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A modular building-block framework for navigating circular carbon pathways

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Effective decarbonization and carbon removal require tools that facilitate holistic yet detailed decision-making across interconnected carbon pathways; however, existing research often isolates technologies and focuses on linear process chains. To bridge this gap, we present a modular framework for carbon pathways based on process interfaces. Through an adapted iterative taxonomy-development method, we decompose and abstract the anthropogenic carbon cycle into 40 technological building blocks defined by their input and output streams. From this component library, pathway configurations can be assembled and classified by carbon source and fate (Carbon Capture and Storage, CCS; Carbon Capture and Utilization, CCU; Carbon Capture Utilization and Storage, CCUS) and categorized by their resulting carbon balances (net-negative, net-zero, net-positive). The resulting three-level abstraction model links policy-relevant carbon balances to pathway configurations and specific technologies, enabling flexible navigation between emerging technologies and established circular value chains and revealing synergies and trade-offs. The framework equips decision-makers with a practical tool to design and assess systemic circular carbon strategies.

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Sustainability spotlight

Limiting global warming demands both rapid emission reductions and active CO₂ removal, yet research typically examines individual carbon management technologies in isolation, obscuring critical synergies and trade-offs. Our work addresses this gap by presenting a systemic framework that maps the anthropogenic carbon cycle into 40 technological building blocks spanning capture, conversion, utilization, and storage. By integrating the energy sector with materials production, recycling, and negative emission technologies, the framework enables assembly of complete pathways yielding net-negative, net-zero, or net-positive carbon balance outcomes. Treating carbon as a circular resource, it equips policymakers and engineers with a practical tool to compare strategies and design integrated carbon management systems. Our work emphasizes the importance of the following UN Sustainable Development Goals: affordable and clean energy (SDG 7), industry, innovation, and infrastructure (SDG 9), responsible consumption and production (SDG 12), and climate action (SDG 13).

1 Introduction

Over the past two centuries, human-driven carbon extraction has established a parallel anthropogenic carbon cycle¹ 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 CO₂, 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 CO₂ 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 economies¹⁷ stress the need for more systemic attempts to reduce fossil dependence. However, achieving rapid and comprehensive transitions requires

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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 framework for carbon pathways based on process interfaces that systematizes the anthropogenic carbon cycle into four quadrants: capture, conversion, utilization, and storage. Using an adapted iterative taxonomy-development method, we decompose the cycle into 40 technological building blocks defined by their input and output streams. These blocks form a component library from which diverse pathway configurations (CCS, CCU, CCUS) can be assembled and classified by carbon source and fate to yield their carbon-balance outcome (net-negative, net-zero, net-positive), linking high-level policy objectives to the specific technologies required to achieve them.

The primary novelty of this work lies in its departure from linear, technology- or pathway-specific analyses towards a systemic perspective. Treating the carbon cycle as an interconnected system and its pathways as combinations of building blocks highlights the intersections, circular loops, and system-wide dependencies. This allows decision-makers to evaluate individual technologies, the pathways they enable, and the resulting carbon balance outcomes.

2 Proposed conceptualization of the anthropogenic carbon cycle

This section presents the conceptual layer of the modular framework. The carbon cycle is organized into four quadrants: Q1 – capture (Section 2.1), Q2 – conversion (Section 2.2), Q3 – utilization (Section 2.3), and Q4 – storage (Section 2.4). Carbon-bearing and carbon-free streams are categorized into eight types, indicated by the color code in Fig. 1. The gray inner circle represents carbon-based pathways, while carbon-free pathways such as hydrogen and ammonia are shown outside the circle. The quadrants and stream types provide the structural basis for defining the technological building blocks (Sections 5–8) and for constructing complete carbon pathways (Section 9).

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.[†] Environmental sources include atmospheric CO₂ 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 (CH₄), methanol (CH₃OH), and syngas (CO + H₂), 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 CO₂, either electrochemically or using hydrogen (H₂). 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, CO₂ and/or H₂ can be converted into a platform chemical for transport *via* existing infrastructure, then converted into other materials or decomposed after transport to recover H₂ and CO₂ 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, red), chemicals, and materials such as plastics, char, and carbon black (Fig. 1, red), 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).[‡] This removal is achieved through two principal strategies: long-term geological sequestration of captured CO₂, 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

[†] 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.

[‡] 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

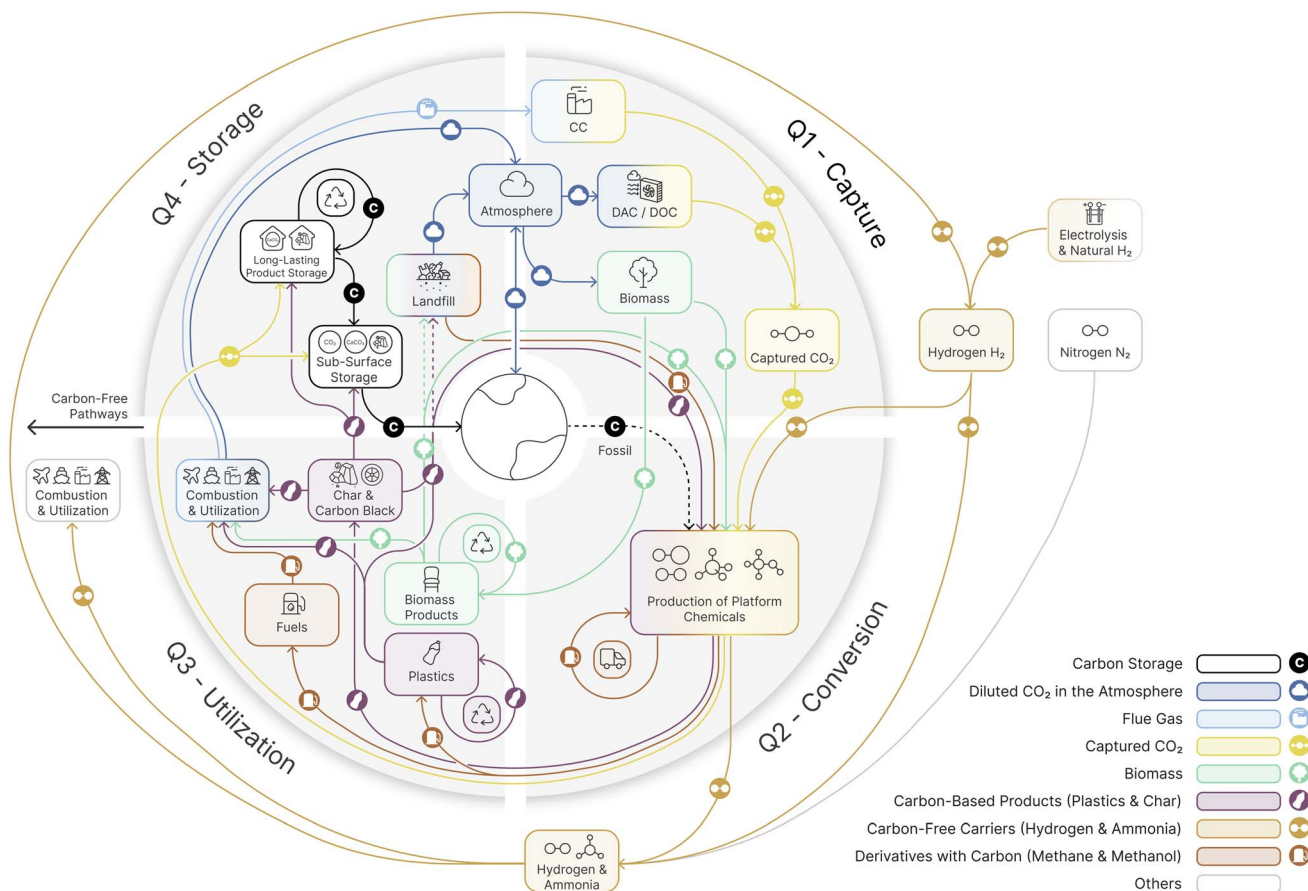


Fig. 1 Conceptual layer of the modular building block framework for the anthropogenic carbon cycle. The cycle is organized into four functional quadrants: Q1 – capture, Q2 – conversion, Q3 – utilization, and Q4 – storage. Carbon-bearing and carbon-free streams are categorized into eight types (color-coded; see legend). The gray inner circle represents carbon-based pathways, while carbon-free pathways such as hydrogen and ammonia are shown outside the circle.

products such as concrete and building materials, provided they do not release CO₂ at their end-of-life¹⁴ (Fig. 1, black).

3 Methodology

We adopt the taxonomy-development method of Nickerson *et al.*,²¹ incorporating its *meta*-characteristics and iterative structure with ending conditions, while adding domain-specific rules for merging and exclusion (see Fig. 2).

3.1 Point of departure and *meta*-characteristic

Conventionally, carbon management pathways are distinguished as CCS, CCU, and CCUS, with their climate relevance expressed as net-negative, net-zero, or net-positive emission balances. Both distinctions come down to where carbon enters and leaves the cycle, yet neither comes with a systematic account of the underlying technologies. We therefore asked which technological decomposition would populate this classification, inverting the usual direction that Nickerson *et al.*²¹ accommodate as a conceptual-to-empirical first pass. The resulting taxonomy classifies pathways by carbon source and fate, read from their starting and ending building blocks (Fig. 12).

The intended users are decision-makers who need to consider different technological choices, pathway configurations, and emission balances. The framework serves two purposes: classifying pathways by carbon source and fate, and representing the technological space in sufficient detail to enable representative pathways to be assembled from it. We define the *meta*-characteristic as “the transformation a process performs on carbon-bearing streams within the anthropogenic carbon cycle”, from which the stream typology, quadrant assignment, and block granularity follow.

3.2 Sourcing, decomposition, and rules

Pathways were identified using a seed-and-snowball strategy.²² This involved starting with well-established concepts (CCS, CCU, and the methanol, hydrogen, and ammonia economies) and then expanding through citation tracking and industry documentation of operating and demonstration-scale installations. We then broke these pathways into process steps, each characterized by its input and output streams, listed in Tables 1–6. Building blocks were merged when their carbon-containing input and output interfaces and their pathway functions were equivalent (*e.g.*, steam explosion and biomass torrefaction, which differ in reactor design but not in their input and output

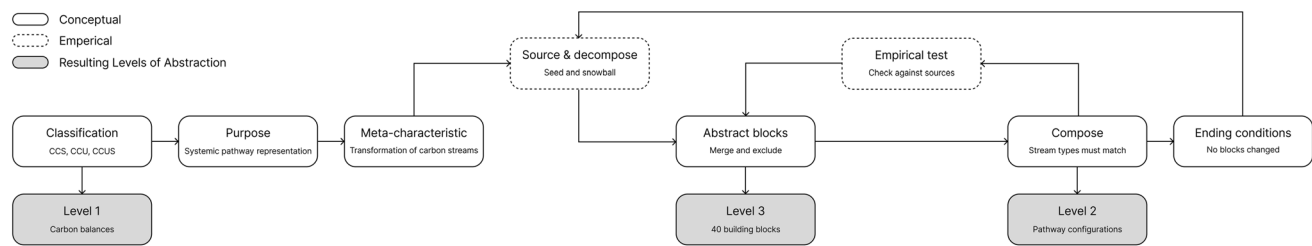


Fig. 2 Development of the framework adopting the taxonomy-development method of Nickerson *et al.*,²¹ alternating between conceptual-to-empirical and empirical-to-conceptual passes until no blocks were added, merged, or split. The three levels of abstraction emerged at different points: the classification taken as the point of departure (Level 1), the block library resulting from block abstraction (Level 3), and the pathway configurations obtainable through the composition rule (Level 2).

streams). We retained processes with the same broad stream types but different principal products or sink mechanisms separately when those differences affect downstream pathway construction, storage permanence, or policy interpretation (*e.g.*, methanol synthesis *vs.* methane synthesis; geological injection *vs.* *in situ* mineralization). They were excluded if they did not act on a discrete stream that could be exchanged with another block (*e.g.*, enhanced rock weathering, which binds dilute atmospheric CO₂ in spread minerals with no stream to pass on, see also Section 8). Blocks were also excluded on relevance grounds (*e.g.*, deep-sea injection, see also Section 8). The resulting library of 40 blocks forms the most detailed level of the framework (Level 3).

The final building blocks are composable, with the output stream of one matching the input of the next, making pathway construction systematic. Applied to the library, this rule allows generating pathway configurations that connect individual technologies to the above-defined classification (Level 2 of the framework), providing a basis for future computational pathway generation. However, this does not automatically establish

technical feasibility, since factors such as pressure, temperature, purity, conversion efficiency, energy demand, and material compatibility are not represented at this level of abstraction (see Section 11.2).

3.3 Iterative development and ending conditions

Development alternated between conceptual-to-empirical passes, in which the quadrant structure, stream typology, and building blocks were tested against documented technologies, and empirical-to-conceptual passes, in which documented installations and pathways were decomposed and abstracted into blocks. Iteration continued until the objective and subjective ending conditions were met.

The objective ending condition was that no blocks were added, merged, or split in the final iteration. The subjective conditions were assessed as follows. The library is concise, comprising decision-relevant technology choices; robust, in that the blocks are fine-grained enough to distinguish pathways with different outcomes; comprehensive, in that documented configurations are reconstructible from it; extendible, in that

Table 1 The five building blocks of Q1 capture

Building block	Input	Output	Examples
Biomass growth 5.1	Air (CO ₂)	Biomass	Climeworks Orca ²⁷
Direct air capture (DAC) 5.2	Air (CO ₂)	Captured CO ₂	Climeworks Mammoth ²³ 1PointFive Stratos ²⁸
Direct ocean capture (DOC) 5.3	Ocean water	Captured CO ₂ CaCO ₃	Brineworks ²⁹ Captura ³⁰ SeaO ₂ (ref. 31)
Point-source carbon capture (CC) 5.4	Flue gas	Captured CO ₂	See Table 5
Landfill with gas recovery 5.5	Biomass Plastics	CH ₄ /CO ₂ to air Methane	Rumpke Sanitary ³² Olinda ³³

Table 2 Part 1 of Q2, conversion: nine building blocks for the biomass and plastics routes. The fossil building block is included for completion and does not count toward the total building block count

Building block		Input	Output	Examples
Fossil (not counted)		Fossil	Fuel	
Fermentation 6.1.1		Biomass	Captured CO ₂ Ethanol	Bonanza bioenergy ⁵⁸ POET plants ⁵⁹ South bend ethanol ⁶⁰
Anaerobic digestion 6.1.2		Biomass	Captured CO ₂ Methane	Apsley farms ⁶¹ Nesselbach plant ⁶² Limeco powerToGas ⁶³
Biomass gasification 6.1.3		Biomass	Captured CO ₂ Syngas	Güssing plant ⁶⁴
Biomass torrefaction 6.1.4		Biomass	Captured CO ₂ Bio-coal	Duiven plant ⁶⁵ Arbafame arbaone plant ⁶⁶
Biomass liquefaction 6.1.5		Biomass	Bio-oil Hydrochar	Chuntoh ghuna ⁶⁷ Licella GS-1 (ref. 68)
Biomass pyrolysis 6.1.6		Biomass	Syngas Bio-oil Biochar	Valmet R&D center ⁶⁹ TSK pyrolysis plant ⁷⁰
Plastic waste gasification 6.2.1		Plastics	Captured CO ₂ Syngas	SVZ Schwarze Pumpe ⁷¹ Kawasaki plant ⁷² InEnTec Columbia Ridge ⁷³
Plastic waste pyrolysis 6.2.2		Plastics	Syngas Liquid-oil Char	Arcus plant ⁷⁴ Beston 30 T/D ⁷⁵ Sapporo plant ⁷⁶
Plastic waste liquefaction 6.2.3		Plastics	Liquid oil (Char)	OMV ReOil ⁷⁷ Carboliq pilot ⁷⁸

new technologies can be added without requiring structural change; and explanatory, in that a block's quadrant and stream types indicate its systemic function without requiring process-level detail. Exemplary installations (Tables 1–6) provide the empirical grounding for the blocks. Section 4 describes the three levels and the navigation they support.

4 Levels of abstraction

4.1 Navigating the levels of abstraction

To navigate the solution space of carbon pathway configurations (Fig. 1), the three levels introduced above provide a structured design foundation (Fig. 3). While not a strict implementation of platform-based design,^{24,25} the framework

adopts key concepts from this theory. 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).

Table 3 Part 2 of Q2 conversion: six building blocks for the hydrogen and ammonia routes

Building block		Input	Output	Examples
Electrolysis 6.3.1		Electricity Water	H ₂ (g)	OMV plant ¹²⁶ NEOM project ¹²⁷ Envision Chifeng plant ¹²⁸
Co-electrolysis 6.3.2		Captured CO ₂ Electricity Water	Syngas	Arnstadt SOEC pilot ¹²⁹ Sunfire pilot ¹³⁰
Reverse water gas shift 6.3.3		Captured CO ₂ H ₂	Syngas	Ineratec ERA ONE ¹³¹
Fischer Tropsch synthesis 6.4		Syngas	Liquid synfuel	Ineratec synhelion ¹³² DG fuels plant ¹³³ Sasol secunda CTL plant ¹³⁴
Ammonia synthesis (Haber-Bosch) 6.5.1		H ₂ N ₂	NH ₃	Envision Chifeng plant ¹²⁸ NEOM project ¹²⁷ Jilin electric plant ¹³⁵
Ammonia decomposition 6.5.2		NH ₃	H ₂ N ₂	Mitsubishi pilots ¹³⁶

4.2 Level 1: emission balances

At the highest level of abstraction, pathways are classified by their net carbon balance, a metric particularly relevant for policymakers when considering pathway emissions. This classification addresses the carbon balance of the pathway and does not account for secondary greenhouse gas (GHG) emissions (see

Section 10.1); a net-negative classification is a necessary but not sufficient condition for carbon removal.

Fig. 4 illustrates the emission balances resulting from the pathway's source (Q1) and sink (Q3/Q4). We define the sign convention relative to the atmosphere: removal or storage is

Table 4 Part 3 of Q2 conversion: six building blocks for the methanol and methane routes

Building block		Input	Output	Examples
Methanol synthesis 6.6.1		H ₂ /syngas Captured CO ₂	MeOH	Kassø plant ¹⁷⁸ Tianying plant ¹⁷⁹ Mexinol project ¹⁸⁰
Methanol steam reforming 6.6.2		MeOH	H ₂ Captured CO ₂	HYGEAR Hy.GEN ¹⁸¹ Mahler Hydroform-M ¹⁸²
Methanol to olefins 6.6.3		MeOH	Olefins	Baotou plant ¹⁸³ Zhongtian Hechuang plant ¹⁸⁴
Methane synthesis 6.6.1		H ₂ /syngas Captured CO ₂	CH ₄	Hycamite plant ¹⁸⁵ Limeco powerToGas plant ⁶³
Methane steam reforming 6.7.2		CH ₄	H ₂ Captured CO ₂	Shell quest plant CC ¹⁸⁶ Port arthur II plant ¹⁸⁷ Synhelion dawn ¹⁸⁸
Methane pyrolysis 6.7.3		CH ₄	H ₂ Carbon black	Ekona pilot ¹⁸⁹ Graphitic C-zero pilot ¹⁹⁰ Tech Cluster Zug pilot ¹⁹¹

Table 5 The nine building blocks of Q3 utilization

Building block		Input	Output	Examples
Biomass products 7.1.1		Biomass	Biomass products	
Char & carbon black in products 7.1.2		Char Carbon black	Char products Carbon black products	
Plastics and other 7.1.3		Fuel	Plastics	
Ammonia-based products 7.1.4		NH ₃	NH ₃ -based product	
Synthetic and bio-fuels 7.2.1		Fuel	CO ₂ to air Heat	
Hydrogen as fuel (carbon-free) 7.2.2		H ₂	Water Heat	
Power plants & industry 7.3.1		Syngas Fuel Char/coal	Flue gas Power/heat	Boundary dam unit 3 (ref. 219) Mikawa plant ²²⁰ Stockholm exergi ²²¹
Waste incineration 7.3.2		Biomass products Plastics	Flue gas Power/heat	Klemetsrud plant ²²² AVR duiven ²²³ Hafslund celsio ²²⁴
Cement plant 7.3.3		CaCO ₃ Fuel	Flue gas Cement	Holcim GO4ZERO ²²⁵ Brevik plant ²²⁶ CLEANKER ²²⁷

“negative”, while fossil extraction or release is “positive”, in line with IPCC conventions.²⁶

- Net-negative: the pathway sources atmospheric carbon and permanently stores it (Fig. 4a). The net balance is negative, effectively reducing atmospheric CO₂. These correspond to carbon-dioxide-removal (CDR) pathways, whether they bypass utilization (CCS) or pass through it (CCUS).

- 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. 4c); or (2) fossil-based pathways where the carbon is captured and permanently stored (Fig. 4d).

- Net-positive: the pathway sources fossil carbon and releases it to the atmosphere (Fig. 4f), resulting in a net increase in atmospheric CO₂.

Pathways ending in products (*e.g.*, plastics) represent a temporary state, with the final balance depending on end-of-life fate. Atmospheric sourcing gives a temporary balance that is net-negative (stored in product) or net-zero (circular use) (Fig. 4b); fossil sourcing gives a temporary net-zero (stored in product) or net-positive balance (delayed release) (Fig. 4e).

Temporary retention in products (Q3) must therefore be separated from permanent storage (Q4) when assessing removal claims.

4.3 Level 2: pathways

The mid-level of abstraction focuses on pathway configurations, connecting carbon capture (Q1) to final storage (Q4) or utilization and release (Q3). Pathways are constructed by assembling building blocks from the component library (Level 3) according to the composition rule given in Section 3. The color-coding in Fig. 1 provides a visual guide. This allows structured comparison of pathways, which is particularly relevant for regulation, system design, and holistic assessment. It also serves as a critical link between technological realities (Level 3) and carbon-balance categories (Level 1).

Fig. 3 illustrates two configurations to demonstrate the framework. Although both pathways start with Direct Air Capture (DAC), their trajectories diverge significantly. Pathway (a), representing the Climeworks Mammoth project,²³ moves directly from capture to storage (CCS). In contrast, Pathway (b),

Table 6 The five building blocks of Q4 storage

Building block		Input	Output	Examples
CO ₂ ground injection 8.1		Captured CO ₂	CO ₂ in ground	Northern lights ²⁵¹ Aramco Jubail ²⁵²
<i>In situ</i> mineralization 8.2		Captured CO ₂	CaCO ₃ in ground	Carbfix ²⁵³ Big sky carbon ²⁵⁴
Product mineralization 8.3		Captured CO ₂	CaCO ₃ in product	CarbonBuilt ²⁵⁵ Neustark ²⁵⁶ CarbonCure ²⁵⁷
Solid carbon product deposition 8.4		Solid carbon	Solid carbon in product	Alterbiota ²⁵⁸ Pyrogen ²⁵⁹
Solid carbon ground deposition 8.5		Solid carbon	Solid carbon in ground	AirEx energy biochar ²⁶⁰ Swiss biochar ²⁶¹

representing the “Mining the Atmosphere” vision,¹⁴ includes conversion and utilization steps (CCUS) before final storage.

utilization or storage, as summarized in Table 1 and detailed as process diagrams in Fig. 5.

4.4 Level 3: building blocks

The most detailed level of abstraction consists of the building blocks: a component library of 40 technological units organised by quadrant (Sections 5–8), comprising 5 in Q1, 21 in Q2, 9 in Q3, and 5 in Q4. The fossil building block (Table 2) is included for completeness and excluded from this total. Each block represents a specific process step and is defined by its input and output streams (color-coded in Fig. 3 to match the cycle in Fig. 1).

This level enables examination of individual technologies and their interfaces. 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.

The remainder of the manuscript proceeds bottom-up, starting from these building blocks (Level 3), assembling them into pathway configurations (Level 2), and evaluating carbon-balance outcomes (Level 1). In the following, we describe the blocks for each quadrant and illustrate their input–output interfaces and representative implementations (Fig. 5–10).

5 Building blocks quadrant 1: capture

First, we introduce the building blocks for carbon capture (Section 2.1), including biomass growth and four technological building blocks that capture atmospheric CO₂ or circulate carbon within the anthropogenic carbon cycle for subsequent

5.1 Biomass growth

As trees and plants grow, they absorb atmospheric CO₂ 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,^{34,35} acting as a temporary or potentially long-term carbon sink, depending on subsequent use and management.^{36–38} Biomass thus serves as a key input for the biomass-route in Q2 (Section 6.1) or for bio-based products in Q3 (Section 7.1.1), and can be seen as the natural counterpart to DAC and DOC (Sections 5.2 and 5.3).

5.2 Direct air capture (DAC)

Direct Air Capture (DAC) removes CO₂ directly from ambient air. Current systems use engineered contactors with liquid solvents or solid sorbents to capture and subsequently release high-purity CO₂ for storage or utilization.^{39–41} Typically, CO₂ 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 CO₂ 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.^{42,43} Selected examples are listed in Table 1.

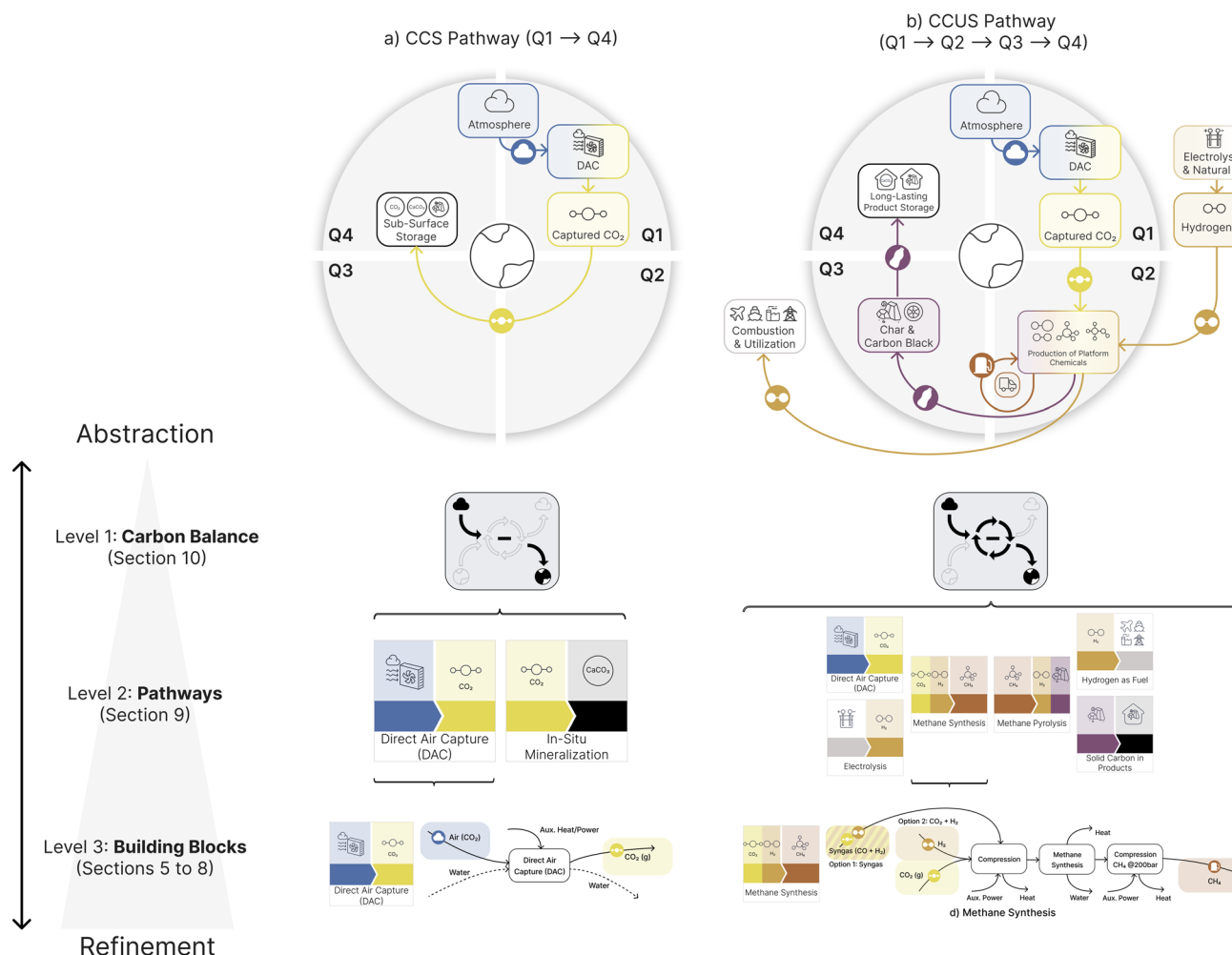


Fig. 3 Three abstraction levels of the modular building-block framework for carbon pathways. Technological building blocks (Level 3) form a component library that can be assembled into pathway configurations (Level 2) to determine their carbon-balance outcomes (Level 1). This structure supports the alignment of emission policies with specific technologies (refinement) and the qualitative comparison of pathways across technological options (abstraction). (a) A direct net-negative CCS pathway (e.g., Climeworks' Mammoth project²³); (b) a net-negative CCUS pathway integrating conversion to methane for transport and subsequent utilization (hydrogen) and storage (char) (e.g., Mining the Atmosphere¹⁴).

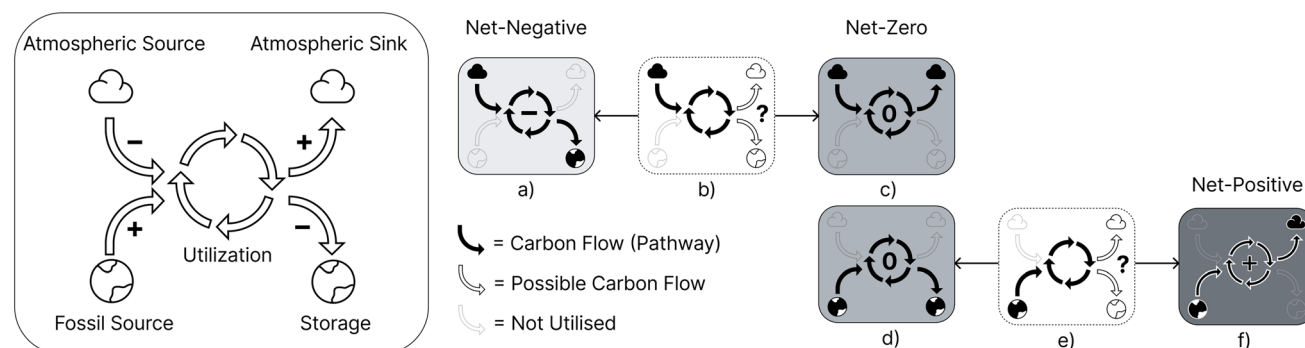


Fig. 4 Carbon-balance outcomes of pathways based on their source and sink. The net carbon balance relative to the atmosphere is shown for different combinations of carbon source (atmospheric vs. fossil) and final fate (permanent storage vs. release). Pathways are classified as net-negative [(a), net = 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.

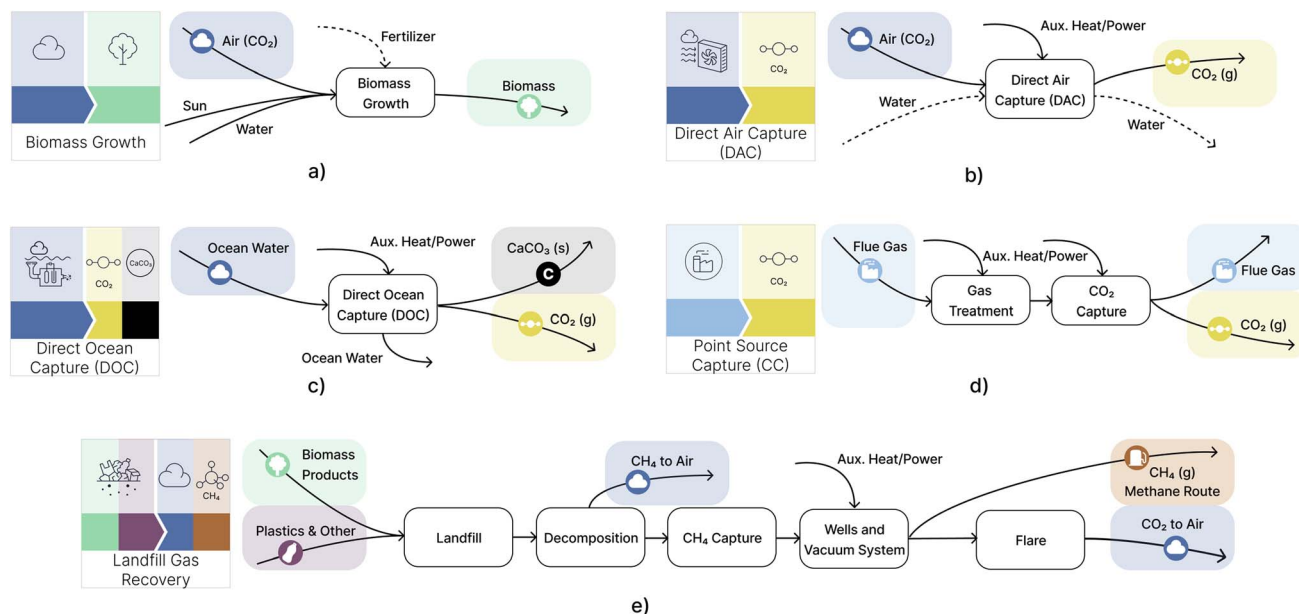


Fig. 5 Process diagrams of Q1 building blocks. (a) biomass growth; (b) direct air capture (DAC); (c) direct ocean capture (DOC); (d) point-source carbon capture (CC); (e) landfill gas recovery.

5.3 Direct ocean capture (DOC)

Oceans constitute a major sink for anthropogenic CO_2 , absorbing approximately 30% of global emissions.⁴⁴ Direct Ocean Capture (DOC) removes dissolved CO_2 by shifting carbonate speciation in seawater, typically *via* electrochemical pH-swing processes.^{45–47} 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 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 Table 1.

5.4 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.⁴⁸ 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,⁴⁹ and can contribute to decarbonizing hard-to-abate sectors when coupled with storage (Q4).^{48,50–52} Various technical approaches are available, including absorption, adsorption, membrane separation, cryogenic processes, and electro-swing methods.^{48,53} 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 Table 5 under Q3 utilization (Section 7.3).

5.5 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,⁵⁴ 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 (Section 7.3.1), or upgraded to renewable natural gas (Section 6.7). Unlike sealed anaerobic digestion (Section 6.1.2), landfill systems are less efficient, and even well-managed sites typically capture only about 85% of methane emissions.^{55–57} Selected examples are listed in Table 1.

6 Building blocks quadrant 2: conversion

Quadrant Q2 (Section 2.2) encompasses the conversion of raw carbon inputs from Q1 into platform chemicals, substituting fossil carbon sources (Fig. 1, dotted black line in Q2) with captured atmospheric or recycled carbon. A “Fossil” building block is included for completeness (Table 2, first row), but the focus is on the alternative conversion routes organized into biomass (Section 6.1), plastics (Section 6.2), hydrogen (Section 6.3), ammonia (Section 6.5), methanol (Section 6.6), and methane (Section 6.7). All 21 building blocks are listed in Tables 2 and 3 and shown as process diagrams in Fig. 6, 7, and 8.

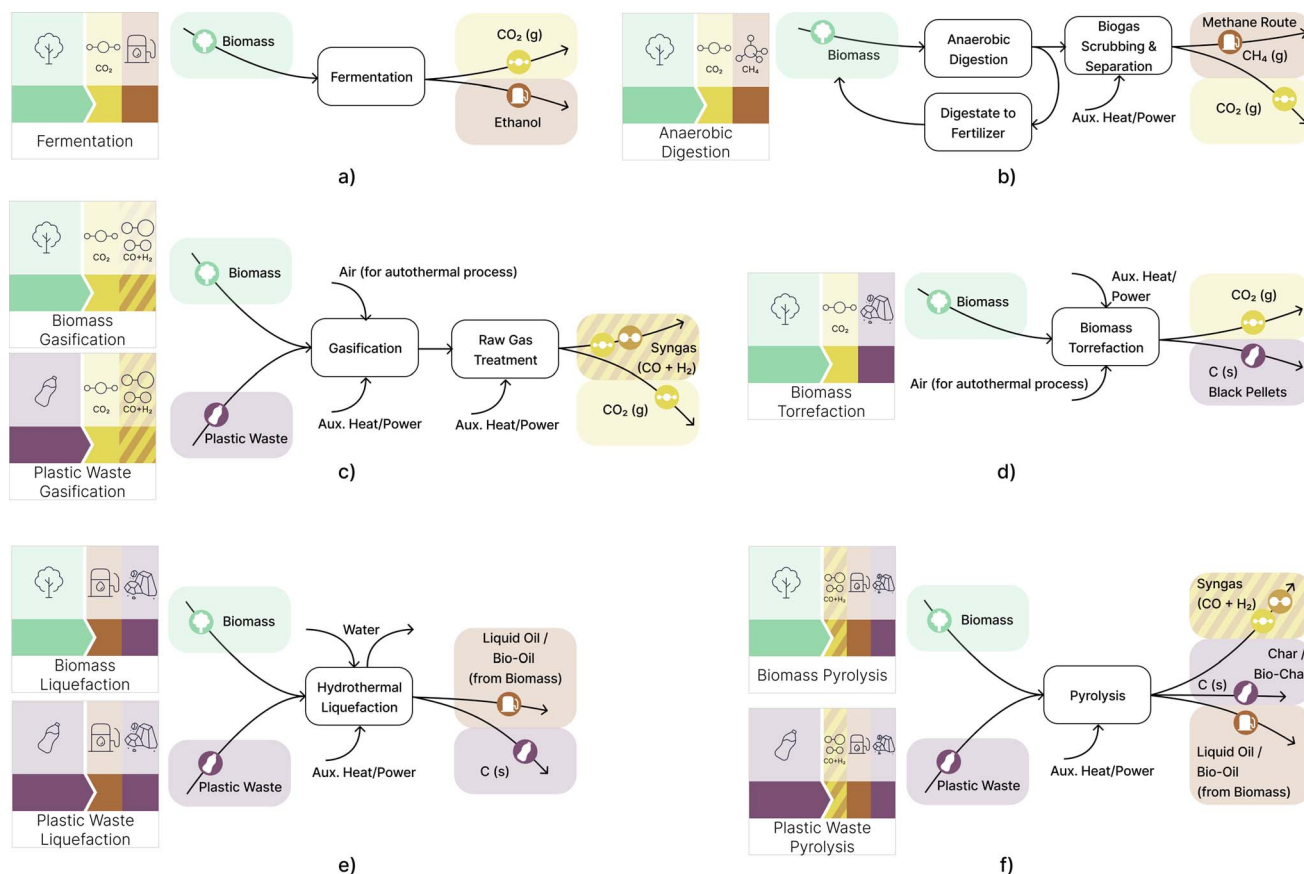


Fig. 6 Part 1 of Q2 process diagrams illustrating the biomass and plastic routes: (a) fermentation; (b) anaerobic digestion; (c) biomass and plastic waste gasification; (d) biomass torrefaction; (e) biomass and plastic waste liquefaction; (f) biomass and plastic waste pyrolysis.

6.1 Biomass route

The biomass route lists identified building blocks to convert biomass (Section 5.1) into platform chemicals *via* thermochemical and biochemical processes. Beyond direct energy use (Section 7.3.2) and bio-based products (Section 7.1.1), 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.^{79–81}

6.1.1 Fermentation. Fermentation of biomass is a biological process in which microorganisms convert sugars primarily into ethanol and CO₂ (ref. 82) (see Fig. 6a). Ethanol serves as a major pathway for biofuel production⁸³ and can be further processed to bio-ethylene *via* ethanol dehydration,⁸⁴ linking biomass fermentation to established petrochemical value chains for plastics and chemical products. Meanwhile, the relatively high-purity CO₂ stream released during fermentation can be captured, compressed, and dehydrated for subsequent utilization or storage.^{85–87} In the United States, several bio-ethanol facilities already capture CO₂, and large-scale pipeline infrastructure is under development to transport it.⁸⁸ Selected examples are listed in Table 1.

6.1.2 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.⁸⁹ As shown in Fig. 6b, the resulting biogas consists primarily of approximately two-thirds CH₄ and one third CO₂.⁹⁰ Anaerobic digestion is widely implemented because it simultaneously addresses renewable energy production, waste management, climate mitigation, and agricultural sustainability.⁹¹ Biogas is commonly used in combined heat and power systems, although the CO₂ fraction can also be separated for utilization.^{61,62,92} Alternatively, it can be upgraded to additional CH₄ through methanation with added H₂.^{63,93}

6.1.3 Biomass gasification. Biomass gasification (Fig. 6c) converts biomass through high-temperature thermochemical reactions, producing syngas (CO and H₂) as the main output, along with CO₂ and smaller amounts of CH₄.^{94,95} 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,^{96–98} but syngas can also be further converted into biofuels and other platform chemicals.⁹⁹ Integration of carbon capture enables removal of CO₂ either from raw syngas or downstream flue gases.^{100,101} Table 1 lists the Güssing plant,⁶⁴ a discontinued facility that successfully demonstrated Fischer–

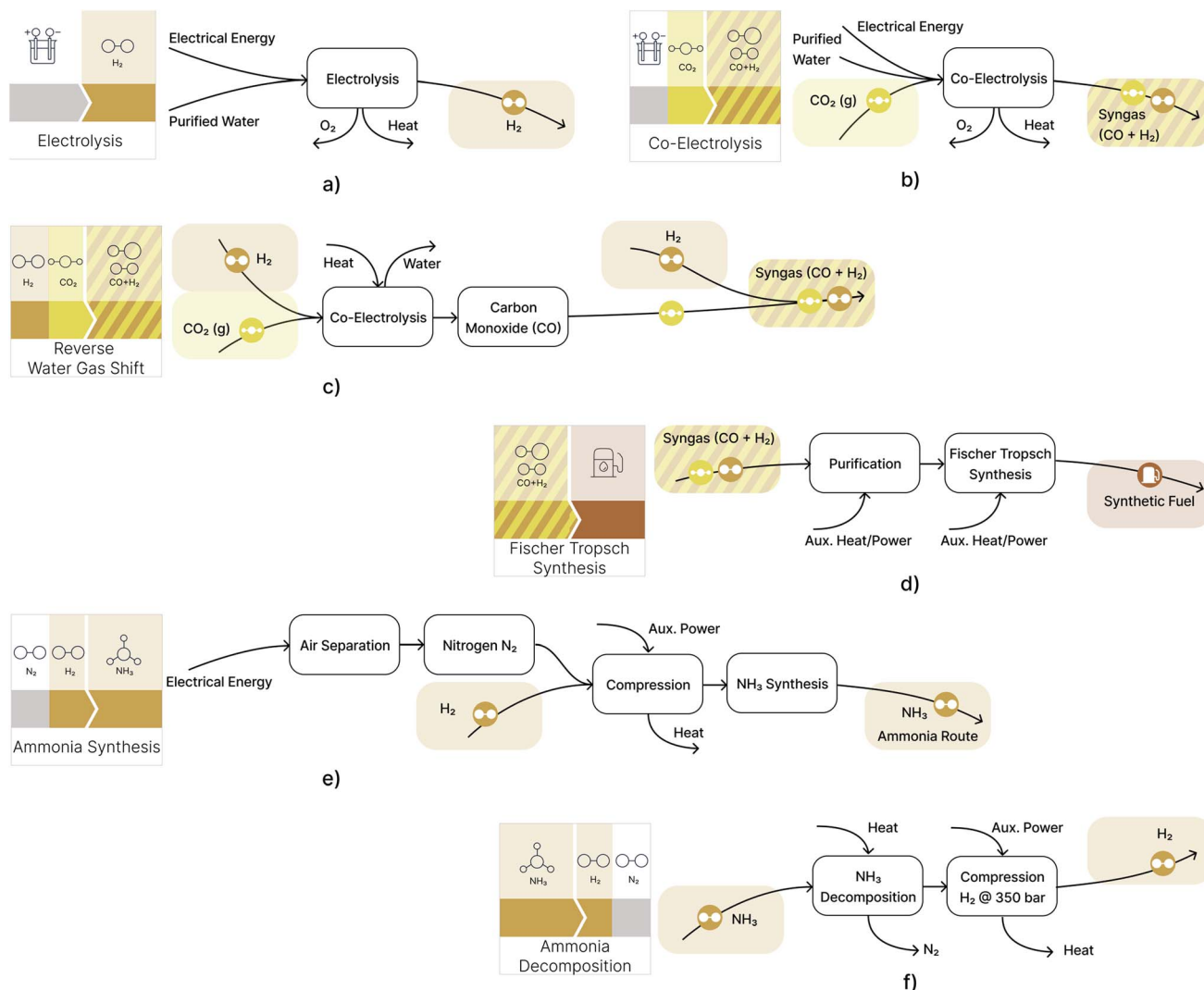


Fig. 7 Part 2 of Q2 process diagrams for the hydrogen and ammonia routes: (a) electrolysis; (b) co-electrolysis; (c) reverse water–gas shift (RWGS); (d) Fischer–Tropsch synthesis; (e) ammonia synthesis (Haber–Bosch); (f) ammonia decomposition.

Tropsch fuel production; however, ongoing pilot and demonstration projects suggest further developments in this field.⁹⁸

6.1.4 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.¹⁰² It upgrades solid biomass into more energy-dense, hydrophobic, and stable “black pellets” that can substitute fossil coal,¹⁰³ and has also been proposed as a net-negative pathway when combined with subsequent ground storage.³⁷ 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 .^{104,105} A competing biomass pellet technology, not listed as a separate building block due to similar input and output streams, is steam explosion.¹⁰⁶ Examples include the Blackwood Technology plant in Duiven for torrefaction⁶⁵ and the Arbaflame Arbaone plant⁶⁶ for steam explosion.

6.1.5 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.¹⁰⁷ Its key advantage over other thermochemical 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.¹⁰⁸ Bio-oil yield is highly dependent on process conditions and feedstock,^{108,109} and the accompanying hydro-char is gaining attention for potential product applications.¹¹⁰ Selected emerging examples are listed in Table 1.

6.1.6 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.^{111,112} 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.

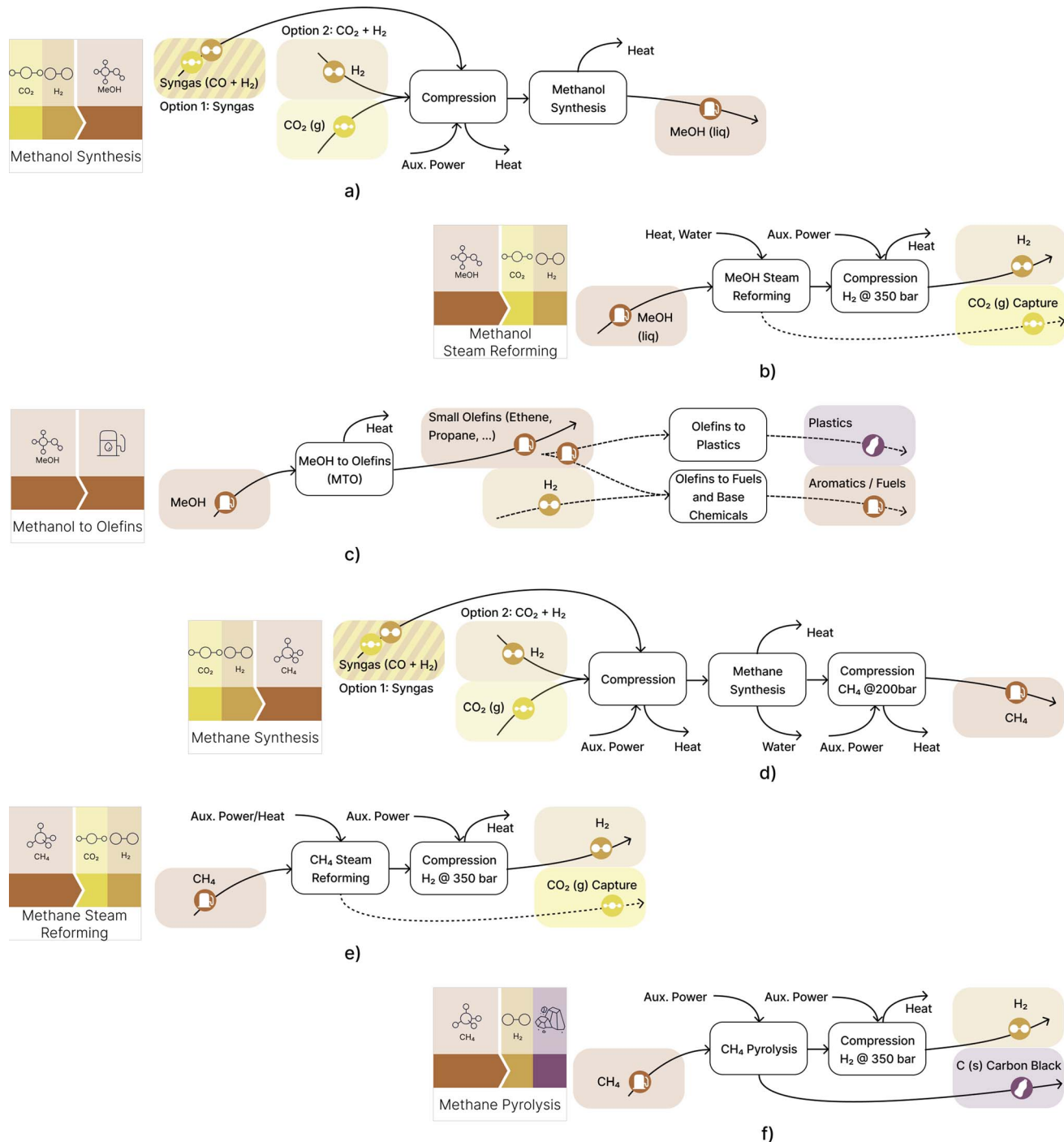


Fig. 8 Part 3 of Q2 process diagrams for the methanol and methane routes: (a) methanol synthesis; (b) methanol steam reforming; (c) methanol to olefins (MTO); (d) methane synthesis; (e) methane steam reforming; (f) methane pyrolysis.

Variants such as catalytic pyrolysis employ catalysts to enhance product quality, particularly by promoting deoxygenation of bio-oil to yield higher-value hydrocarbons.¹¹¹ Selected facilities are listed in Table 1.

6.2 Plastics route

Plastics constitute a major carbon reservoir within the anthropogenic carbon cycle;¹¹³ however, a substantial share of plastic

waste is still landfilled or incinerated,¹¹³ as predominant mechanical recycling back into plastic products in Q3 is unsuitable for most mixed or contaminated streams (Section 7.1.3). Thermochemical recycling of plastic waste to platform chemicals (“Waste-to-X”) is therefore increasingly regarded as a promising alternative,^{114–119} 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 conventional¹¹⁶ and bio-based plastics.¹¹⁷ Given the relative immaturity of the plastics route, its technologies remain difficult to systematize; the three building blocks presented here intend to capture prominent approaches.

6.2.1 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,^{115,116,118,120} analogous to biomass gasification (Section 6.1.3). 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 CO₂ is essential for achieving low-carbon hydrogen *via* gasification pathways.^{121,122} A variety of waste gasification technologies are available, building on experience from coal and biomass gasification systems.¹²⁰ Lee *et al.*¹¹⁵ reviews past pilot plants and ongoing developments; selected examples are listed in Table 1.

6.2.2 Plastic waste pyrolysis. Thermal and catalytic pyrolysis convert plastic waste into liquid oil with properties comparable to conventional diesel or jet fuel.^{114,123–125} 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 (Section 6.1.6). The char can be utilized as a product or for carbon storage, while syngas serves as an energy carrier.¹²³ Several commercial facilities are in operation, including the Arcus plant,⁷⁴ the Sapporo plant,⁷⁶ and the Beston Group plant.⁷⁵

6.2.3 Plastic waste liquefaction. Plastic waste liquefaction encompasses processes that thermally or catalytically crack plastics in the presence of a liquid phase.¹¹⁶ 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.¹³⁷ Compared to biomass liquefaction, which is predominantly hydrothermal (Section 6.1.5), plastic liquefaction may employ a variety of hydrogen-donating solvents and reaction pathways.^{138–140} Hydrothermal liquefaction of plastic waste (Fig. 6e) is also increasingly explored in research,^{141–145} typically producing liquid oil with minimal char formation.¹⁴² Two operational liquefaction plants are listed in Table 1.

6.3 Hydrogen route

Hydrogen (H₂) is a flexible, non-carbon-based energy carrier and industrial feedstock that enables decarbonization across multiple sectors¹⁴⁶ in power-to-gas process chains.^{147–149} It can operate independently of the carbon cycle (Fig. 1), for example when produced *via* renewable electrolysis (Section 6.3.1) or natural processes such as serpentinization,¹⁵⁰ 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 reforming¹⁵¹ (Section 6.7.2), but can also be derived from biomass or plastics gasification and pyrolysis (Sections 6.1.3, 6.1.6, 6.2.1 and 6.2.2). In turn, H₂ and syngas (CO + H₂) can

serve as a feedstock for synthetic methanol, methane, or other hydrocarbon production¹⁵² (Sections 6.6, 6.7).

6.3.1 Water electrolysis. Water electrolysis (Fig. 7a) is a key technology for hydrogen production, splitting water (H₂O) into hydrogen (H₂) and oxygen (O₂) using electricity.¹⁵¹ 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.*,¹⁵³ Shiva Kumar and Lim.¹⁵⁴

6.3.2 Co-electrolysis and CO₂-electrolysis. CO₂-electrolysis (Fig. 7b) is an advanced electrochemical process that simultaneously reduces CO₂ and water producing syngas composed of hydrogen (H₂) and carbon monoxide (CO)¹⁵⁵ (co-electrolysis) or directly small hydrocarbons or alcohols. In contrast to separate water electrolysis (Section 6.3.1) followed by the reverse water-gas shift reaction (Section 6.3.3), 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;¹⁵⁶ selected examples are listed in Table 3. At lower technology readiness levels, substantial research efforts focus on low-temperature electrochemical reduction of CO₂ to value-added chemicals.^{157–159} To date, the products with the highest Faradaic efficiencies are carbon monoxide and ethene (C₂H₄).¹⁶⁰

6.3.3 Reverse water gas shift. The reverse water-gas shift (RWGS) reaction (Fig. 7d) catalytically converts carbon dioxide (CO₂) and hydrogen (H₂) into carbon monoxide (CO) and water (H₂O). This endothermic reaction is a key step in CO₂ utilization, producing CO as an intermediate for fuel and chemical synthesis, including Fischer–Tropsch processes (Section 6.4). Within renewable energy pathways, RWGS enables the conversion of captured CO₂ into syngas for subsequent sustainable fuel production.^{161,162} Selected examples are listed in Table 3.

6.4 Fischer–Tropsch synthesis route

Fischer–Tropsch synthesis (Fig. 7e) is a catalytic process that converts syngas, a mixture of carbon monoxide (CO) and hydrogen (H₂), into liquid hydrocarbons for fuels and chemicals.¹⁶³ It underpins coal-to-liquid (CTL) and gas-to-liquid (GTL) technologies and is increasingly used to produce carbon-neutral fuels from biomass- or CO₂-derived syngas.^{164,165} 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.¹⁶⁶ Examples are listed in Table 3.

6.5 Ammonia route

Ammonia (NH₃) 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,^{17,167} offering advantages over hydrogen in storage, energy density, and infrastructure compatibility.¹⁶⁸ Today, ammonia is mainly produced *via* the Haber–Bosch process using fossil-based hydrogen, accounting for

over 1% of global GHG emissions.¹⁶⁹ However, renewable hydrogen enables “green ammonia”.¹⁷⁰ Environmental concerns include toxicity and potential N₂O emissions.^{171,172}

6.5.1 Ammonia synthesis (Haber–Bosch). Ammonia is predominantly synthesized *via* the Haber–Bosch process (Fig. 7e), which catalytically combines nitrogen (N₂) and hydrogen (H₂) at high pressures and temperatures. Nitrogen is produced by air separation, while hydrogen is typically derived from steam methane reforming (Section 6.7.2). 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.^{173,174} “Green” ammonia can be produced with established processes from biomass or using water electrolysis to produce green hydrogen (Sections 6.1.3, 6.3.1). Emerging electrochemical pathways aim to synthesize NH₃ directly from N₂.¹⁷ Examples are listed in Table 3.

6.5.2 Ammonia decomposition. Ammonia decomposition (Fig. 7g) is the reverse process of ammonia synthesis, cracking ammonia (NH₃) into hydrogen (H₂) and nitrogen (N₂). It enables ammonia to serve as a liquid hydrogen carrier for transport and storage¹⁷⁵ and can also remove ammonia from reformat streams in integrated gasification combined cycle (IGCC) systems proposed for future CO₂-removal applications.¹⁷⁶ The endothermic reaction generally requires temperatures above 400 °C and suitable catalysts to achieve high conversion rates.^{175–177} Most systems remain at demonstration or pilot scale; selected examples are listed in Table 3.

6.6 Methanol route

Methanol (CH₃OH, 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 CO₂ or CO and H₂ into methanol (CH₃OH). When produced from biogenic or atmospheric CO₂ and renewable or bio-based H₂, methanol can replace fossil-based feedstocks across large parts of the economy, enabling a carbon-neutral cycle referred to as the “methanol economy”.^{1,192}

6.6.1 Methanol synthesis. Methanol synthesis (Fig. 8a, Option 1) is an established industrial process in which methanol is produced by reacting syngas (H₂ + CO) over catalysts.¹⁹³ Today, most syngas for methanol production is derived from natural gas *via* steam methane reforming followed by a water-gas shift reaction (Sections 6.7.2 and 6.3.3). An alternative route (Fig. 8a, Option 2) synthesizes methanol directly from CO₂ and H₂,^{193,194} enabling CO₂ sourcing from flue gases or air and hydrogen from renewable electrolysis (often termed e-methanol) or biomass. Examples are listed in Table 4.

6.6.2 Methanol steam reforming. Methanol steam reforming (Fig. 8b), essentially the reverse of methanol synthesis, is a catalytic process that converts CH₃OH into a hydrogen-rich gas, yielding H₂ and CO₂.¹⁹⁵ The process enables efficient hydrogen production due to methanol's high hydrogen-to-carbon ratio and its lower reforming temperature compared

to methane.¹⁹⁵ Although other hydrogen production routes from methanol exist, most implementations have focused on steam reforming, particularly when considering hydrogen yield and carbon monoxide formation and mitigation.¹⁹⁵ Ongoing development aims to scale the technology for distributed use in vehicles¹⁹⁶ and ships,¹⁹⁷ but also for broader industrial use, with examples listed in Table 4.

6.6.3 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).^{198–201} 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.²⁰² Several plants are operational (see Table 4).

6.7 Methane route

Methane (CH₄) is a versatile energy carrier and chemical feedstock,¹⁰ widely used for hydrogen production *via* steam methane reforming (Section 6.7.2). Methane is today predominantly supplied from fossil natural gas.²⁰³ Synthetic methane, or synthetic natural gas (SNG),²⁰⁴ can instead be produced from biomass^{205,206} or renewable hydrogen and captured CO₂ *via* power-to-gas processes,^{147,149} enabling renewable electricity storage within existing gas infrastructure.^{207,208} Since methane combustion releases CO₂, its sustainability depends on renewable or recycled carbon sources,²⁰⁹ and leakage remains a major concern due to its high global warming potential.^{210,211}

6.7.1 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 (CO₂) with hydrogen (H₂) in an exothermic reaction into methane (CH₄) and water over metal catalysts.²¹² Discovered in 1902 by Sabatier and Senderens, it has regained attention for applications in synthetic natural gas production and power-to-gas energy storage.²¹² The reaction can use syngas (Fig. 8d, Option 1) or pure CO₂ and H₂ (Fig. 8d, Option 2) as feedstock.^{206,212} Two examples involving carbon capture and biological feedstock are listed in Table 4.

6.7.2 Methane steam reforming. Methane steam reforming (Fig. 8f) is currently the dominant industrial process for large-scale hydrogen production, in which CH₄ reacts with steam over catalysts.²¹³ The endothermic reaction produces H₂, CO, and CO₂. To maximize hydrogen yield, subsequent water-gas shift stages (Section 6.3.3) convert remaining CO into CO₂ while generating additional H₂. Capturing CO₂ from the syngas or flue gas streams²¹⁴ enables low-carbon hydrogen production, sometimes referred to as “blue” hydrogen.¹⁵¹ Solar-assisted heating has been proposed to reduce fossil energy input for the high operating temperatures required.²¹⁵ Well-known examples are listed in Table 4.

6.7.3 Methane pyrolysis. Methane pyrolysis (Fig. 8g) is an endothermic thermochemical process that decomposes CH₄ at high temperatures or using plasmas in the absence of oxygen

into H_2 and solid carbon.^{216–218} The solid carbon byproduct can take various forms, ranging from carbon black and graphitic materials to specialized carbon nanotubes and fibers.²¹⁶ 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 biogenic or atmospheric sources and the solid carbon is permanently stored.¹⁴ Operational pilots are listed in Table 4.

7 Building blocks quadrant 3: utilization

This section outlines the identified building blocks for Q3 – utilization, as introduced in Section 2.3. It is organized according to how carbon is used within and ultimately exits Q3: material and product utilization (Section 7.1), combustion of energy carriers with atmospheric emissions (Section 7.2), and stationary energy conversion with potential carbon capture (Section 7.3). An overview of all building blocks is provided in Table 5 and Fig. 9.

7.1 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”,²²⁸ such as reuse and recycling, extend effective product lifetimes, reduce new resource input, and increase temporary carbon retention. Included building blocks comprise biomass products (Section 5.1), plastics and other carbon-based products (Section 7.1.3), and char and carbon black (Section 7.1.2). The final sink depends on subsequent treatment, such as landfilling (Section 5.5), waste incineration with or without point-source capture (Sections 7.3.2 and 5.4), thermochemical valorization *via* the biomass or plastics routes (Section 6.1 and 6.2), or long-lasting storage (Section 8).

7.1.1 Biomass products. Biomass has long been an important source of materials. Wood remains widely used in construction, furniture, packaging, and paper,²²⁹ with growing interest in advanced wood-based materials.^{230,231} Bio-based products can temporarily store atmospheric carbon,

particularly in long-lived applications such as buildings.^{232–234} 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,⁸⁰ and potential conflicts with ecosystem protection and food security.⁷⁹ Nonetheless, cascading use and improved utilization of wood residues could allow for sustainable scaling²²⁹ and extend carbon residence time.¹⁹

7.1.2 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 (Section 6.1.4 and 6.1.6).²³⁵ Solid carbon materials can also arise from pyrolysis of plastics (Section 6.2.2), or from methane (Section 6.7.3); 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 (Section 8.4) or applied for soil amendment (Section 8.5) do they function as carbon removal pathways ending in Q4. Key challenges are process inherent contaminations with hydrocarbons (esp. polycyclic aromatic hydrocarbons, PAH).²³⁶

7.1.3 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,²³⁷ they can also be synthesized from biomass-based or CO_2 -derived platform chemicals (Section 6). Plastics constitute one of the largest anthropogenic carbon reservoirs,¹¹³ temporarily storing carbon in stable polymer structures. This residence time can be extended through mechanical recycling, as exemplified by PET,²³⁸ although repeated processing often reduces material

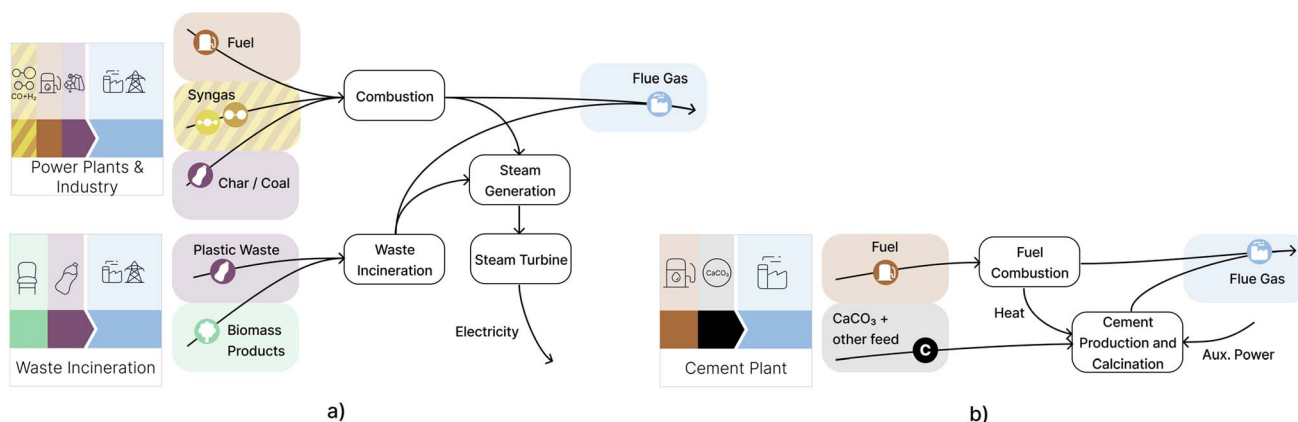


Fig. 9 Process diagrams of Q3 building blocks: (a) power plants and waste incineration; (b) cement plant.

quality and requires relatively clean waste streams. At end-of-life, plastics may accumulate as environmentally harmful debris,²³⁹ be landfilled and lost as a resource (Section 5.5), incinerated with potential carbon capture (Section 7.3.2), or thermochemically converted back into platform chemicals (Section 6.2). Other carbon-based products such as solvents, coatings, and cosmetics¹⁰ follow similar production and end-of-life pathways and are therefore included in this building block.

7.1.4 Ammonia-based products. Ammonia is a key feedstock for fertilizers and explosives¹⁰ 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.^{17,167} Although ammonia itself contains no carbon, it is often produced from fossil feedstock for hydrogen production (Section 6.5.1) or converted to urea by reaction with CO₂ for fertilizer production, and further to melamine for resins and plastics,¹⁰ thereby interacting again with the anthropogenic carbon cycle.

7.2 Combustion without carbon capture

The second utilization category within Q3 covers carbon-containing fuels used in applications where post-combustion carbon capture (Section 5.4) is technically infeasible or economically unrealistic (Section 7.2.1). This primarily includes mobile and small-scale uses such as aviation, maritime, and road transport. A carbon-free alternative is to use hydrogen as a fuel (Section 7.2.2).

7.2.1 Synthetic and bio-based carbon containing fuels. Synthetic and bio-based fuels are liquid or gaseous energy carriers produced from biomass (Section 6.1), plastics (Section 6.2), or by reducing CO₂ with H₂ or directly electrochemically (Sections 6.6.1 and 6.7.1). When renewable electricity is used to produce hydrogen *via* electrolysis for this conversion, they are referred to as e-fuels or electrofuels (Sections 6.3.1, 6.3.2 and 6.3.3). 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.²⁰² Unlike hydrogen (Section 7.2.2), synthetic and bio-based fuels are compatible with existing combustion engines and turbines and can achieve net-zero or net-negative balances depending on the carbon source.²⁴⁰ Vogt *et al.*,²¹² Table 1 provide an overview of advantages and disadvantages across Power-to-X fuel pathways.

7.2.2 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.²⁴⁰ While hydrogen use emits no CO₂, its overall climate impact depends on emissions from production (Section 6.3) and its role as an indirect greenhouse gas.²⁴¹

7.3 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 (Section 5.4) can be implemented. This includes fuel-based power plants and industrial boilers and furnaces (Section 7.3.1), waste incineration facilities (Section 7.3.2), and cement plants (Section 7.3.3).

7.3.1 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%,²⁴² and are typically combusted as coal, oil, or natural gas. However, biomass is an increasingly used alternative (Section 5.1), including emerging pathways such as bioenergy with carbon capture and sequestration (BECCS),²⁴³ as well as synthetic and bio-based fuels (Section 7.2.1). 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 CO₂ in flue gases, which can be treated and captured post-combustion (Section 5.4). Selected examples are listed in Table 5.

7.3.2 Waste incineration. Waste incineration is widely adopted in developed countries, with more than 1700 plants operating.²⁴⁴ The process (Fig. 9a) is similar to the previous building block (Section 7.3.1), but uses mixed waste as feedstock, typically comprising roughly equal shares of biomass-derived products (Section 7.1.1) and plastics in European municipal waste streams.²⁴⁵ Unlike fossil fuels, waste generation cannot simply be phased out. Carbon capture (Section 5.4) is therefore considered central to its decarbonization,²⁴⁶ and several plants are transitioning from pilot to full-scale implementation. Selected examples are listed in Table 5.

7.3.3 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 (Section 7.3.1), but mainly from the calcination of limestone (CaCO₃), which accounts for about 60% of the sector's total emissions.²⁴⁷ 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,²⁴⁸ with post-process carbon capture from kiln flue gases representing one of the main mitigation strategies^{249,250} (Fig. 9b). Real-world deployments are becoming increasingly common (see Table 5).

8 Building blocks quadrant 4: storage

This section presents the building blocks identified for carbon storage (Section 2.4), focusing on artificial geological storage and long-term stabilization of carbon in solid products. Enhanced rock weathering^{262,263} is not included as a building block, as it is a standalone removal pathway that directly stores atmospheric CO₂ in soils without the possibility to utilize concentrated CO₂ streams as a resource. Deep-sea carbon injection⁷ is likewise excluded due to environmental impact concerns.²⁶⁴ Furthermore, carbon-containing products such as bio-based materials and plastics are classified under

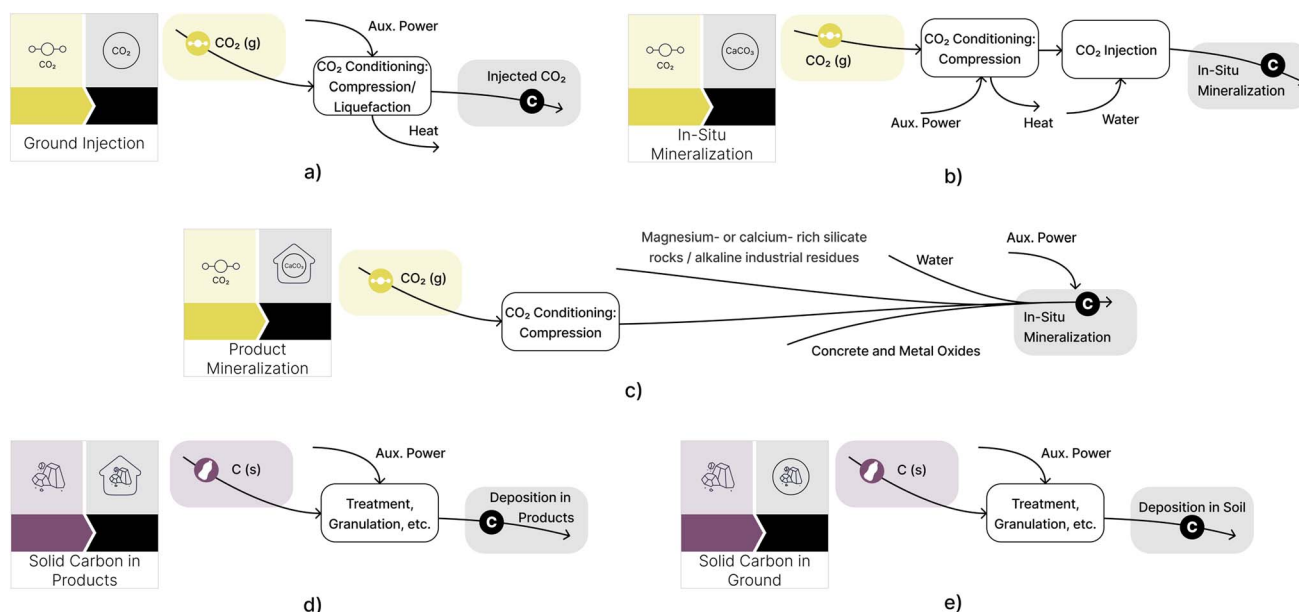


Fig. 10 Process diagrams of Q4 building blocks: (a) CO₂ ground injection; (b) *in situ* mineralization; (c) product mineralization; (d) solid carbon in long-lasting products; (e) solid carbon in ground.

“utilization” (Section 7), 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 Table 6 and Fig. 10.

8.1 CO₂ ground injection in geological formations

CO₂ can be injected into deep geological formations for long-term storage^{265–267} (Fig. 10a). Storage typically involves injection into porous rock formations where CO₂ is retained through structural trapping beneath caprocks, residual trapping in pore spaces by capillary forces, and solubility trapping *via* dissolution in formation fluids.²⁶⁸ Deep saline aquifers offer the largest global storage capacity,²⁶⁹ while depleted oil and gas reservoirs provide established infrastructure and monitoring experience.²⁷⁰ Additional options include adsorption in unmineable coal seams²⁷¹ and high-pressure storage in salt caverns.^{266,272} Key challenges across all approaches include ensuring long-term seal integrity to prevent leakage and managing site-specific geological uncertainties. Large-scale CO₂ storage also requires dedicated transport infrastructure, with pipelines and ship transport likely to be the most economical options.²⁷³ Lane *et al.*²⁷⁴ discuss uncertainties in global geological storage capacity.

CO₂ injection has also long been practiced for enhanced oil recovery (EOR), including projects such as Bell Creek,²⁷⁵ Weyburn–Midale,²⁷⁶ and Petrobras’ Santos Basin reinjection.²⁷⁷ In EOR, injected CO₂ mobilizes additional oil by reducing viscosity and swelling the oil phase.²⁷⁸ Although technically similar to geological storage and sometimes framed as an economically profitable “bridge” technology,²⁷⁹ EOR differs fundamentally in climate terms: combustion of the additional oil generates downstream emissions that typically outweigh by factors the benefit of stored CO₂.²⁸⁰

8.2 CO₂ *in situ* mineralization

In situ carbon mineralization is an engineered process in which CO₂, dissolved in water prior to injection into geological formations, reacts with calcium- and magnesium-rich minerals to form stable carbonate solids^{281,282} (Fig. 10b). This reaction immobilizes CO₂ in solid form over geological timescales. A prominent example is the Carbfix project in Iceland, which captures atmospheric CO₂ *via* DAC and stores it in basalt formations, demonstrating large-scale *in situ* mineralization (Table 6). Compared to conventional geological injection, *in situ* mineralization is considered more permanent and stable,²⁶⁸ while transport infrastructure requirements remain similar.

8.3 CO₂ mineralization in products

CO₂ that is chemically bound into stable carbonates through a reaction with calcium- or magnesium-containing materials can be used as storage^{283,284} (Fig. 10c). Unlike *in situ* mineralization (Section 8.2), this approach integrates mineralization directly into products, most prominently in cement and concrete, which represent the largest and most commercially viable applications.²⁸⁵ Emerging technologies include carbonated concrete products (*e.g.*, CarbonBuilt²⁵⁵), carbonated aggregates (*e.g.*, Neustark²⁵⁶), clinker substitutes (*e.g.*, Fortera²⁸⁶), and accelerated curing methods (*e.g.*, CarbonCure²⁵⁷) (Table 6).

8.4 Deposition of solid carbon in products

A second approach to storing carbon in durable products is to incorporate solid carbon (Fig. 10d). This carbon is typically biochar or carbon black (Section 7.1.2), derived from biomass pyrolysis (Section 6.1.6), plastic pyrolysis (Section 6.2.2), recycled plastic waste,²⁸⁷ or methane pyrolysis (Section 6.7.3). Solid carbon is embedded in long-lasting construction materials such

as concrete, asphalt, or polymers,²⁸⁸ with current applications focusing mainly on concrete, either as a partial replacement for cement or as aggregates.^{288–293} Early commercial deployments are emerging; see Table 6 for examples.

8.5 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 (Section 8.4), this approach generally lacks strong economic incentives, except where biochar is applied to enhance soil quality^{294,295} and erosion protection.²⁹⁶ Most current applications rely on biochar (Section 7.1.2) produced *via* biomass pyrolysis (Section 6.1.6) or torrefaction (Section 6.1.4) for carbon removal purposes. Other carbon blacks may offer comparable soil benefits, although their carbon is not necessarily of atmospheric origin.²⁹⁷ Examples of biochar producers for agricultural use are listed in Table 6.

9 Demonstration: pathway construction and interpretation

The preceding sections define the framework's structure and its three levels of abstraction. Here, we demonstrate how the framework is used to construct, compare, and interpret carbon pathways, showing that the building blocks connect into coherent representative pathway configurations that illustrate typical CCS, CCU, and CCUS patterns, as well as more complex carbon loops (Fig. 11).

Pathways are assembled from the building-block library by connecting blocks whose output stream types match the input stream types of the next block (Section 3); the color-coding in Fig. 1 provides a visual guide. The configurations presented below (Fig. 11) are not exhaustive or optimized designs, but test whether the framework's structure suffices to represent realistic and policy-relevant carbon-management strategies.

9.1 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).^{26,298} Recent literature also introduces the term Biomass Carbon Removal and Storage (BiCRS) for bio-based CCS pathways.²⁹⁹ 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 Section 8. Fig. 11a illustrates a representative CCS pathway, in which atmospheric CO₂ is captured *via* DAC (Section 5.2) and permanently stored through subsurface mineralization (Section 8.2), as exemplified by the Climeworks Orca and Mammoth projects.^{23,27}

9.2 Carbon capture and utilization (CCU)

Carbon Capture and Utilization (CCU) pathways aim to capture CO₂ 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 (Section 10) is made between pathways producing durable products that act as temporary carbon sinks (9.2.1) and those producing fuels intended for near-term combustion (9.2.2).

9.2.1 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 CO₂ is captured *via* DAC (Section 5.2), converted into platform chemicals using H₂ produced by electrolysis (Section 6.3.1), here *via* methanol synthesis (Section 6.6.1) and olefins (Section 6.6.3), and subsequently transformed into plastics (Section 7.1.3). In this configuration, plastics act as a temporary reservoir of atmospheric carbon within the anthropogenic carbon cycle. Bio-based utilization routes, 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 (Section 9.2.2), although this remains uncommon in practice. Recycling plays a critical role in extending carbon residence times within these temporary sinks.

9.2.2 CCU fuels. If a CCU pathway ends with fuels intended for near-term combustion, the captured carbon is ultimately released back into the atmosphere. 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 (Section 6.1.3), subsequently transformed into bio-based synthetic fuels through Fischer–Tropsch synthesis (Section 6.4), and used to replace fossil fuels in transport, with the resulting CO₂ ultimately returning to the atmosphere upon combustion.

9.2.3 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 (Section 9.2.2). 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 Section 6.3, 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 (Section 6.3.1) is used directly as a fuel in transport or industrial applications, resulting in no direct CO₂ emissions at the point of use. This carbon-free pathway is included to show how the framework situates hydrogen- and ammonia-based routes relative to carbon-containing pathways. It demonstrates that the framework can

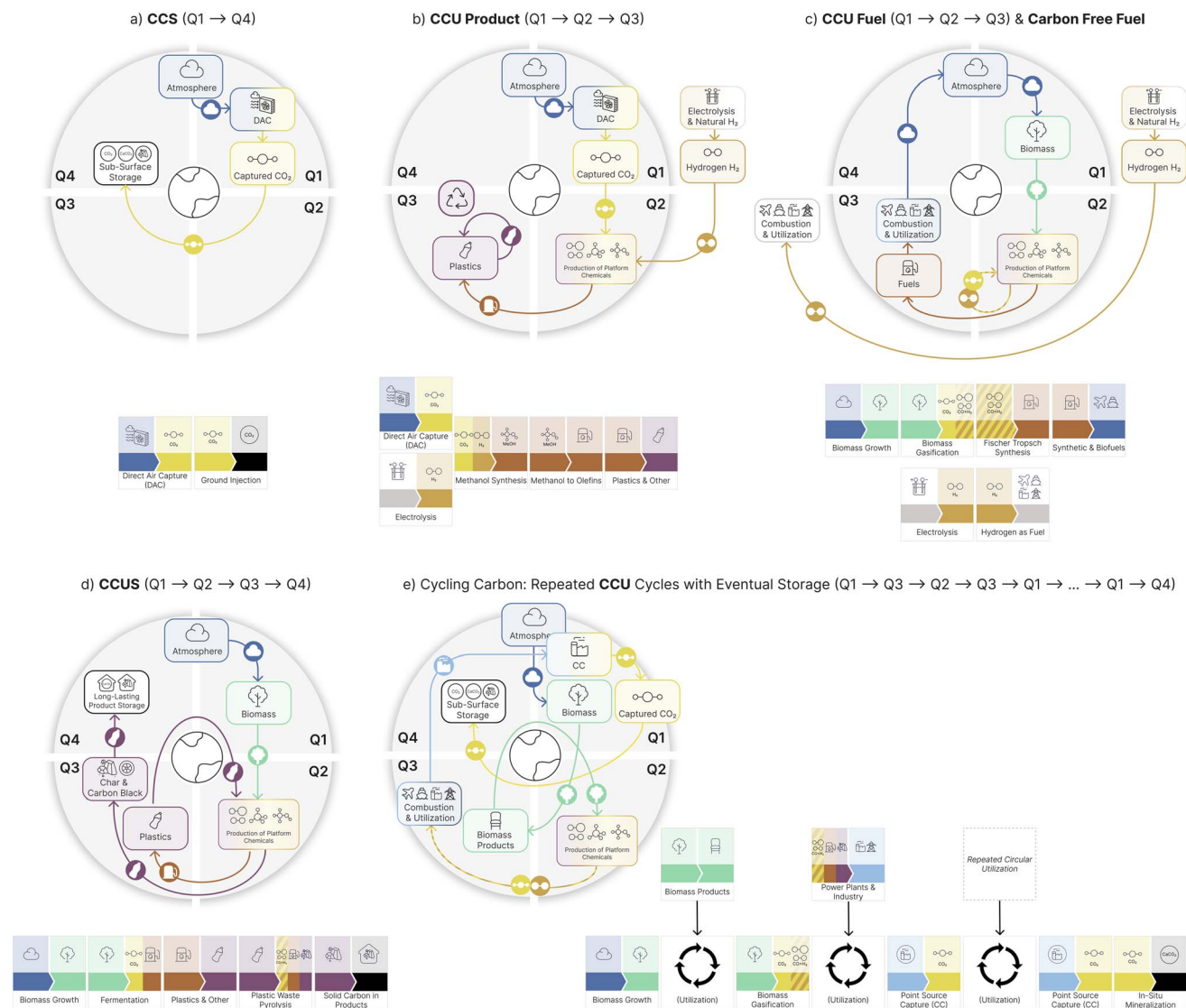


Fig. 11 Representative carbon pathway configurations constructed from the building-block component library used to demonstrate the framework. (a) Carbon Capture and Storage (CCS) from Q1 to Q4; (b) Carbon Capture and Utilization (CCU) product pathway with temporary product storage from Q1 to Q3; (c) CCU fuel pathways without point-source capture from Q1 to Q3 alongside a carbon-free hydrogen pathway with the same purpose for comparison; and (d) Carbon Capture, Utilization, and Storage (CCUS) from Q1 via Q3 to Q4; (e) cycling pathway illustrating repeated CCU with eventual storage.

represent both carbon-based and carbon-free options within the same framework.

9.3 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 (Section 9.1), 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 (Section 6.1.1) and subsequently processed into plastic products (Section 7.1.3). At end of life, the plastics are thermochemically valorized *via* pyrolysis (Section 6.2.2), and the resulting char (Section 7.1.2) is permanently stored in durable products such as concrete (Section 8.4). This configuration passes through a utilization phase yet still achieves for the solid carbon stream a net-negative balance, showing that utilization and removal can be sequential steps.

9.4 Carbon loops: repeated CCU with eventual storage

Although overlapping with the previously described pathway types, particularly CCUS pathways (Section 9.3), the pathway abstraction level allows to represent more complex carbon loops, in which carbon repeatedly cycles through capture (Q1), conversion (Q2), and utilization (Q3) stages 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 (Section 7.1.1) and subsequently valorized *via* gasification (Section 6.1.3). The syngas is then utilized for combined heat and power production (Section 7.3.1), after which the resulting flue gas is captured and CO₂ absorbed *via* point-source capture (Section 5.4). From this point, additional conversion and utilization phases may follow before the CO₂ is permanently stored through underground cavern storage (Section 8.1). Although such pathways may appear complex due to repeated transitions within the carbon cycle, representing them using building blocks clarifies their structure; any cycling pathway decomposes into a sequence of CCU segments with eventual storage, so that no additional pathway type is required to describe them.

The conceptualization also facilitates the identification of intersecting pathways by highlighting shared building blocks. For example, the CCUS pathway shown in Fig. 11c intersects with pathway e), as both follow a similar biomass sequence up to biomass gasification. Pathways may further branch into

multiple subsequent routes, as illustrated in Fig. 11b: following plastic pyrolysis, the resulting char is stored in long-lived products. However, this only covers part of the full route, since syngas and synthetic crude oil branch off into other pathways after plastic pyrolysis. As with cycling pathways, such branching configurations require careful assessment to determine the relevant route for evaluating the overall emission balance.

10 Linking pathways to carbon balances

The pathways described in Section 9 can be qualitatively assessed based on their carbon-balance outcomes (Fig. 4, Level 1), following the principles outlined in Section 4.2. Because these balances depend on the carbon trajectory from source to sink or release, pathways can be categorized systematically as net-negative, net-zero, or net-positive with their respective starting and ending building blocks. Fig. 12 presents an overview matrix organized by pathway type (columns: CCS, CCUS, CCU) and carbon source (rows: fossil, atmospheric, and recycled). Throughout this work, these terms refer to the carbon balance of a pathway and not to its full life-cycle greenhouse-gas performance; a net-negative classification is therefore a necessary but not sufficient condition for carbon removal. Scope 1–3 pathway emissions (Section 10.1), including lifecycle emissions

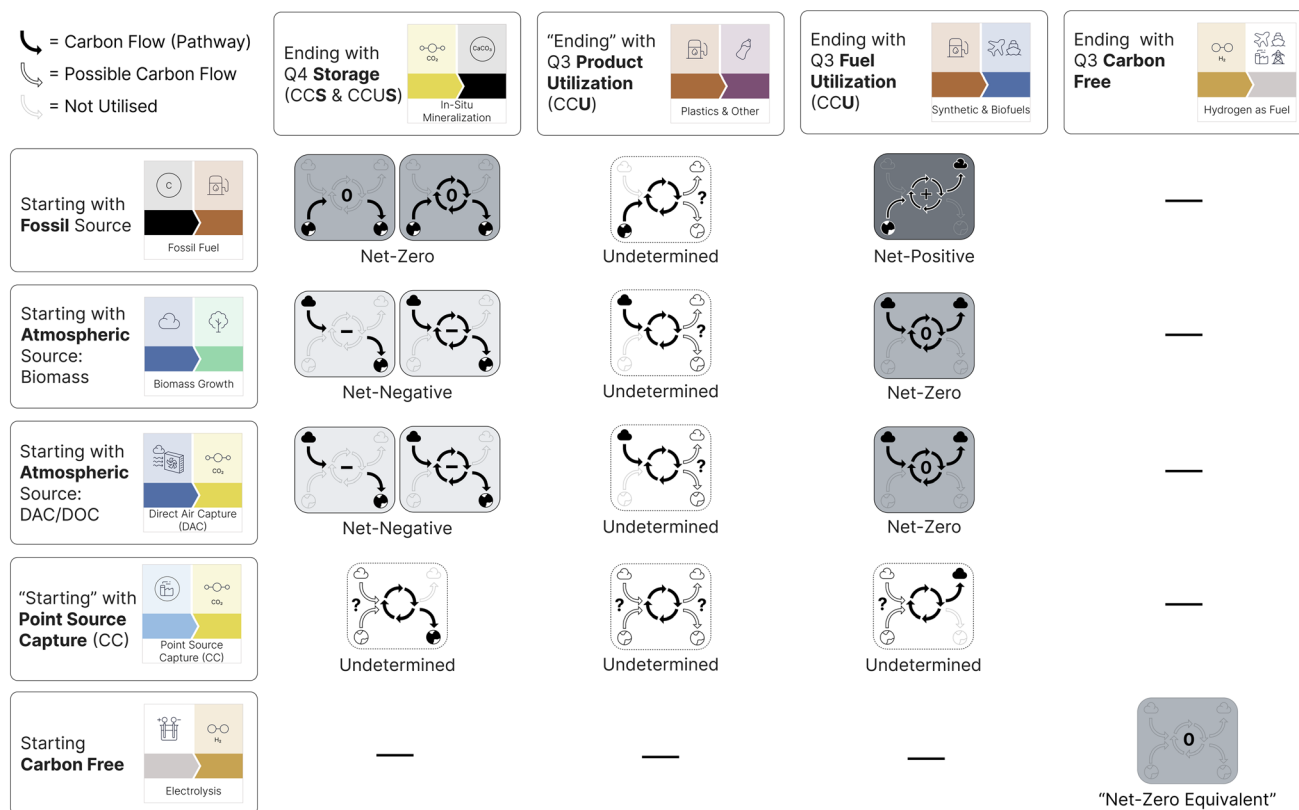


Fig. 12 Overview matrix of pathway carbon balance outcomes by starting and ending building blocks. Pathways are classified according to their carbon source (fossil vs. atmospheric/biogenic) and fate (permanent storage vs. release). The matrix reflects carbon flows only and does not account for full life-cycle greenhouse-gas emissions (Section 10.1).

from energy supply, production, transport, and conversion, are discussed separately in Section 10.1. For comparison, carbon-free hydrogen pathways (*e.g.*, green hydrogen) are included in a fourth row.

10.1 Pathway emissions

Scope 1, 2, and 3 emissions from energy, transport, and production of carbon pathways play a critical role in the final climate performance and are not considered in Fig. 12. These life-cycle emissions can shift a pathway's overall greenhouse-gas balance from net-negative to net-zero or even net-positive, even when its carbon-balance is negative.

10.1.1 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.

10.1.2 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). CO₂ 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.

10.1.3 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).

11 Discussion

11.1 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.

11.1.1 Synfuels or hydrogen? The debate over basing the economy on carbon-free carriers (hydrogen,¹⁶ ammonia¹⁷) or carbon-based synfuels (*e.g.*, methanol¹) often centers on infrastructure. While hydrogen requires new distribution networks, synfuels can leverage existing infrastructure.³⁰⁰

Our building block analysis (Section 6) 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. Coupling 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,¹⁵¹ highlighting that the ultimate goal is to integrate fossil-free carbon into the carbon cycle.

11.1.2 Biomass or DAC? In our conceptualization, both biomass (Section 5.1) and Direct Air Capture (DAC) (Section 5.2) 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,^{79,80} whereas DAC pathways are limited by their high energy demand and current technological maturity.^{37,41}

The framework therefore shows 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 Section 11.2).

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

11.1.3.1 Removal (CDR). While Carbon Dioxide Removal (CDR) is often associated with direct capture and storage (CCS) bypassing utilization (Section 9.1), our framework defines it by the net outcome rather than the specific technology. Consistent with IPCC definitions,²⁶ any pathway sourcing atmospheric carbon (Q1) and achieving permanent storage (Q4) qualifies as removal. This broadens the scope to include CCUS pathways (Section 9.3) that pass through utilization stages but still result in a net-negative outcome.

11.1.3.2 Storage. The term “storage” is often applied ambiguously to both permanent sequestration and temporary retention in products. To resolve this, our framework imposes a 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, Section 8.4) which falls under Q4, and temporary retention in biogenic or synthetic materials (*e.g.*, wooden buildings²³³ 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 buildings³⁰¹), they remain chemically reversible (*e.g.*, via incineration or decay), unlike the permanent sinks in Q4.

11.1.3.3 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.⁴⁹ 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.

11.2 Limitations and future perspectives

11.2.1 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.

11.2.2 Evolving technology. The library of 40 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.

11.2.3 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, enabling software-based exploration of pathway configurations that link high-level emission goals directly to engineering constraints. Future work should build on this potential by applying the framework to concrete case studies and further developing the computational tools it enables.

11.2.4 From qualitative to quantitative. Currently, the framework focuses on qualitative carbon balances (Level 1). While it does not explicitly track non-carbon GHG emissions (*e.g.*, methane leakage, N₂O) or Scope 1–3 pathway emissions (Section 10.1), 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,^{198,302,303} 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.

12 Conclusion

This study establishes a modular framework for the anthropogenic carbon cycle comprising 40 technological building blocks, each of which is defined by its input and output streams and their position in the respective functional quadrant of the carbon cycle: capture, conversion, utilization, and storage. With that, the framework integrates traditionally isolated concepts, such as CCS, CCU, CCUS, and hydrogen pathways, into a single systemic model. This reveals critical intersections and synergies that are often obscured in linear analyses. The building block can be assembled into pathways and classified by carbon source and fate, yielding the carbon balance. 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 goals (Level 1).

At the core of the framework lies a fundamental change in perspective: 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 simplifies technical complexities and classifies pathways according to carbon flow rather than full life-cycle performance, it provides the essential architecture for a coherent, system-wide understanding of carbon management, as well as a standardized structural basis on which life-cycle assessment can build. The block library is designed to be extended as the technological landscape evolves. Future work should leverage this foundation to design robust policy instruments that guide the incentives, investments, and certification needed to create a truly circular carbon economy.

Author contributions

CRDiT Statement 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.

Conflicts of interest

The authors declare no competing interests.

Data availability

The building-block library (Tables 1–6) underlying the anthropogenic carbon cycle framework is included in this article. A structured version of this data in spreadsheet (XLSX) format, along with vector (SVG) and PDF pictograms for each building block, is available at Zenodo: <https://doi.org/10.5281/zenodo.22743641>.

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