCUS) before final storage. This illustrates that pathways sharing common building blocks can perform distinct systemic functions and lead to different outcomes.

Evaluating building blocks in isolation can therefore be misleading. The pathway abstraction level enables structured comparison of complete systems, which is particularly relevant for regulation, system design, and holistic assessment. It serves as a critical link between technological realities (Level 3) and desired emission outcomes (Level 1).

### 3.4 Level 3: Building blocks

The lowest level of abstraction consists of the Building Blocks - a library of 46 discrete technological units, organised by quandrants Q1 to Q4 (Sec. 4-7). Each block represents a specific process step and is defined by specific inputs and outputs (color-coded in Fig.4 to match the cycle in Fig.1).

This level enables examination of individual technologies. In the following sections, each building block is illustrated with a process schematic, while comprehensive technical descriptions are available in the cited literature. Where applicable, exemplary market-ready or prototypical technologies are identified. Collectively, these blocks serve as the fundamental modular components from which broader carbon pathways and strategies are constructed.

In the following chapters, we detail the three levels of abstraction. While the framework was introduced top-down (from emission balances to technology), the subsequent analysis proceeds bottom-up, starting with the foundational building blocks (Level 3). For each of the 46 building blocks, we also provide a corresponding process diagram (Figs. 5–10) illustrating key technical details.

## 4 Building Blocks Quadrant 1: Capture

First, we introduce the building blocks for carbon capture (Sec. 2.1), including biomass growth and four technological building blocks that capture atmospheric $CO_2$ or circulate carbon within the anthropogenic carbon cycle for subsequent utilization or storage, as summarized in Tab. 1 and detailed as process diagrams in Fig. 5.

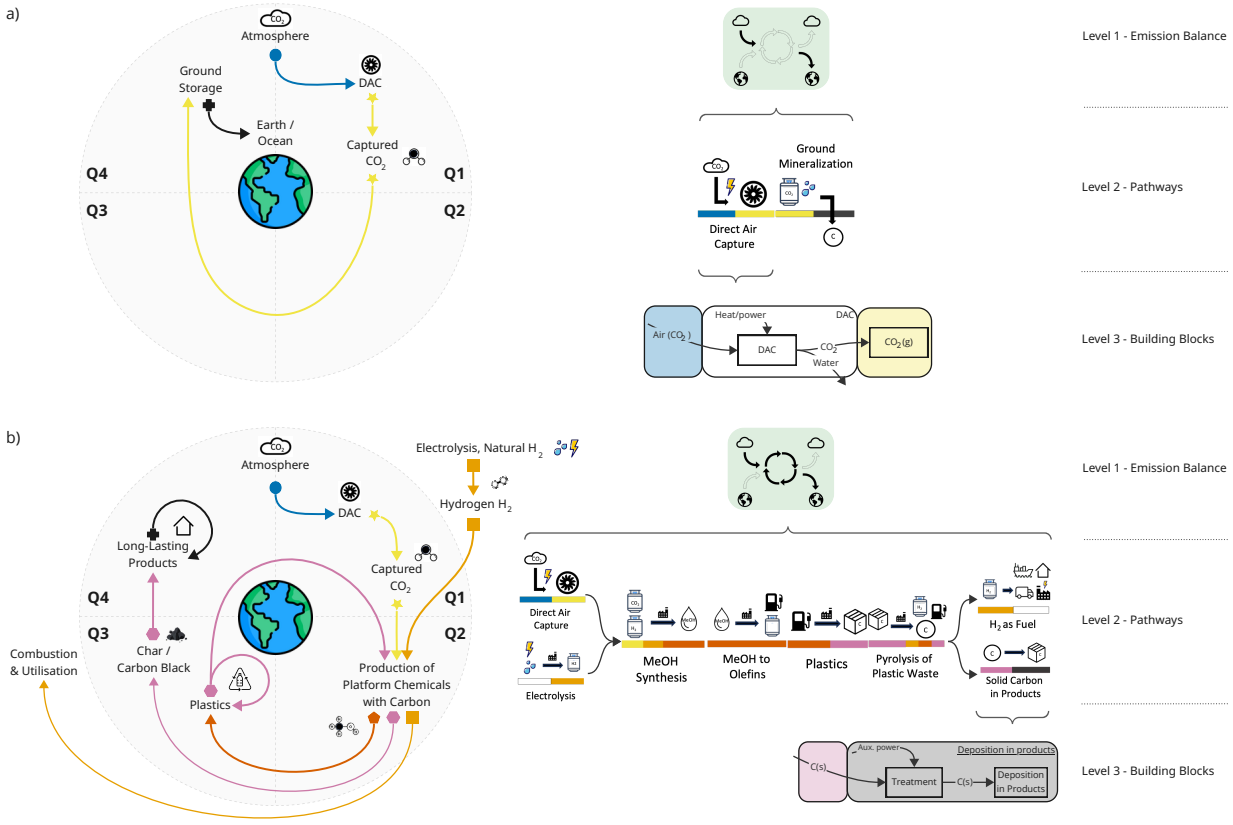



Figure 4: Navigation across abstraction levels: Technological building blocks (Level 3) are assembled into pathways (Level 2) to determine the resulting emission balance (Level 1). (a) A direct CCS pathway (e.g., Climeworks Mammoth [24]); (b) A CCUS pathway integrating conversion and utilization (e.g., Mining the Atmosphere [14]).

### 4.1 Biomass Growth

As trees and plants grow, they absorb atmospheric $CO_2$ through photosynthesis, incorporating carbon into carbohydrates, cellulose, and other organic compounds (Fig. 5a). This process stores atmospheric carbon in living biomass and soil organic matter [32, 33], acting as a temporary or potentially long-term carbon sink, depending on subsequent use and management [34–36]. Biomass thus serves as a key input for the biomass-route in Q2 (Sec. 5.1) or for bio-based products in Q3 (Sec. 6.1.1), and can be seen as the natural counterpart to DAC and DOC (Sec. 4.2 and 4.3).

### 4.2 Direct Air Capture (DAC)

Direct Air Capture (DAC) removes $CO_2$ directly from ambient air. Current systems use engineered contactors with liquid solvents or solid sorbents to capture and subsequently release high-purity $CO_2$ for storage or utilization [37–39]. Typically, $CO_2$ is bound to a sorbent and released by reversing its uptake through changes in chemical potential. A range of process configurations is being explored, relying on waste or geothermal heat, electricity, or sunlight, while most systems require electrical energy to circulate air through the sorbent material. Fig. 5b illustrates the high-level process, with air, heat, and power as inputs and captured $CO_2$ as output. Water can be an input and/or output stream of the process. DAC has advanced rapidly in recent years, with commercial deployment underway and prospects for significant scaling [40, 41]. Selected examples are listed in Tab. 1.

### 4.3 Direct Ocean Capture (DOC)

Oceans constitute a major sink for anthropogenic $CO_2$, absorbing approximately 30% of global emissions [42]. Direct Ocean Capture (DOC) removes dissolved $CO_2$ by shifting carbonate speciation in seawater, typically via electrochemical pH-swing processes [43–45]. In contrast to DAC, the ocean–atmosphere interface replaces the engineered contactor, while seawater itself acts as the sorbent. Following treatment, the decarbonized water is returned to the ocean, where it

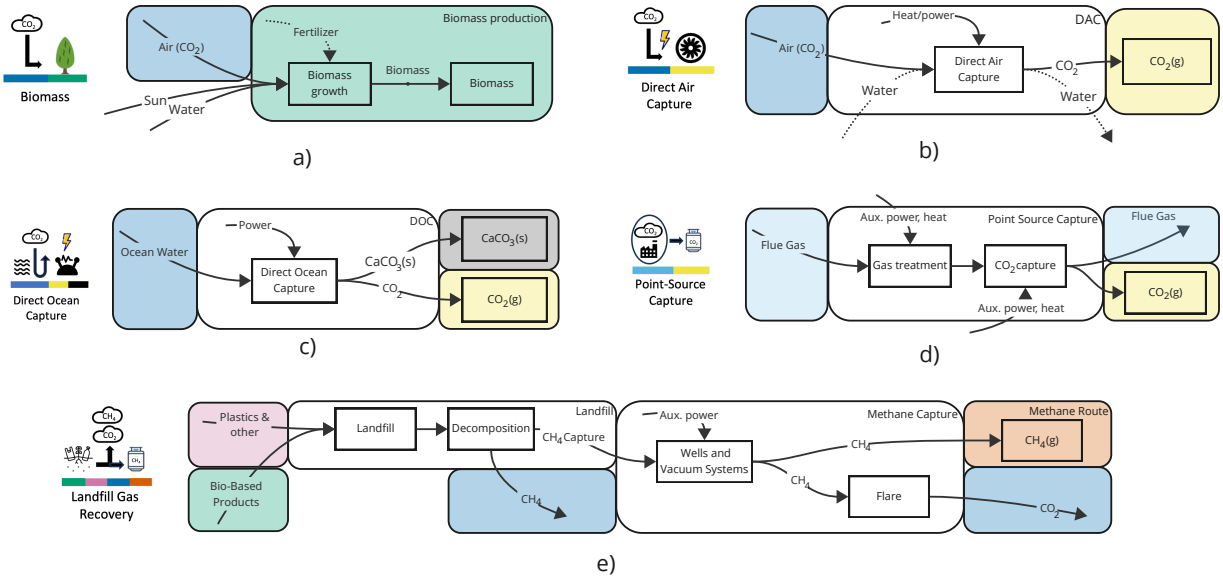



Figure 5: Process diagrams of Q1 building blocks: (a) photosynthetic $CO_2$ fixation; (b) Direct Air Capture (DAC); (c) Direct Ocean Capture (DOC); (d) point-source $CO_2$ capture; and (e) landfill gas recovery.

reabsorbs atmospheric $CO_2$. Fig. 5c illustrates the high-level process, with seawater and electricity as primary inputs and decarbonized water, gaseous $CO_2$, or mineralized products such as $CaCO_3$ as outputs. The technology remains at an early stage of development; selected emerging examples are listed in Tab. 1.

### 4.4 Point-Source Carbon Capture (CC)

Point-source carbon capture (CC) removes $CO_2$ from concentrated emission streams at stationary industrial facilities such as power plants, cement kilns, refineries, or waste incinerators [46]. Unlike DAC and DOC, it does not directly remove atmospheric carbon but captures and recycles carbon within the anthropogenic carbon cycle from utilization (Q3) into new feedstock for further use [47], and can contribute to decarbonizing hard-to-abate sectors when coupled with storage (Q4) [46, 48–50]. Various technical approaches are available, including absorption, adsorption, membrane

Table 1: The five building blocks of the first quadrant: *Capture*.

| Building Block | | Input | Output | Examples |
|---|---|---|---|---|
| Biomass growth 4.1 | Biomass | Air<br>Sun/Water | Biomass | |
| Direct Air Capture (DAC) 4.2 | Direct Air Capture | Air<br>Power/Heat<br>Water | Captured $CO_2$<br>Air<br>Water | Climeworks Orca [25]<br>Climeworks Mammoth [24]<br>1PointFive Stratos [26] |
| Direct Ocean Capture (DOC) 4.3 | Direct Ocean Capture | Ocean Water<br>Power | Captured $CO_2$<br>$CaCO_3$<br>Water | Brineworks [27]<br>Captura [28]<br>SeaO2 [29] |
| Point-Source Carbon Capture (CC) 4.4 | Point-Source Capture | Flue Gas<br>Power/Heat | Captured $CO_2$<br>Flue Gas | |
| Landfill with Gas Recovery 4.5 | Landfill Gas Recovery | Plastics<br>Bio-Products | Methane<br>$CH_4/CO_2$ | Rumpke Sanitary [30]<br>Olinda [31] |

separation, cryogenic processes, and electro-swing methods [46, 51]. Fig. 5d illustrates the high-level process, with flue gas and energy as inputs and purified $CO_2$ as the primary output. Selected commercial-scale installations are listed in Tab. 5 under Q3 utilization (Sec. 6.3).

### 4.5 Landfill Gas Recovery

A distinct capture building block is landfill gas recovery, which targets methane ($CH_4$) rather than $CO_2$ to recover carbon. A substantial share of global municipal solid waste remains landfilled [52], where anaerobic decomposition of organic matter generates methane. Given its high $CO_2$-equivalent impact, effective $CH_4$ capture is critical for climate mitigation. Landfill gas systems extract methane through networks of wells and pipes for centralized treatment (Fig. 5e). The recovered gas can be flared, converting $CH_4$ to $CO_2$ with lower global warming potential, used for energy generation (Sec. 6.3.1), or upgraded to renewable natural gas (Sec. 5.7). Unlike sealed anaerobic digestion (Sec. 5.1.2), landfill systems are less efficient, and even well-managed sites typically capture only about 85% of methane emissions [53–55]. Selected examples are listed in Tab. 1.

## 5 Building Blocks Quadrant 2: Conversion

This section presents the identified building blocks for converting carbon into platform chemicals, corresponding to Q2 of the anthropogenic carbon cycle (Sec. 2.2). The primary objective is to substitute fossil carbon sources (Fig. 1, dotted black line in Q2) with captured atmospheric or recycled carbon. For completeness, a "Fossil" building block is included to represent fossil-based pathways (Tab. 2, first row). However, the primary focus is on the alternative conversion routes organized into biomass (Sec. 5.1), plastics (Sec. 5.2), hydrogen (Sec. 5.3), ammonia (Sec. 5.5), methanol (Sec. 5.6), and methane (Sec. 5.7). A comprehensive overview of all 27 building blocks is provided in Tables 2 and 3, as well as Fig. 6, 7, and 8.

### 5.1 Biomass Route

The biomass route lists identified building blocks to convert biomass (Sec. 4.1) into platform chemicals via thermochemical and biochemical processes. Beyond direct energy use (Sec. 6.3.2) and bio-based products (Sec. 6.1.1), biomass can be converted into platform chemicals that replace fossil feedstocks. The climate performance of the biomass route depends critically on feedstock sourcing, land-use impacts, process energy inputs, and carbon retention along the value chain [77–79].

#### 5.1.1 Fermentation

Fermentation of biomass is a biological process in which microorganisms convert sugars primarily into ethanol and $CO_2$ [80] (see Fig. 6a). Ethanol serves as a major pathway for biofuel production [81] and can be further processed to bio-ethylene via ethanol dehydration [82], linking biomass fermentation to established petrochemical value chains for plastics and chemical products. Meanwhile, the relatively high-purity $CO_2$ stream released during fermentation can be captured, compressed, and dehydrated for subsequent utilization or storage [83–85]. In the United States, several bioethanol facilities already capture $CO_2$, and large-scale pipeline infrastructure is under development to transport it [86]. Selected examples are listed in Tab. 1.

#### 5.1.2 Anaerobic Digestion

Methane can be produced from biomass via anaerobic digestion, a multistep biological process in which microbial communities decompose organic matter in the absence of oxygen [87]. As shown in Fig. 6b, the resulting biogas consists primarily of approximately two-thirds $CH_4$ and one third $CO_2$ [88]. Anaerobic digestion is widely implemented because it simultaneously addresses renewable energy production, waste management, climate mitigation, and agricultural sustainability [89]. Biogas is commonly used in combined heat and power systems, although the $CO_2$ fraction can also be separated for utilization [59, 60, 90]. Alternatively, it can be upgraded to additional $CH_4$ through methanation with added $H_2$ [61, 91].

#### 5.1.3 Biomass Gasification

Biomass gasification (Fig. 6c) converts biomass through high-temperature thermochemical reactions, producing syngas (CO and $H_2$) as the main output, along with $CO_2$ and smaller amounts of $CH_4$ [92, 93]. The process operates with a limited supply of oxygen or air (autothermal), steam, or a combination thereof. Biomass gasification is increasingly applied for power and heat generation via subsequent combustion [94–96], but syngas can also be further converted

Table 2: The first 10 out of 27 building blocks of the second quadrant: *Conversion*.

| Building Block | | Input | Output | Examples |
|---|---|---|---|---|
| Fossil |   | Fossil | Fuel | |
| Fermentation 5.1.1 |   | Biomass | Captured $CO_2$<br>Ethanol | Bonanza BioEnergy [56]<br>POET Plants [57]<br>South Bend Ethanol [58] |
| Anaerobic Digestion 5.1.2 |   | Biomass<br>Power/Heat | Captured $CO_2$<br>Methane | Apsley Farms [59]<br>Nesselnbach Plant [60]<br>Limeco PowerToGas [61] |
| Biomass Gasification 5.1.3 |   | Biomass<br>Power/Heat | Captured $CO_2$<br>Syngas | Güssing Plant [62] |
| Biomass Torrefaction 5.1.4 |   | Biomass<br>Power/Heat | Captured $CO_2$<br>Bio-Coal | Duiven Plant [63]<br>Arbaflame Arbaone plant [64] |
| Biomass Liquefaction 5.1.5 |   | Biomass<br>Water<br>Power/Heat | Bio-Oil<br>Hydrochar<br>(Water) | Chuntoh Ghuna [65]<br>Licella GS-1 [66] |
| Biomass Pyrolysis 5.1.6 |   | Biomass<br>Power/Heat | Syngas<br>Bio-Oil<br>Biochar | Valmet R&D Center [67]<br>TSK pyrolysis plant [68] |
| Plastic Waste Gasification 5.2.1 |   | Plastics<br>Power/Heat | Captured $CO_2$<br>Syngas | SVZ Schwarze Pumpe [69]<br>Kawasaki Plant [70]<br>InEnTec Columbia Ridge [71] |
| Plastic Waste Pyrolysis 5.2.2 |   | Plastics<br>Power/Heat | Syngas<br>Liquid-Oil<br>Char | Arcus Plant [72]<br>Beston 30T/D [73]<br>Sapporo Plant [74] |
| Plastic Waste Liquefaction 5.2.3 |   | Plastics<br>(Water)<br>Power/Heat | Liquid Oil<br>(Char)<br>(Water) | OMV ReOil [75]<br>Carboliq Pilot [76] |

into biofuels and other platform chemicals [97]. Integration of carbon capture enables removal of $CO_2$ either from raw syngas or downstream flue gases [98, 99]. Tab. 1 lists the Güssing plant [62], a discontinued facility that successfully demonstrated Fischer–Tropsch fuel production; however, ongoing pilot and demonstration projects suggest further developments in this field [96].

### 5.1.4 Biomass Torrefaction

Biomass torrefaction (Fig. 6d) is a thermal pretreatment process conducted at moderate temperatures in an inert or low-oxygen environment and is commonly described as a mild form of pyrolysis [100]. It upgrades solid biomass into more energy-dense, hydrophobic, and stable "black pellets" that can substitute fossil coal [101], and has also been proposed as a net-negative pathway when combined with subsequent ground storage [35]. Although $CO_2$ emissions are lower than in combustion or full pyrolysis, process-integrated $CO_2$ capture is theoretically feasible, for example through additives or mineral wastes that adsorb and store $CO_2$ [102, 103]. A competing biomass pellet technology, not listed as a separate building block due to similar input and output streams, is steam explosion [104]. Examples include the Blackwood Technology plant in Duiven for torrefaction [63] and the Arbaflame Arbaone plant [64] for steam explosion.

### 5.1.5 Biomass Hydrothermal Liquefaction

Hydrothermal liquefaction (Fig. 6e) is a thermochemical process that converts wet biomass into liquid at moderate temperatures and high pressures, often called bio-oil or bio-crude [105]. Its key advantage over other thermochemical

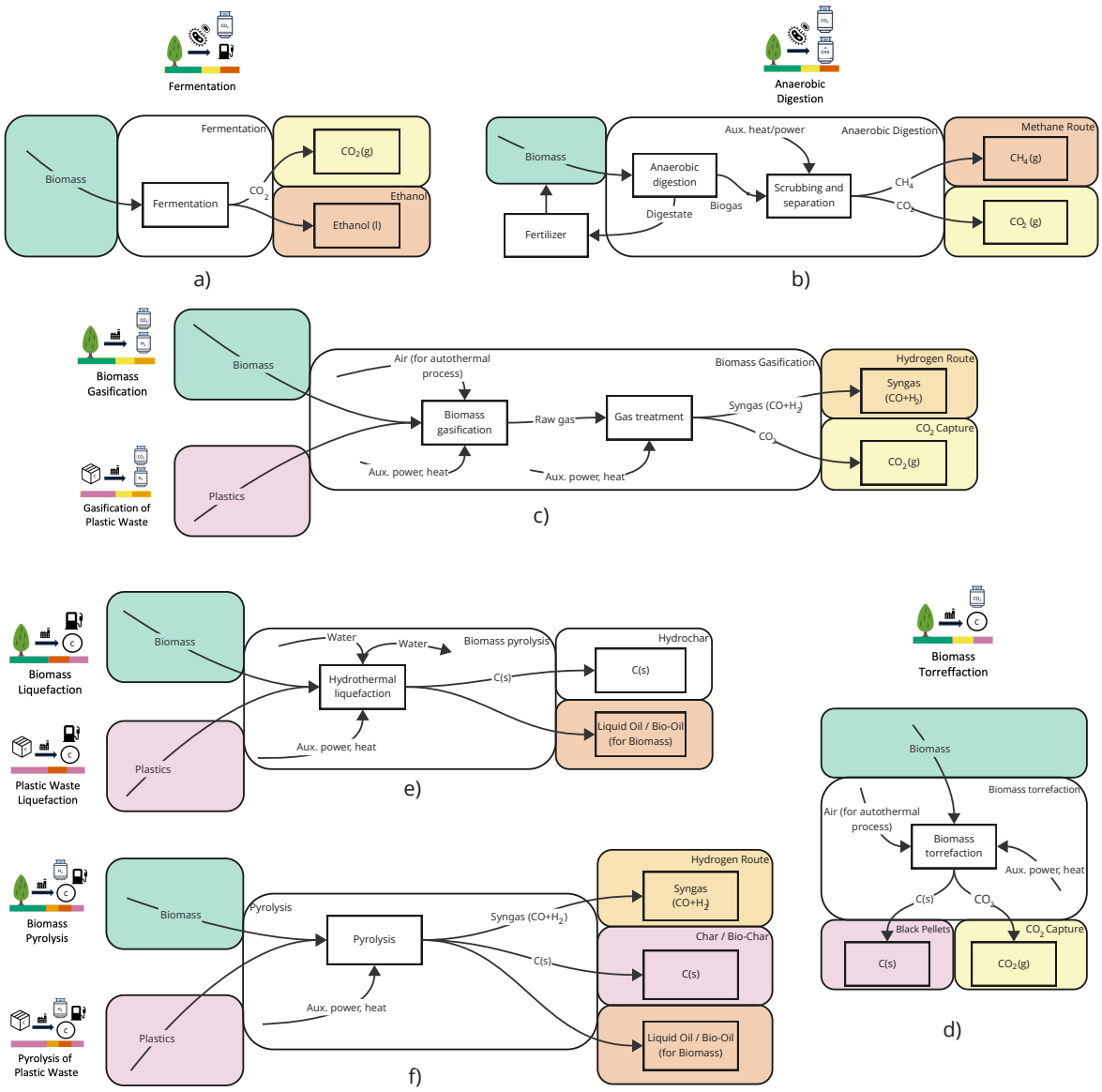



Figure 6: Part 1 of Q2 process diagrams illustrating the biomass and plastic routes: (a) fermentation; (b) anaerobic digestion; (c) gasification of biomass or plastics; (d) biomass torrefaction; (e) hydrothermal liquefaction of biomass or plastics; and (f) pyrolysis of biomass or plastics.

routes lies in its ability to process high-moisture feedstocks, such as algae, without energy-intensive drying, as well as in its relatively low operating temperature, high energy efficiency, and low tar yield compared to pyrolysis [106]. Bio-oil yield is highly dependent on process conditions and feedstock [106, 107], and the accompanying hydrochar is gaining attention for potential product applications [108]. Selected emerging examples are listed in Tab. 1.

### 5.1.6 Biomass Pyrolysis

Biomass pyrolysis (Fig. 6f) is a thermochemical process in which dry biomass decomposes under heat in the absence of oxygen, producing bio-oil, syngas, and biochar [109, 110]. Bio-oil can serve as a renewable fuel or chemical feedstock, biochar is applicable for soil amendment and carbon storage, and syngas can be used for heat and power generation or further conversion into platform chemicals. Variants such as catalytic pyrolysis employ catalysts to enhance product quality, particularly by promoting deoxygenation of bio-oil to yield higher-value hydrocarbons [109]. Selected facilities are listed in Tab. 1.

### 5.2 Plastics Route

Plastics constitute a major carbon reservoir within the anthropogenic carbon cycle [111]; however, a substantial share of plastic waste is still landfilled or incinerated [111], as predominant mechanical recycling back into plastic products in Q3 is unsuitable for most mixed or contaminated streams (Sec. 6.1.3). Thermochemical recycling of plastic waste to platform chemicals ("Waste-to-X") is therefore increasingly regarded as a promising alternative [112–117], enabling plastics to serve as an intermediate carbon stock within Q3 that can be redirected to Q2 for more diverse downstream utilization beyond plastics. Chemical recycling comprises a broad and technically diverse set of approaches applicable to both conventional [114] and bio-based plastics [115]. Given the relative immaturity of the plastics route, its technologies remain difficult to systematize; the three building blocks presented here intend to capture prominent current approaches.

#### 5.2.1 Plastic Waste Gasification

Gasification of plastic waste into syngas (Fig. 6c) involves high-temperature thermochemical processing with a controlled supply of oxygen, air, or steam [113, 114, 116, 118], analogous to biomass gasification (Sec. 5.1.3). The resulting syngas can be used for hydrogen production, methanol or methane synthesis, or power generation following gas cleanup. Carbon capture of the co-produced $CO_2$ is essential for achieving low-carbon hydrogen via gasification pathways [119, 120]. A variety of waste gasification technologies are available, building on experience from coal and biomass gasification systems [118]. Lee et al. [113] reviews past pilot plants and ongoing developments; selected examples are listed in Tab. 1.

#### 5.2.2 Plastic Waste Pyrolysis

Thermal and catalytic pyrolysis convert plastic waste into liquid oil with properties comparable to conventional diesel or jet fuel [112, 121–123]. As shown in Fig. 6f, the process produces liquid oil as the main output of value, but also syngas, and char, analogous to biomass pyrolysis (Sec. 5.1.6). The char can be utilized as a product or for carbon storage, while syngas serves as an energy carrier [121]. Several commercial facilities are in operation, including the Arcus plant [72], the Sapporo plant [74], and the Beston Group plant [73].

#### 5.2.3 Plastic Waste Liquefaction

Plastic waste liquefaction encompasses processes that thermally or catalytically crack plastics in the presence of a liquid phase [114]. In contrast to conventional thermal pyrolysis, liquefaction involves hydrogen-donating components in either liquid or gaseous form, which alters the depolymerization mechanism of the plastic waste [124]. Compared to biomass liquefaction, which is predominantly hydrothermal (Sec. 5.1.5), plastic liquefaction may employ a variety of hydrogen-donating solvents and reaction pathways [125–127]. Hydrothermal liquefaction of plastic waste (Fig. 6e) is also increasingly explored in research [128–132], typically producing liquid oil with minimal char formation [129]. Two operational liquefaction plants are listed in Tab. 1.

### 5.3 Hydrogen Route

Hydrogen ($H_2$) is a flexible, non-carbon-based energy carrier and industrial feedstock that enables decarbonization across multiple sectors [144] in power-to gas process chains [145–147]. It can operate independently of the carbon cycle (Fig. 1), for example when produced via renewable electrolysis (Sec. 5.3.1) or natural processes such as serpentinization [148], offering a substitute for carbon-based fuels. However, hydrogen also intersects with the carbon cycle in both production and downstream use. Today, it is predominantly produced via steam methane reforming [149] (Section 5.7.3), but can also be derived from biomass or plastics gasification and pyrolysis (Sec. 5.1.3, 5.1.6, 5.2.1, 5.2.2). In turn, $H_2$ and syngas ($CO+H_2$) can serve as a feedstock for synthetic methanol, methane, or other hydrocarbon production [150] (Sections 5.6, 5.7).

#### 5.3.1 Water Electrolysis

Water electrolysis (Figure 7a) is a key technology for hydrogen production, splitting water ($H_2O$) into hydrogen ($H_2$) and oxygen ($O_2$) using electricity [149]. The process occurs in electrolyzers and produces near-zero-emission hydrogen when powered by renewable energy, commonly referred to as “green hydrogen.” Comprehensive overviews of available electrolysis technologies are provided by Shih et al. [151], Shiva Kumar and Lim [152].

Table 3: (Table 2 continued) The second 9 out of 27 building blocks of the second quadrant: *Conversion*.

| Building Block | | Input | Output | Examples |
|---|---|---|---|---|
| Electrolysis 5.3.1 |  Electrolysis | Electricity<br>Water | $H_2$ (g) | OMV Plant [133]<br>NEOM Project [134]<br>Envision Chifeng Plant [135] |
| Co-Electrolysis 5.3.2 |  Co-Electrolysis | Captured $CO_2$<br>Electricity<br>Water | Syngas | Arnstadt SOEC Pilot [136]<br>Sunfire Pilot [137] |
| $H_2$ Compression 5.3.3 |  $H_2$ Compression | $H_2$ (g)<br>Power | $H_2$ (g)<br>Heat | |
| $H_2$ Liquefaction 5.3.3 |  $H_2$ Liquefaction | $H_2$ (g)<br>Power | $H_2$ (l)<br>Heat | |
| $H_2$ Regasification 5.3.3 |  $H_2$ Regasification | $H_2$ (l)<br>Power/Heat | $H_2$ (g) | |
| Reverse Water Gas Shift 5.3.4 |  Reverse Water Gas Shift | Captured $CO_2$<br>$H_2$<br>Heat | Syngas<br>Water | Ineratec ERA ONE [138] |
| Fischer Tropsch Synthesis 5.4 |  Fischer Tropsch Synthesis | Syngas<br>Power/Heat | Liquid Synfuel | Ineratec Synhelion [139]<br>DG Fuels Plant [140]<br>Sasol Secunda CTL Plant [141] |
| Ammonia Synthesis 5.5.1 |  Ammonia Synthesis | $H_2$<br>$N_2$<br>Power/Heat | $NH_3$ | Envision Chifeng Plant [135]<br>NEOM Project [134]<br>Jilin Electric Plant [142] |
| Ammonia Decomposition 5.5.2 |  Ammonia Decomposition | $NH_3$<br>Power/Heat | $H_2$<br>$N_2$ | Mitsubishi Pilots [143] |

### 5.3.2 Co-Electrolysis and $CO_2$-Electrolysis

$CO_2$-electrolysis (Fig. 7b) is an advanced electrochemical process that simultaneously reduces $CO_2$ and water producing syngas composed of hydrogen ($H_2$) and carbon monoxide (CO) [153] (co-electrolysis) or directly small hydrocarbons or alcohols. In contrast to separate water electrolysis (Sec. 5.3.1) followed by the reverse water–gas shift reaction (Sec. 5.3.4), co-electrolysis generates syngas directly in a single step. The high temperature solid oxide electrolysis technology is approaching commercialization, with several startups, pilot plants, and large-scale initiatives underway [154]; selected examples are listed in Tab. 3. At lower technology readiness levels, substantial research efforts focus on low-temperature electrochemical reduction of $CO_2$ to value-added chemicals [155–157]. To date, most important products achieved at high Faradayic efficiency are carbon monoxide and ethene ($C_2H_4$) [158].

### 5.3.3 Hydrogen Conditioning

Hydrogen conditioning comprises essential post-production steps for safe and efficient handling, transport, and storage. Compression increases hydrogen pressure to approximately 200–900 bar for storage and pipeline transport [159]. Liquefaction cools hydrogen to $-253^{\circ}\mathrm{C}$ to produce liquid hydrogen, significantly increasing volumetric energy density for long-distance shipping or space-constrained storage, albeit with high energy and infrastructure demands [160]. Regasification converts liquid hydrogen back to its gaseous state for end use [161]. Fig. 7c illustrates the associated building blocks and high-level conditioning processes.

### 5.3.4 Reverse Water Gas Shift

The reverse water–gas shift (RWGS) reaction (Fig. 7d) catalytically converts carbon dioxide ($CO_2$) and hydrogen ($H_2$) into carbon monoxide (CO) and water ($H_2O$). This endothermic reaction is a key step in $CO_2$ utilization, producing CO

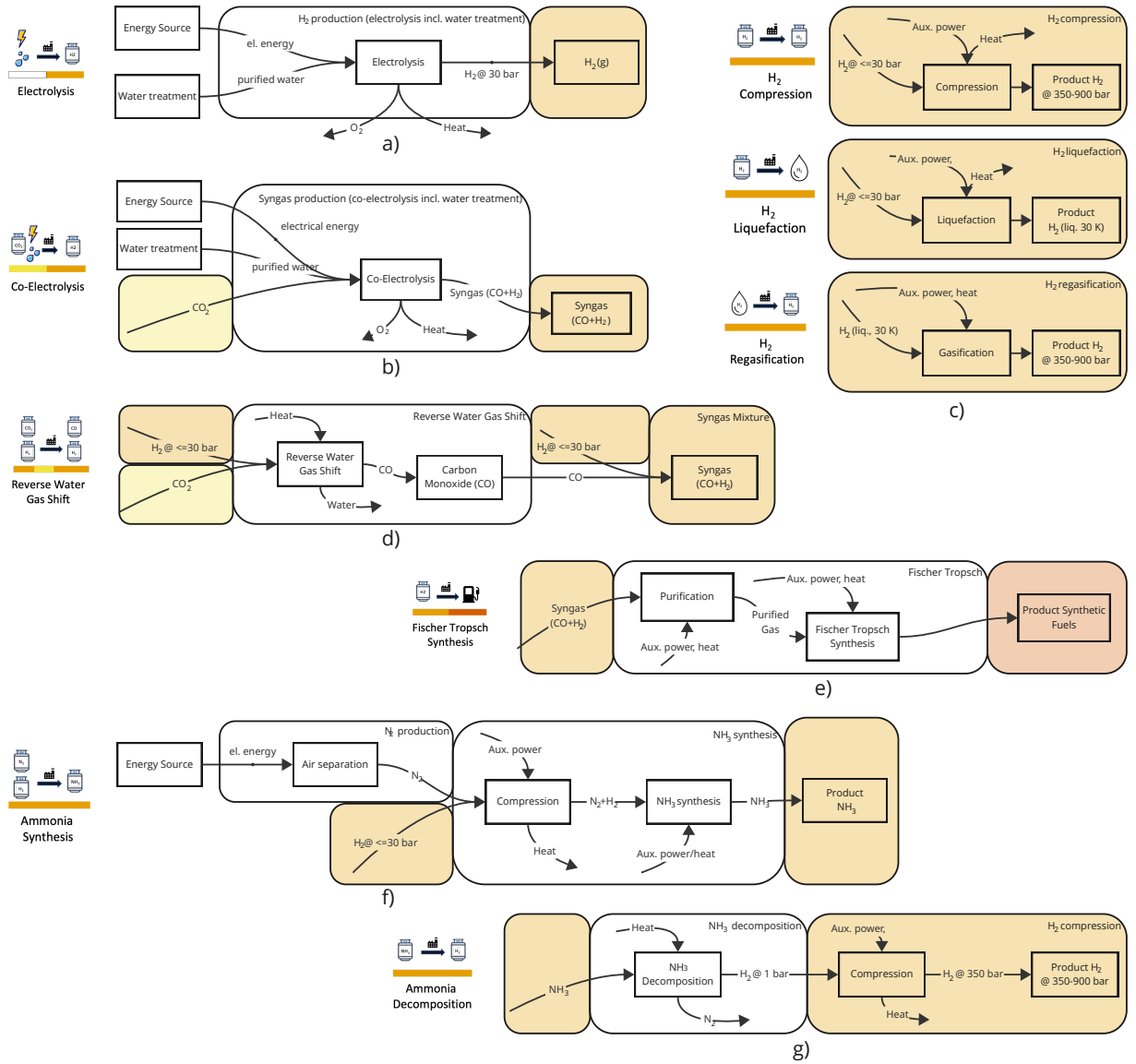



Figure 7: Part 2 of Q2 process diagrams for the hydrogen and ammonia routes: (a) electrolysis; (b) co-electrolysis; (c) hydrogen conditioning; (d) reverse water–gas shift; (e) Fischer–Tropsch synthesis; (f) ammonia synthesis; and (g) ammonia decomposition

as an intermediate for fuel and chemical synthesis, including Fischer–Tropsch processes (Sec. 5.4). Within renewable energy pathways, RWGS enables the conversion of captured $CO_2$ into syngas for subsequent sustainable fuel production [162, 163]. Selected examples are listed in Tab. 3.

### 5.4 Fischer Tropsch Synthesis Route

Fischer-Tropsch synthesis (Fig. 7e) is a catalytic process that converts syngas, a mixture of carbon monoxide (CO) and hydrogen ($H_2$), into liquid hydrocarbons for fuels and chemicals [164]. It underpins coal-to-liquid (CTL) and gas-to-liquid (GTL) technologies and is increasingly used to produce carbon-neutral fuels from biomass- or $CO_2$-derived syngas [165, 166]. The hydrocarbons can be refined into sustainable aviation fuel, diesel, and other drop-in fuels, with catalyst selection and operating conditions determining efficiency, selectivity, and product distribution [167]. Examples are listed in Tab. 3.

Table 4: (Table 2 continued) The final 8 out of 27 building blocks of the second quadrant: *Conversion*.

| Building Block | | Input | Output | Examples |
|---|---|---|---|---|
| Methanol Synthesis 5.6.1 |  MeOH Synthesis | $H_2$ / Syngas<br>Captured $CO_2$ | MeOH | Kassø plant [179]<br>Tianying plant [180]<br>Mexinol project [181] |
| Methanol Steam Reforming 5.6.2 |  MeOH Steam Reforming | MeOH<br>Power/Heat | $H_2$<br>Captured $CO_2$ | HYGEAR Hy.GEN [182]<br>Mahler Hydroform-M [183] |
| Methanol to Olefins 5.6.3 |  MeOH to Olefins | MeOH | Olefins<br>Heat | Baotou Plant [184]<br>Zhongtian Hechuang Plant [185] |
| Methane Synthesis 5.6.1 |  $CH_4$ Synthesis | $H_2$ / Syngas<br>Captured $CO_2$ | $CH_4$<br>Water | Hycamite Plant [186]<br>Limeco PowerToGas Plant [61] |
| $CH_4$ Liquefaction 5.7.2 |  $CH_4$ Liquefaction | $CH_4$ (g)<br>Power | $CH_4$ (l)<br>Heat | |
| $CH_4$ Regasification 5.7.2 |  $CH_4$ Regasification | $CH_4$ (l)<br>Power/Heat | $CH_4$ (g) | |
| Methane Steam Reforming 5.7.3 |  CC - $CH_4$ Steam Reforming | $CH_4$<br>Power/Heat | $H_2$<br>Captured $CO_2$ | Shell Quest Plant CC [187]<br>Port Arthur II Plant [188]<br>Synhelion Dawn [189] |
| Methane Pyrolysis 5.7.4 |  $CH_4$ Pyrolysis | $CH_4$<br>Power/Heat | $H_2$<br>Carbon Black | Ekona Pilot [190]<br>Graphitic C-Zero Pilot [191]<br>Tech Cluster Zug Pilot [192] |

### 5.5 Ammonia Route

Ammonia ($NH_3$) is a synthetic non-carbon platform chemical and energy carrier that can operate independently of the carbon cycle (Fig. 1). Beyond fertilizers, it is increasingly considered as a fuel for shipping, transport, and power generation [17, 168], offering advantages over hydrogen in storage, energy density, and infrastructure compatibility [169]. Today, ammonia is mainly produced via the Haber–Bosch process using fossil-based hydrogen, accounting for over 1% of global GHG emissions [170]. However, renewable hydrogen enables "green ammonia" [171]. Environmental concerns include toxicity and potential $N_2O$ emissions [172, 173].

#### 5.5.1 Ammonia Synthesis (Haber Bosch)

Ammonia is predominantly synthesized via the Haber–Bosch process (Fig. 7e), which catalytically combines nitrogen ($N_2$) and hydrogen ($H_2$) at high pressures and temperatures. Nitrogen is produced by air separation, while hydrogen is typically derived from steam methane reforming (Sec. 5.7.3). Despite its high energy demand and fossil reliance, Haber–Bosch remains the most established large-scale production route, with improved catalysts and electrification offering efficiency gains [174, 175]. "Green" ammonia can be produced with established processes from biomass or using water electrolysis to produce green hydrogen (Sections 5.1.3, 5.3.1). Emerging electrochemical pathways aim to synthesize $NH_3$ directly from $N_2$ [17]. Examples are listed in Tab. 3.

#### 5.5.2 Ammonia Decomposition

Ammonia decomposition (Fig. 7g) is the reverse process of ammonia synthesis, cracking ammonia ($NH_3$) into hydrogen ($H_2$) and nitrogen ($N_2$). It enables ammonia to serve as a liquid hydrogen carrier for transport and storage [176] and can also remove ammonia from reformate streams in integrated gasification combined cycle (IGCC) systems proposed for future $CO_2$-removal applications [177]. The endothermic reaction generally requires temperatures above 400 °C and suitable catalysts to achieve high conversion rates [176–178]. Most systems remain at demonstration or pilot scale; selected examples are listed in Tab. 3.

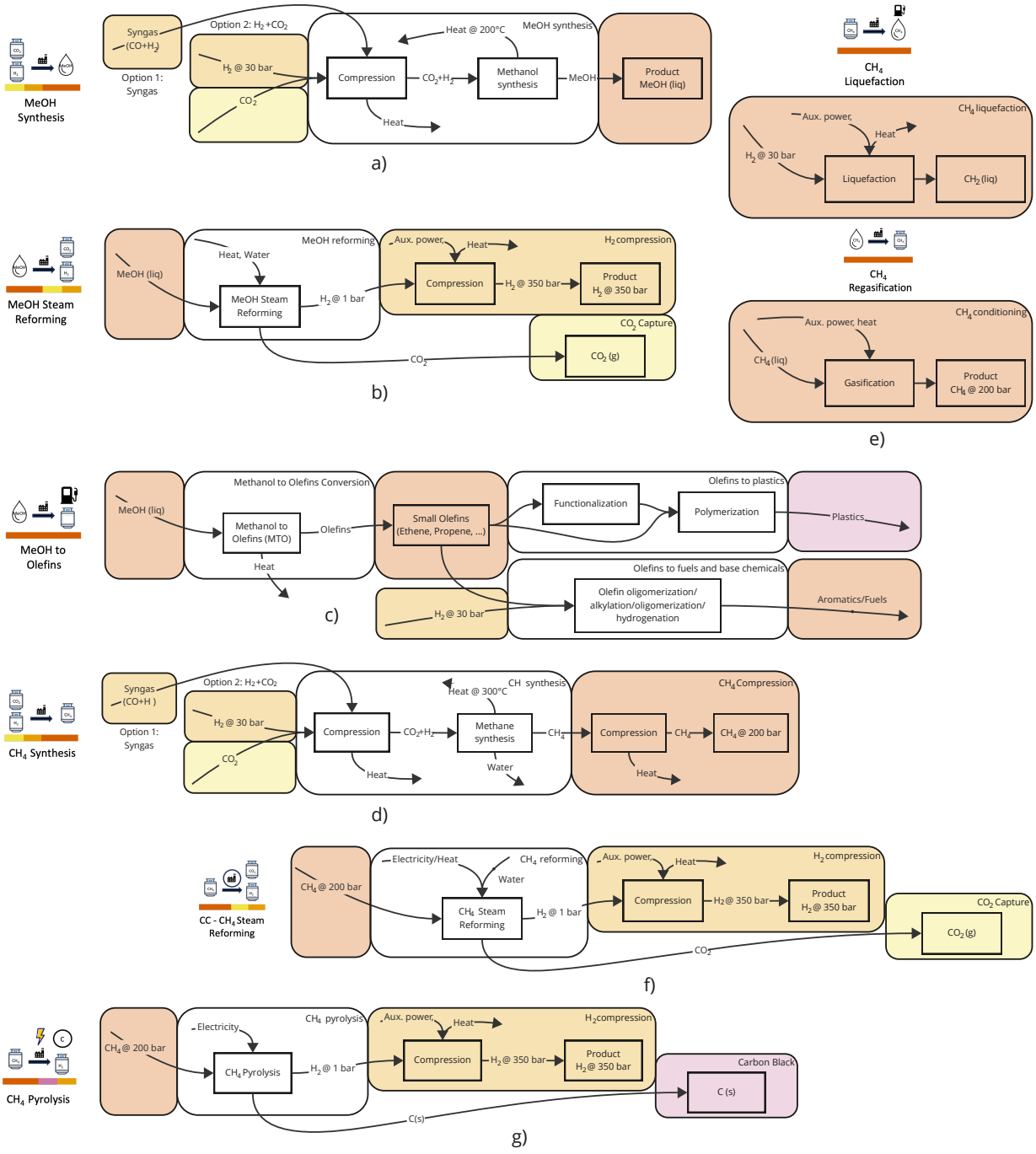



Figure 8: Part 3 of Q2 process diagrams for the methanol and methane routes: (a) methanol synthesis; (b) methanol reforming; (c) methanol to olefins; (d) methane synthesis; (e) methane conditioning; (f) steam methane reforming; and (g) methane pyrolysis.

### 5.6 Methanol Route

Methanol ($CH_3OH$, but often abbreviated by MeOH), is one of the highest-volume commodity chemicals worldwide and serves as a versatile liquid feedstock for formaldehyde, acetic acid, olefins, and plastics, as well as a fuel, fuel additive, and solvent [10]. Within the anthropogenic carbon cycle (see Fig. 1), the methanol route synthesizes $CO_2$ or CO and $H_2$ into methanol ($CH_3OH$). When produced from biogenic or atmospheric $CO_2$ and renewable or bio-based

$H_2$, methanol can replace fossil-based feedstocks across large parts of the economy, enabling a carbon-neutral cycle referred to as the "methanol economy" [1, 193].

### 5.6.1 Methanol Synthesis

Methanol synthesis (Fig. 8a, Option 1) is an established industrial process in which methanol is produced by reacting syngas ($H_2$ + CO) over catalysts [194]. Today, most syngas for methanol production is derived from natural gas via steam methane reforming followed by a water–gas shift reaction (Sections 5.7.3 and 5.3.4). An alternative route (Fig. 8a, Option 2) synthesizes methanol directly from $CO_2$ and $H_2$ [194, 195], enabling $CO_2$ sourcing from flue gases or air and hydrogen from renewable electrolysis (often termed e-methanol) or biomass. Examples are listed in Tab. 4.

### 5.6.2 Methanol Steam Reforming

Methanol steam reforming (Fig. 8b), essentially the reverse of methanol synthesis, is a catalytic process that converts $CH_3OH$ into a hydrogen-rich gas, yielding $H_2$ and $CO_2$ [196]. The process enables efficient hydrogen production due to methanol's high hydrogen-to-carbon ratio and its lower reforming temperature compared to methane [196]. Although other hydrogen production routes from methanol exist, such as partial oxidation (POx), autothermal reforming (ATR), and decomposition, most implementations have focused on steam reforming, particularly when considering hydrogen yield and carbon monoxide formation and mitigation [196]. Ongoing development aims to scale the technology for distributed use in vehicles [197] and ships [198], but also for broader industrial use, with examples listed in Table 4.

### 5.6.3 Methanol to Olefins for Chemicals, and Fuels

A palette of established and emerging processes (Fig. 8c) exploits methanol's flexibility as a platform chemical to produce olefins (Methanol to Olefins, MtO), gasoline (MtG), aromatics (MtA), or directly jet fuel (MtJ) [199–202]. The processes generally use acid catalysts, mainly zeolites, to convert methanol via dehydration to light olefins, followed by oligomerization and hydrogenation to obtain the desired hydrocarbon products. The process chains excel through high selectivity on tailored product ranges [203]. Several plants are operational (see Table 4).

## 5.7 Methane Route

Methane ($CH_4$) is a versatile energy carrier and chemical feedstock [10], widely used for hydrogen production via steam methane reforming (Sec. 5.7.3). Methane is today predominantly supplied from fossil natural gas [204]. Synthetic methane, or synthetic natural gas (SNG) [205], can instead be produced from biomass [206, 207] or renewable hydrogen and captured $CO_2$ via Power-to-Gas processes [145, 147], enabling renewable electricity storage within existing gas infrastructure. Since methane combustion releases $CO_2$, its sustainability depends on renewable or recycled carbon sources [208], and leakage remains a major concern due to its high global warming potential [209, 210].

### 5.7.1 Methane Synthesis

Methane synthesis, also known as catalytic methanation or the Sabatier reaction, is a chemical process that converts carbon monoxide (CO) and carbon dioxide ($CO_2$) with hydrogen ($H_2$) in an exothermic reaction into methane ($CH_4$) and water over metal catalysts [211]. Discovered in 1902 by Sabatier and Senderens, it has regained attention for applications in synthetic natural gas production and Power-to-Gas energy storage [211]. The reaction can use syngas (Fig. 8d, Option 1) or pure $CO_2$ and $H_2$ (Fig. 8d, Option 2) as feedstock [207, 211]. Two examples involving carbon capture and biological feedstock are listed in Table 4.

### 5.7.2 Methane Conditioning

Methane conditioning for transport involves compression, liquefaction, and regasification to enable long-distance handling. Liquefaction cools natural gas to $-162^{\circ}\mathrm{C}$, producing liquefied natural gas (LNG) with high energy density for efficient storage and shipping [212]. At the destination, regasification converts LNG back to its gaseous state for pipeline injection or direct fuel use [213]. Fig. 8e illustrates the associated building blocks and high-level conditioning processes.

### 5.7.3 Methane Steam Reforming

Methane steam reforming (Fig. 8f) is currently the dominant industrial process for large-scale hydrogen production, in which $CH_4$ reacts with steam over catalysts [214]. The endothermic reaction produces $H_2$, CO, and $CO_2$. To maximize hydrogen yield, subsequent water–gas shift stages (Sec. 5.3.4) convert remaining CO into $CO_2$ while generating

additional $H_2$. Capturing $CO_2$ from the syngas or flue gas streams [215] enables lower-carbon hydrogen production, sometimes referred to as "blue" hydrogen [149]. Solar-assisted heating has been proposed to reduce fossil energy input for the high operating temperatures required [216]. Well-known examples are listed in Table 4.

#### 5.7.4 Methane Pyrolysis

Methane pyrolysis (Fig. 8g) is an endothermic thermochemical process that decomposes $CH_4$ at high temperatures or using plasmas in the absence of oxygen into $H_2$ and solid carbon [217–219]. The solid carbon byproduct can take various forms, ranging from carbon black and graphitic materials to specialized carbon nanotubes and fibers [217]. As no direct $CO_2$ is formed during the reaction, it is considered a low-carbon hydrogen production pathway, with potential for net-negative emission balances if the methane originates from biologenic or athmospheric sources and the solid carbon is permanently stored [14]. Operational pilots are listed in Tab. 4.

## 6 Building Blocks Quadrant 3: Utilization

This section outlines the identified building blocks for Q3 - utilization, as introduced in Sec. 2.3. It is organized according to how carbon is used within and ultimately exits Q3: material and product utilization (Sec. 6.1), combustion of energy carriers with atmospheric emissions (Sec. 6.2), and stationary energy conversion with potential carbon capture (Sec. 6.3). An overview of all building blocks is provided in Tab. 5 and Fig. 9.

### 6.1 Material and Product Use

The first utilization category covers material and product use within Q3, where carbon is incorporated into materials and retained for a finite period before end-of-life. Circular economy "R-strategies" [220], such as reuse and recycling, extend effective product lifetimes, reduce new resource input, and increase temporary carbon retention. Included building blocks comprise biomass products (Sec. 4.1), plastics and other carbon-based products (Sec. 6.1.3), and char and carbon black (Sec. 6.1.2). The final sink depends on subsequent treatment, such as landfilling (Sec. 4.5), waste incineration with or without point-source capture (Sec. 6.3.2, 4.4), thermochemical valorization via the biomass or plastics routes (Sec. 5.1, 5.2), or long-lasting storage (Sec. 7).

#### 6.1.1 Biomass products

Biomass has long been an important source of materials. Wood remains widely used in construction, furniture, packaging, and paper [230, Fig.1], with growing interest in advanced wood-based materials [231, 232]. Bio-based products can temporarily store atmospheric carbon, particularly in long-lived applications such as buildings [233–235]. However, their long-term sink potential depends on durability and end-of-life treatment, which is why they are classified here under Q3 utilization rather than Q4 storage, where stricter permanence criteria apply [20]. Large-scale substitution of fossil-based products faces challenges related to land-use change, harvest-related carbon costs [78], and potential conflicts with ecosystem protection and food security [77]. Nonetheless, cascading use and improved utilization of wood residues could allow for sustainable scaling [230] and extend carbon residence time [19].

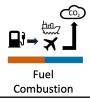
#### 6.1.2 Char & Carbon Black

Biochar has gained prominence in carbon removal discussions as a solid carbon material produced from biomass via thermochemical processes such as torrefaction or pyrolysis (Sec. 5.1.4, 5.1.6) [236]. Solid carbon materials can also arise from pyrolysis of plastics (Sec. 5.2.2), or from methane (Sec. 5.7.4); in these cases they are referred to as char or carbon black and can likewise achieve net-zero or net-negative emission balances if subsequently stored. Within this framework, char and carbon black are classified under Q3 utilization because they are used in industrial applications such as pigments and tires or are energetically valorized, as is common for torrefied bio-coal. Only when permanently stored in long-lasting products (Sec. 7.4) or applied for soil amendment (Sec. 7.5) do they function as carbon removal pathways within Q4. Key challenges are process inherent contaminations with hydrocarbons (esp. polycyclic aromatic hydrocarbons, PAH) [237].

#### 6.1.3 Plastics and Other Carbon-Based Products

Plastics are versatile polymer materials valued for their light weight, durability, and moldability, and are used across industries in forms such as fibres, foils, particles, foams, and moldings [10]. Traditionally produced from fossil-derived naphtha or natural gas with growing environmental footprint [238], they can also be synthesized from biomass-based or $CO_2$-derived platform chemicals (Sec. 5). Plastics constitute one of the largest anthropogenic carbon reservoirs

Table 5: The 9 building blocks of the third quadrant: *Utilization*.

| Building Block | | Input | Output | Examples |
|---|---|---|---|---|
| Biomass Products 6.1.1 |   | Biomass | Biomass product | |
| Char & Carbon Black 6.1.2 |   | Biomass<br>Plastics<br>Methane | Biochar / Bio-Coal<br>Char<br>Carbon Black | |
| Plastics and Other 6.1.3 |   | Fuel | Plastics | |
| $NH_3$-Based Products 6.1.4 |   | $NH_3$ | $NH_3$-based product | |
| Synthetic and Bio-Fuels 6.2.1 |   | Fuel | Released $CO_2$<br>Heat | |
| $H_2$ as Fuel (carbon-free) 6.2.2 |   | $H_2$ | Water<br>Heat | |
| Power Plants / Industry 6.3.1 |   | Fuel<br>Syngas / $H_2$ | Flue Gas<br>Power/Heat | Boundary Dam Unit 3 [221]<br>Mikawa Plant [222]<br>Stockholm Exergi [223] |
| Waste Incineration 6.3.2 |   | Biomass Products<br>Plastics | Flue Gas<br>Power/Heat | Klemetsrud Plant [224]<br>AVR Duiven [225]<br>Hafslund Celsio [226] |
| Cement Plant 6.3.3 |   | $CaCO_3$<br>Fuel | Flue Gas<br>Cement | Holcim GO4ZERO [227]<br>Brevik Plant [228]<br>CLEANKER [229] |

[111], temporarily storing carbon in stable polymer structures. This residence time can be extended through mechanical recycling, as exemplified by PET [239], although repeated processing often reduces material quality and requires relatively clean waste streams. At end-of-life, plastics may accumulate as environmentally harmful debris [240], be landfilled and lost as a resource (Sec. 4.5), incinerated with potential carbon capture (Sec. 6.3.2), or thermochemically converted back into platform chemicals (Sec. 5.2). Other carbon-based products such as solvents, coatings, and cosmetics [10] follow similar production and end-of-life pathways and are therefore included in this building block.

### 6.1.4 Ammonia-Based Products

Ammonia is a key feedstock for fertilizers and explosives [10, p. 110] and is increasingly considered a carbon-free fuel alternative due to its high hydrogen content and ease of storage, with potential in power generation, maritime shipping, and heavy industry [17, 168]. Although ammonia itself contains no carbon, it is often produced from fossil feedstock for hydrogen production (Sec.5.5.1) or converted to urea by reaction with $CO_2$ for fertilizer production, and further to melamine for resins and plastics [10], thereby interacting again with the anthropogenic carbon cycle.

## 6.2 Combustion without Carbon Capture

The second utilization category within Q3 covers carbon-containing fuels used in applications where post-combustion carbon capture (Sec. 4.4) is technically infeasible or economically unrealistic (Sec. 6.2.1). This primarily includes mobile and small-scale uses such as aviation, maritime, and road transport. The carbon-free counterpart, hydrogen as a fuel (Sec. 6.2.2), is also included.

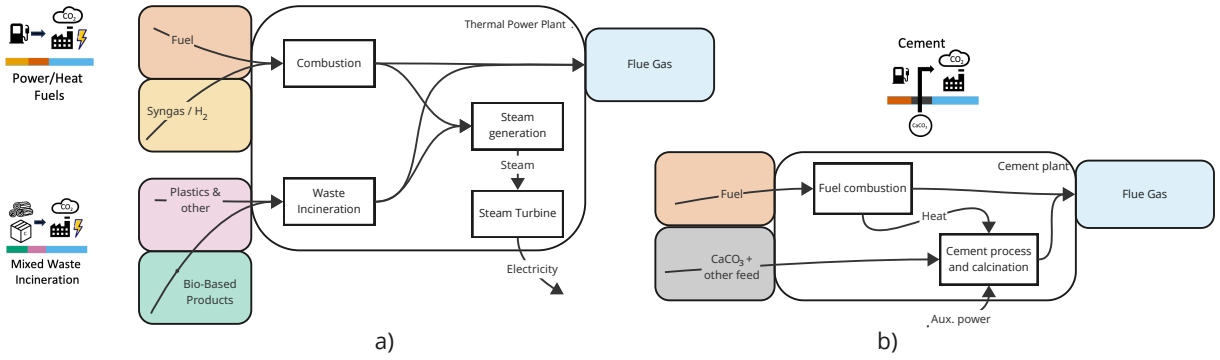



Figure 9: Process diagrams of Q3 building blocks: (a) stationary energy conversion through fuel-based combustion and mixed waste incineration; (b) cement production.

### 6.2.1 Synthetic and Bio-Based Carbon Containing Fuels

Synthetic and bio-based fuels are liquid or gaseous energy carriers produced from biomass (Sec. 5.1), plastics (Sec. 5.2), or by reducing $CO_2$ with $H_2$ or directly electrochemically (Sec. 5.6.1, 5.7.1). When renewable electricity is used to produce hydrogen via electrolysis for this conversion, they are referred to as e-fuels or electrofuels (Sec. 5.3.1, 5.3.2, 5.3.4). They target hard-to-electrify sectors such as aviation, shipping, and heavy industry, with Sustainable Aviation Fuels among the most prominent applications [13], linking back to various Q2 platform chemicals [203]. In contrast to hydrogen (Sec. 6.2.2), synthetic and bio-based fuels are compatible with existing combustion engines and turbines and can still achieve net-zero or net-negative balances depending on carbon sourcing [241]. Vogt et al. [211, Tab. 1] provide an overview of advantages and disadvantages across Power-to-X fuel pathways.

### 6.2.2 Hydrogen as Fuel

As the carbon-free counterpart to synthetic or bio-based fuels, hydrogen can be used for combustion or in fuel cells in large parts of our economy [16]. However, its volumetric energy density is significantly lower than that of fossil or synthetic fuels, posing storage challenges [241]. While hydrogen use emits no $CO_2$, its overall climate impact depends on emissions from production (Sec. 5.3) and its role as an indirect greenhouse gas [242].

## 6.3 Stationary Energy Conversion with Carbon Capture

The third utilization category in Q3 comprises carbon-containing fuels or feedstocks combusted at large, stationary plants where carbon capture (Sec. 4.4) can be implemented. This includes fuel-based power plants and industrial boilers and furnaces (Sec. 6.3.1), waste incineration facilities (Sec. 6.3.2), and cement plants (Sec. 6.3.3).

### 6.3.1 Power Plants and Industrial Boilers and Furnaces

Power plants and industrial boilers and furnaces convert carbon-containing fuels, hydrogen, or ammonia into heat, steam, and electricity at large stationary facilities. Fossil fuels still dominate the global energy mix at 86% [243], and are typically combusted as coal, oil, or natural gas. However, biomass is an increasingly used alternative (Sec. 4.1), including emerging pathways such as bioenergy with carbon capture and sequestration (BECCS) [244], as well as synthetic and bio-based fuels (Sec. 6.2.1). In thermal power plants, combustion generates steam to drive a turbine for electricity production (Fig. 9a), while industrial facilities supply process heat for mechanical or chemical manufacturing. Regardless of fuel origin, combustion releases carbon mainly as $CO_2$ in flue gases, which can be treated and captured post-combustion (Sec. 4.4). Selected examples are listed in Tab. 5.

### 6.3.2 Waste Incineration

Waste incineration is widely adopted in developed countries, with more than 1700 plants operating [245]. The process (Fig. 9a) is similar to the previous building block (Sec. 6.3.1), but uses mixed waste as feedstock, typically comprising roughly equal shares of biomass-derived products (Sec. 6.1.1) and plastics in European municipal waste streams [246]. Unlike fossil fuels, waste generation cannot simply be phased out. Carbon capture (Sec. 4.4) is therefore considered

central to its decarbonization [247], and several plants are transitioning from pilot to full-scale implementation. Selected examples are listed in Tab. 5.

#### 6.3.3 Cement Plants

Cement plants are treated as a separate building block because their emissions arise not only from use of fuels, covered under the previous power plant and industry category (Sec. 6.3.1), but mainly from the calcination of limestone ($CaCO_3$), which accounts for about 60% of the sector's total emissions [248]. Because cement production releases long-bound geogenic carbon to the atmosphere, it is treated here as a fossil carbon input, yet unlike fossil fuels it is structurally harder to phase out. Decarbonizing cement production is thus critical [249], with post-process carbon capture from kiln flue gases representing one of the main mitigation strategies [250, 251] (Fig. 9b). Real-world deployments are becoming increasingly common (see Tab. 5).

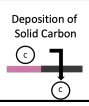
## 7 Building Blocks Quadrant 4: Storage

This section presents the building blocks identified for carbon storage (Sec. 2.4), focusing on artificial geological storage and long-term stabilization of carbon in solid products. Enhanced rock weathering [252, 253] is not included as a building block, as it is a standalone removal pathway that directly stores atmospheric $CO_2$ in soils without the possibility to utilize concentrated $CO_2$ streams as a resource. Deep-sea carbon injection [7] is likewise excluded due to environmental impact concerns [254]. Furthermore, carbon-containing products such as bio-based materials and plastics are classified under "utilization" (Sec. 6), as their long-term carbon retention is uncertain and they frequently degrade in landfills or are incinerated at end of life. An overview of the included storage building blocks is provided in Tab. 6 and Fig. 10.

### 7.1 $CO_2$ Injection in Geological Formations

$CO_2$ can be injected into deep geological formations for long-term storage [266–268] (Fig. 10a). Storage typically involves injection into porous rock formations where $CO_2$ is retained through structural trapping beneath caprocks, residual trapping in pore spaces by capillary forces, and solubility trapping via dissolution in formation fluids [269]. Deep saline aquifers offer the largest global storage capacity [270], while depleted oil and gas reservoirs provide established infrastructure and monitoring experience [271]. Additional options include adsorption in unmineable coal seams [272] and high-pressure storage in salt caverns [267, 273]. Key challenges across all approaches include ensuring long-term seal integrity to prevent leakage and managing site-specific geological uncertainties. Large-scale $CO_2$ storage also requires dedicated transport infrastructure, with pipelines and ship transport likely to be the most economical options [274]. Lane et al. [275] discuss uncertainties in global geological storage capacity.

Table 6: The five building blocks of the fourth quadrant: *Storage*.

| Building Block | | Input | Output | Examples |
|---|---|---|---|---|
| $CO_2$ Injection 7.1 |  | Captured $CO_2$<br>Power | Captured $CO_2$ | Northern Lights [255]<br>Aramco Jubail [256] |
| $CO_2$ In-Situ Mineralization 7.2 |  | Captured $CO_2$<br>Water<br>Power | $CaCO_3$ | Carbfix [257]<br>Big Sky Carbon [258] |
| $CO_2$ Product Mineralization 7.3 |  | Captured $CO_2$<br>Water<br>Power | $CaCO_3$ | CarbonBuilt [259]<br>Neustark [260]<br>CarbonCure [261] |
| Solid Carbon Product Deposition 7.4 |  | Solid Carbon | Solid Carbon | Alterbiota [262]<br>Pyrogen [263] |
| Solid Carbon Ground Deposition 7.5 |  | Solid Carbon | Solid Carbon | AirEx Energy Biochar [264]<br>Swiss Biochar [265] |

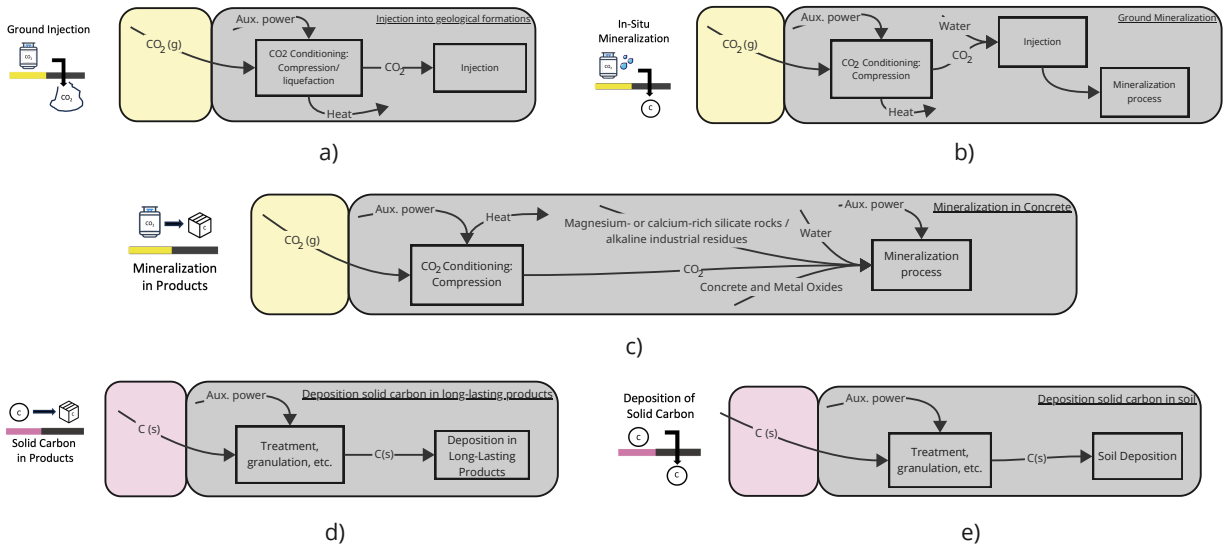



Figure 10: Process diagrams of Q4 building blocks: (a) $CO_2$ injection into geological formations; (b) in situ mineralization of $CO_2$ in the subsurface; (c) mineralization of $CO_2$ within products; (d) incorporation of solid carbon (e.g., biochar, char, or carbon black) into durable products; and (e) deposition of solid carbon in soils to enhance soil properties.

$CO_2$ injection has also long been practiced for enhanced oil recovery (EOR), including projects such as Bell Creek [276], Weyburn–Midale [277], and Petrobras' Santos Basin reinjection [278]. In EOR, injected $CO_2$ mobilizes additional oil by reducing viscosity and swelling the oil phase [279]. Although technically similar to geological storage and sometimes framed as an economical profitable "bridge" technology [280], EOR differs fundamentally in climate terms: combustion of the additional oil generates downstream emissions that typically outweigh by factors the benefit of stored $CO_2$ [281].

### 7.2 $CO_2$ In-Situ Mineralization

In-situ carbon mineralization is an engineered process in which $CO_2$, dissolved in water prior to injection into geological formations, where it reacts with calcium- and magnesium-rich minerals to form stable carbonate solids [282, 283] (Fig. 10b). This reaction immobilizes $CO_2$ in solid form over geological timescales. A prominent example is the Carbfix project in Iceland, which captures atmospheric $CO_2$ via DAC and stores it in basalt formations, demonstrating large-scale in situ mineralization (Tab. 6). Compared to conventional geological injection, in situ mineralization is considered more permanent and stable [269], while transport infrastructure requirements remain similar.

### 7.3 $CO_2$ Mineralization in Products

$CO_2$ chemically bound into stable carbonates through reaction with calcium- or magnesium-containing materials can act as storage [284, 285] (Fig. 10c). Unlike in situ mineralization (Sec. 7.2), this approach integrates mineralization directly into products, most prominently in cement and concrete, which represent the largest and most commercially viable applications [286]. Emerging technologies include carbonated concrete products (e.g., CarbonBuilt [259]), carbonated aggregates (e.g., Neustark [260]), clinker substitutes (e.g., Fortera [287]), and accelerated curing methods (e.g., CarbonCure [261]) (Tab. 6).

### 7.4 Deposition of Solid Carbon in Products

A second approach to carbon storage in durable products involves the incorporation of solid carbon (Fig. 10d). This carbon is typically biochar or carbon black (Sec. 6.1.2), derived from biomass pyrolysis (Sec. 5.1.6), plastic pyrolysis (Sec. 5.2.2), recycled plastic waste [288], or methane pyrolysis (Sec. 5.7.4). Solid carbon is embedded in long-lasting construction materials such as concrete, asphalt, or polymers [289], with current applications focusing mainly on concrete, either as a partial replacement for cement or as aggregates [289–294]. Early commercial deployments are emerging; see Tab. 6 for examples.

### 7.5 Deposition of Solid Carbon in Soil

Solid carbon, such as bio-coal, biochar or carbon black, can be deposited in soils for long-term sequestration (Fig. 10e). Unlike incorporation into durable products (Sec. 7.4), this approach generally lacks strong economic incentives, except where biochar is applied to enhance soil quality [295, 296] and erosion protection [297]. Most current applications rely on biochar (Sec. 6.1.2) produced via biomass pyrolysis (Sec. 5.1.6) or torrefaction (Sec. 5.1.4) for carbon removal purposes. Other carbon blacks may offer comparable soil benefits, although their carbon is not necessarily of atmospheric origin [298]. Examples of biochar producers for agricultural use are listed in Tab. 6.

## 8 Carbon Pathways

After introducing the conceptual carbon cycle and its pathway building blocks, this section details the pathway abstraction level (Fig. 2, Level 2). As described in Sec. 3, pathway combinations can be assembled from the introduced building blocks based on their color codes or by using the respective building block tables (Tab. 1, 2, 3, 5, and 6). In all

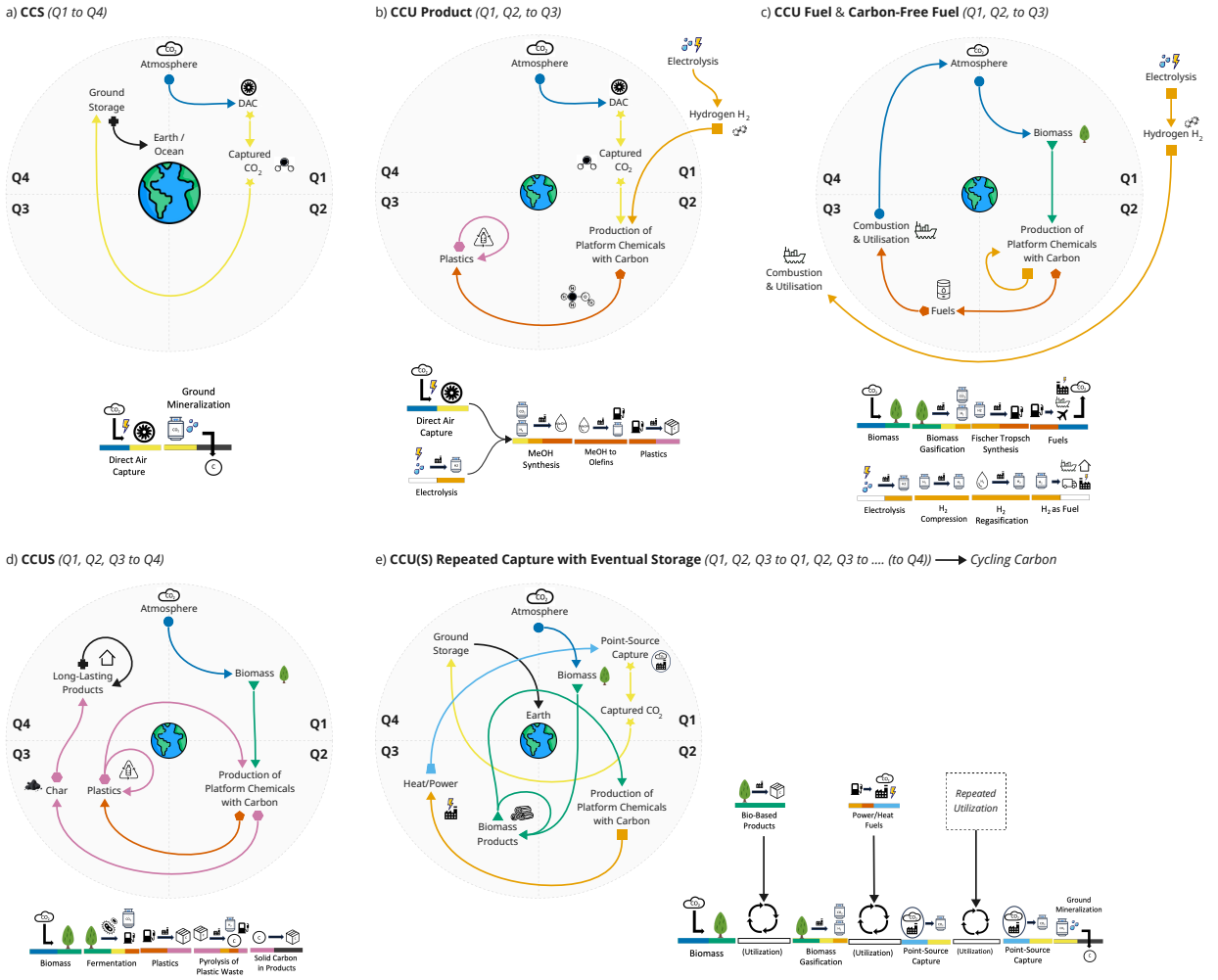



Figure 11: Exemplary pathway configurations within the anthropogenic carbon cycle (Q1–Q4), composed of building blocks and their corresponding color codes. (a) Carbon capture and storage (CCS) from Q1 to Q4; (b) Carbon capture and utilization (CCU) with temporary product storage from Q1 to Q3; (c) CCU fuel pathways without point-source capture from Q1 to Q3; and (d) Carbon capture, utilization, and storage (CCUS) from Q1 via Q3 to Q4. Panel (c) Additionally includes a carbon-free hydrogen pathway for comparison with the CCU fuel pathway, while panel (e) illustrates how repeated carbon capture can retain carbon in the anthropogenic carbon cycle, leading to more complex carbon pathway cycles.

cases, the output of one building block must align with the input of the subsequent one. Although numerous pathway combinations are theoretically possible, they often follow recurring patterns. In the following, we describe the most typical pathway types (Sections 8.1–8.3) and their relationships to the four quadrants of the carbon cycle (Fig. 11).

### 8.1 Carbon Capture and Storage (CCS)

Carbon Capture and Storage (CCS) pathways in this conceptualization involve carbon capture (Q1) followed by permanent storage (Q4), thereby bypassing the conversion and utilization quadrants (Q2 and Q3). In general, CCS pathways aim to remove carbon from the anthropogenic carbon cycle or directly from the atmosphere. When carbon is sourced from the atmosphere via biomass, DAC, or DOC, pathways can achieve a net-negative emission balance and are commonly termed Carbon Dioxide Removal (CDR) [23, 299]. Recent literature also introduces the term Biomass Carbon Removal and Storage (BiCRS) for bio-based CCS pathways [300]. When carbon originates from the anthropogenic carbon-cycle through point-source capture with uncertain, often fossil-based provenance, CCS pathways typically result in a net-zero emission balance. Storage is assumed to be permanent on timescales of hundreds to thousands of years [20], consistent with the storage building blocks described in Sec. 7. Fig. 11a illustrates a representative CCS pathway, in which atmospheric $CO_2$ is captured via DAC (Sec. 4.2) and permanently stored through subsurface mineralization (Sec. 7.2), as exemplified by the Climeworks Orca and Mammoth projects [24, 25].

### 8.2 Carbon Capture and Utilization (CCU)

Carbon Capture and Utilization (CCU) pathways aim to capture $CO_2$ and reuse it as a resource. In this conceptualization, they involve the capture of carbon (Q1) for use in products or fuels (Q3), often passing through Q2 for conversion into platform chemicals. A key distinction for the subsequent assessment of emission balances (Sec. 9) is made between pathways producing durable products that act as temporary carbon sinks (8.2.1) and those producing fuels intended for near-term combustion (8.2.2).

#### 8.2.1 CCU Products

CCU pathways that terminate in products retain carbon temporarily within utilization, but not on timescales sufficient for permanent removal. Fig. 11b illustrates an example in which $CO_2$ is captured via DAC (Sec. 4.2), converted into platform chemicals using $H_2$ produced by electrolysis (Sec. 5.3.1), here via methanol synthesis (Sec. 5.6.1) and olefins (Sec. 5.6.3), and subsequently transformed into plastics (Sec. 6.1.3). In this configuration, plastics act as a temporary reservoir of atmospheric carbon within the anthropogenic carbon cycle. Bio-based alternatives, such as the use of wood in construction, provide analogous temporary storage. Fuels may also be considered products if stored rather than combusted over short timescales (Sec. 8.2.2), although this remains uncommon in practice. Recycling plays a critical role in extending carbon residence times within these temporary sinks.

#### 8.2.2 CCU Fuels

If a CCU pathway ends in fuels intended for near-term combustion, the captured carbon is ultimately released back to the atmosphere, as post-combustion carbon capture is often difficult or infeasible especially in transport applications. Such pathways typically aim to substitute fossil-derived carbon in hard-to-electrify or hard-to-abate sectors, such as transport or selected industrial uses. Fig. 11c illustrates an exemplary pathway in which biomass is converted to syngas via gasification (Sec. 5.1.3), subsequently transformed into bio-based synthetic fuels through Fischer–Tropsch synthesis (Sec. 5.4), and used to replace fossil fuels in transport, with the resulting $CO_2$ ultimately returning to the atmosphere upon combustion.

#### 8.2.3 Carbon-Free Pathways

Carbon-free pathways are not, strictly speaking, CCU pathways, as they do not interact with the carbon cycle. They are nevertheless included here because they represent a direct alternative to CCU fuel pathways (Sec. 8.2.2). These pathways follow hydrogen- or ammonia-based routes when hydrogen is produced via electrolysis using renewable electricity (green hydrogen) or from biological sources, as described in Sec. 5.3, and operate independently of the four quadrants of the conceptualized carbon cycle (i.e., outside the grey circle in Fig. 1). Fig. 11c illustrates such a carbon-free alternative alongside the CCU fuel pathway, in which hydrogen produced by electrolysis (Sec. 5.3.1) is used directly as a fuel in transport or industrial applications, resulting in no direct $CO_2$ emissions at the point of use.

### 8.3 Carbon Capture Utilization and Storage (CCUS)

Carbon Capture, Utilization, and Storage (CCUS) pathways combine carbon capture with an intermediate use phase and eventual permanent storage. Although the term is often used as an umbrella category encompassing both CCU and CCS, it is here defined more specifically within the conceptualized carbon cycle as a progression from Q1 - capture, through Q3 - utilization, and ultimately to Q4 - storage, often including conversion to platform chemicals in Q2. Similar to CCS (Sec. 8.1), CCUS pathways aim to achieve a net-negative emission balance while simultaneously substituting fossil-based carbon products. Compared with direct CCS pathways, carbon typically remains within the anthropogenic carbon cycle for longer periods before permanent storage is achieved.

Fig. 11d illustrates an exemplary CCUS pathway in which biomass is fermented to produce bioethanol (Sec. 5.1.1), subsequently processed into plastic products (Sec. 6.1.3). At end of life, the plastics are thermochemically valorized via pyrolysis (Sec. 5.2.2), and the resulting char (Sec. 6.1.2) is permanently stored in durable products such as concrete (Sec. 7.4).

### 8.4 Carbon Loops: CCU(S) with Repeated Capture and Eventual Storage

Although overlapping with the previously described pathway types, particularly CCUS pathways (Sec. 8.3), the pathway abstraction level allows to represent more complex carbon loops, in which carbon repeatedly cycles through capture (Q1), conversion (Q2), and utilization (Q3) phases before ultimately being released to the atmosphere or permanently stored (Q4).

Fig. 11e illustrates a comparatively simple example of a cycling pathway. Biomass is initially used as a product (Sec. 6.1.1) and subsequently valorized via gasification (Sec. 5.1.3). The syngas is then utilized for combined heat and power production (Sec. 6.3.1), after which the resulting flue gas is captured and $CO_2$ absorbed via point-source capture (Sec. 4.4). From this point, additional conversion and utilization phases may follow before the $CO_2$ is permanently stored through underground cavern storage (Sec. 7.1). Although such pathways may appear complex due to repeated transitions within the carbon cycle, representing them using building blocks clarifies their structure. This representation allows cycling pathways to be decomposed into combinations of CCS, CCU, and CCUS pathway types, thereby facilitating their interpretation.

The conceptualization also facilitates the identification of intersecting pathways by highlighting shared building blocks. For example, the CCUS pathway shown in Fig. 11d intersects with pathway e), as both follow the same sequence up to plastic production. Pathways may further branch into multiple subsequent routes, as illustrated in Fig. 4b: following plastic pyrolysis, the resulting char is stored in long-lived products, while hydrogen is utilized as a fuel in industrial and transport applications. As with cycling pathways, such branching configurations require careful assessment to determine the relevant route for evaluating the overall emission balance.

## 9 Structuring Pathways and Emission Balances

### 9.1 Pathway Assessment based on Emission Balances

The pathways described in Sec. 8 can be qualitatively assessed based on their emission balances (Fig. 2, Level 1), following the principles outlined in Sec. 3.2. Because these balances depend on the carbon trajectory from source to sink or release, pathways can be systematically categorized as **net-negative, net-zero, or net-positive**. Figure 12 presents an overview matrix organized by pathway type (columns: CCS, CCUS, CCU) and carbon source (rows: fossil and atmospheric). While this matrix tracks carbon mass flows, Scope 1–3 pathway emissions (Sec. 9.2), including lifecycle emissions from energy supply, production, transport, and conversion processes, are discussed separately in Sec. 9.2. For comparison, carbon-free hydrogen pathways (e.g., green hydrogen) are included in a fourth row.

### 9.2 Pathway Emissions

Scope 1, 2, and 3 emissions associated with pathway implementation play a critical role in the final carbon balance. By representing **energy, transport, and production** as separate building blocks, Fig. 13 illustrates how reliance on fossil-based inputs can erode climate benefits, potentially shifting a pathway from net-negative to net-zero or even net-positive.

**Origin of Electricity:** Pathway emissions are often driven primarily by energy use (Scope 2 emissions), especially in energy-intensive processes such as electrolysis, DAC, and pyrolysis. If supplied with non-renewable electricity, these processes can dominate the overall footprint.

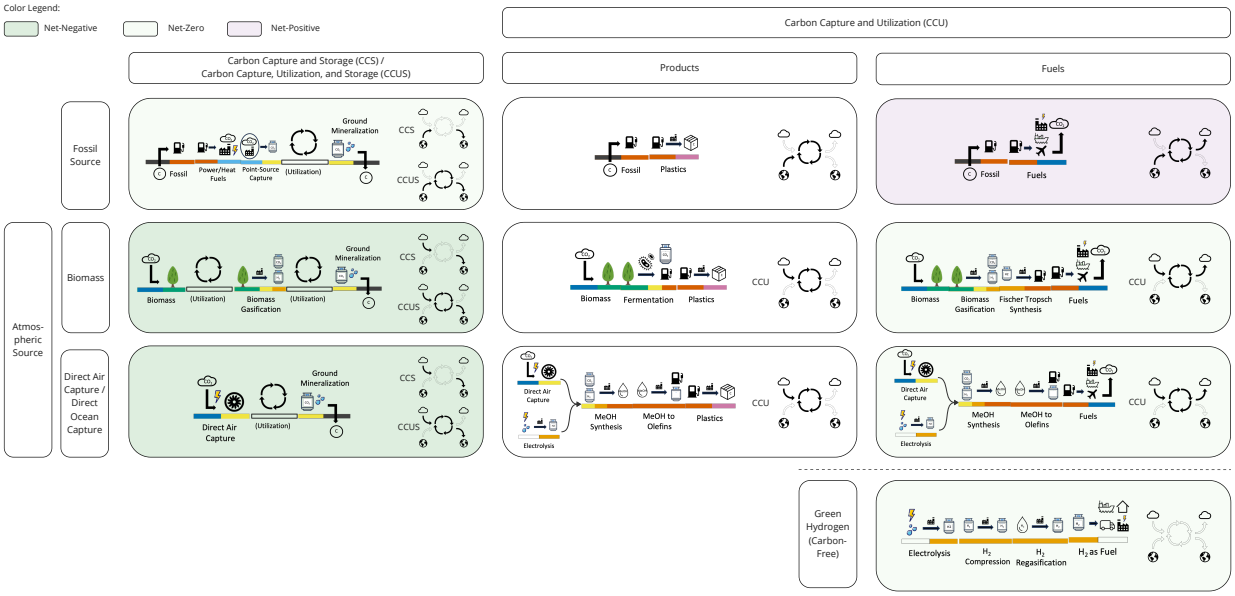



Figure 12: Overview matrix of emission balances by carbon source (rows: fossil, biomass, and DAC/DOC) and pathway type (columns: CCS/CCUS and CCU). Carbon-free "green hydrogen" pathways are shown to be equivalent to net-zero CCU fuel pathways with respect to emission balance.

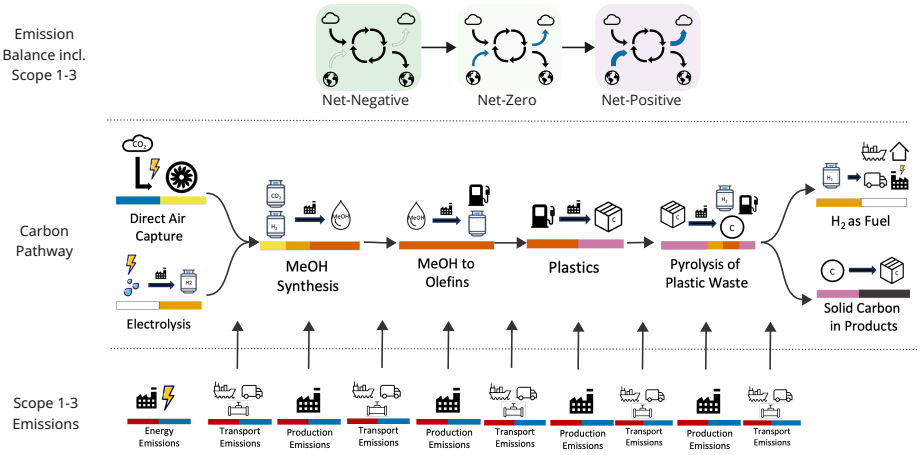



Figure 13: Pathway emissions negatively affect the overall emission balance, shifting it from net-negative to net-zero and ultimately to net-positive when they are fossil-based.

**Transport:** Many carbon management pathways require long-distance transport of gases, fuels, or products due to the geographic separation of process stages (Scope 1 when transport assets are owned or controlled, and Scope 3 when transport is provided by third parties). $CO_2$ must be conveyed from capture to storage or utilization sites, while hydrogen or DAC facilities in renewable-rich but remote regions require distribution to end users. Logistics by pipelines, ships, or trucks can significantly influence both emissions and costs. Reducing transport distances and adopting electrified or renewable-fueled transport are therefore important for lowering associated emissions.

**Production:** Production-related emissions stem from material procurement, technology manufacturing, and industrial operations that often rely on fossil energy. Providing renewable energy inputs, such as solar-driven processes, is crucial for maintaining low emission balances. Beyond direct emissions (Scope 1), production also generates embodied value-chain emissions from material supply and equipment production (Scope 3).

# 10 Discussion

## 10.1 Contextualizing Current Carbon Management Debates

The proposed conceptualization provides a systemic foundation for understanding carbon flows within the interconnected carbon cycle and offers a structured basis for decision-making across multiple levels of abstraction. While a comprehensive analysis of all aspects is beyond the scope of this work, the framework can help clarify key debates. The following sections illustrate how the framework contextualizes selected carbon management topics.

### 10.1.1 Synfuels or Hydrogen?

The debate over basing the economy on carbon-free carriers (hydrogen [16], ammonia [17]) or carbon-based synfuels (e.g., methanol [1]) often centers on infrastructure. While hydrogen requires new distribution networks, synfuels can leverage existing infrastructure [301].

However, our building block analysis (Sec. 5) shows that these are not distinct silos; hydrogen is intrinsically linked to the anthropogenic carbon cycle. It intersects the cycle at multiple points, both as a product of fossil, biomass, or plastic conversion and as a feedstock for methanol, methane, or other hydrocarbon product synthesis. Crucially, this coupling of biogenic or atmospheric carbon with hydrogen enables net-negative utilization pathways if the carbon is ultimately stored long-term, which purely hydrogen-based pathways cannot achieve.

The framework shifts the focus from fuel type to carbon origin. It illustrates that carbon-containing fuels could remain part of a climate-compatible anthropogenic carbon cycle if the carbon is non-fossil and circular. This molecular-level tracking reveals systemic nuances that rigid "color-based" hydrogen classifications (e.g., green vs. blue) often obscure [149], highlighting that the ultimate goal is to integrate fossil-free carbon into the carbon cycle.

### 10.1.2 Biomass or DAC?

In our conceptualization, both biomass (Sec.4.1) and Direct Air Capture (DAC) (Sec.4.2) serve the same function: they act as gateways for atmospheric carbon to enter the anthropogenic cycle. Once captured, the carbon follows similar trajectories through conversion (Q2) to utilization (Q3) or storage (Q4), yielding equivalent net-zero or net-negative outcomes. The distinction lies in the limiting factors. Biomass pathways are mainly constrained by feedstock availability, sustainability, and land-use impacts [77, 78], whereas DAC pathways are limited by their high energy demand and current technological maturity [35, 39].

Consequently, the framework illustrates that there is no single "best" capture technology. Instead, the modular nature of the building blocks enables swapping and comparison of these sources within larger pathway configurations. This flexibility suggests that identifying the most suitable capture method depends on regional constraints and policy goals, and should consider further in-depth assessment of socio-techno-economic life-cycle impacts (see also Sec. 10.2).

### 10.1.3 Removal, Storage, or Utilization?

Inconsistent terminology often hampers carbon management discussions. Our four-quadrant framework (Sec. 2) offers a precise nomenclature based on carbon flow logic, distinguishing clearly between removal outcomes, storage mechanisms, and utilization processes.

**Removal (CDR)**: While Carbon Dioxide Removal (CDR) is often associated with direct capture and storage (CCS) bypassing utilization (Sec. 8.1), our framework defines it by the net outcome rather than the specific technology. Consistent with IPCC definitions [23], any pathway sourcing atmospheric carbon (Q1) and achieving permanent storage (Q4) qualifies as removal. This broadens the scope to include CCUS pathways (Sec. 8.3) that pass through utilization stages but still result in a net-negative balance.

**Storage**: The term "storage" is often applied ambiguously to both permanent sequestration and temporary retention in products. To resolve this, our framework imposes a strict durability criterion for Q4 (Storage), aligning with the 1000-year permanence benchmark [20]. Consequently, we distinguish between chemically stable storage (e.g., mineralization in concrete, Sec. 7.4) which falls under Q4, and temporary retention in biogenic or synthetic materials (e.g., wooden buildings [234] or plastics), which falls under Q3 (Utilization). This distinction is critical: while bio-based materials provide valuable temporary retention (approx. 70 years in the case of buildings [302]), they remain chemically reversible (e.g., via incineration or decay), unlike the permanent sinks in Q4.

**Utilization**: In this conceptualization, Utilization (Q3) refers to the functional use of carbon within the technosphere, either for energy (fuels) or for material applications (products), regardless of the carbon's origin. This systemic view departs from some definitions that limit utilization to recycled point-source emissions [47]. For instance, while

Bioenergy with Carbon Capture and Storage (BECCS) is primarily categorized as a removal strategy [15], our framework explicitly recognizes the intermediate utilization step (combustion for energy, Q3) that precedes storage. This highlights that "utilization" and "removal" are not mutually exclusive categories, but often sequential steps in a single pathway.

### 10.2 Limitations and future perspectives

**Abstraction vs. Granularity**: The proposed framework prioritizes systemic clarity over process-level granularity. While color-coding facilitates the identification of viable pathways, the abstraction intentionally simplifies thermodynamic interfaces (e.g., pressure levels, phase states) and complex branching streams. Navigating these engineering details still requires domain expertise; however, including them at this conceptual level would obscure the systemic interconnections the framework aims to reveal.

**Evolving Technology**: The library of 46 building blocks represents a comprehensive snapshot of the current technological landscape. As carbon management is a rapidly evolving field, the library is designed to be extensible. Future work can systematically expand the repository to include emerging technologies, ensuring the framework remains a living document that evolves alongside the sector.

**Platform-Based Design**: Adopting a platform-based design perspective provides a robust theoretical foundation for this conceptualization. By treating the anthropogenic carbon cycle as a modular system rather than a set of linear chains, it establishes a basis for advanced computational tools. This approach enables software-based exploration of pathway configurations, linking high-level emission goals directly to engineering constraints.

**From Qualitative to Quantitative**: Currently, the framework focuses on qualitative carbon mass balances (Level 1). While it does not explicitly track non-carbon GHG emissions (e.g., methane leakage, $N_2O$) or Scope 1–3 pathway emissions (Sec. 9.2), its modular structure is compatible with Life Cycle Assessment (LCA) methodologies. Future research should link these qualitative building blocks with empirical inventory data. As illustrated by recent studies [199, 303, 304], rigorous LCA is complex and thus often limited to a small subset of pathways. Nevertheless, the framework provides a standardized structural basis for comparing pathways and aggregating system-wide emission data.

## 11 Conclusion

This study establishes a unified framework for the anthropogenic carbon cycle, structuring 46 technological building blocks into four functional quadrants: Capture, Conversion, Utilization, and Storage. By integrating traditionally isolated concepts such as CCS, CCU, and hydrogen pathways into a single systemic model, the framework reveals critical intersections and synergies that are often obscured in linear analyses.

The three-level abstraction hierarchy bridges the gap between engineering reality and climate policy, enabling users to navigate from specific technologies (Level 3) to pathway configurations (Level 2) and high-level emission balances (Level 1). A fundamental insight of this work is the need for a paradigm shift: carbon must be treated not only as an emission to be eliminated, but as a circular resource to be managed. Effective decarbonization therefore requires systematic tracking of carbon flows across sectors, rather than focusing solely on end-of-pipe emissions.

While this conceptualization necessarily simplifies technical complexities, it provides the essential architecture for a coherent, system-wide understanding of carbon management. Future work should leverage this foundation to design robust policy instruments, guiding the incentives, investments, and certification mechanisms required to build a truly circular carbon economy.

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## Declarations

**CReDiT Statement** The contributions of the authors are provided following the CRediT author statement [305]. **Jens Hunhevicz:** Conceptualization, Methodology, Validation, Investigation, Data curation, Writing - Original Draft, Writing - Review & Editing, Visualization **Florian Kiefer:** Conceptualization, Methodology, Validation, Investigation, Data curation, Writing - Original Draft, Writing - Review & Editing, Visualization **Matthias Sulzer:** Conceptualization, Methodology, Validation, Writing - Review & Editing, Visualization

**Competing interests** The authors declare no competing interests.

**Generative AI and AI-assisted technologies in the writing process** During the preparation of this work the authors used ChatGPT 5.2 and 5.3 in order to increase clarity. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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