In collaboration with
Wood Mackenzie

Defossilizing Industry: Considerations for Scaling-up Carbon Capture and Utilization Pathways

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Foreword

Simon Flowers
Chairman & Chief Analyst,
Wood Mackenzie

Fernando J. Gómez
Head, Future of Materials,
Member of the Executive
Committee, World
Economic Forum

Industrial production is the foundation of the global economy, yet it is also a significant source of greenhouse gas emissions. As countries and industrial sectors pursue pathways to net zero, the question is not whether carbon management is needed, but how to do it effectively.

Among the options available, carbon capture and utilization (CCU) offers a promising pathway to convert captured CO_2 into products such as fuels, chemicals and building materials – potentially creating new industrial value streams while reducing reliance on primary fossil feedstocks and contributing to emissions abatement.

While CCU is still at an early stage, with high costs and uneven policy support, its potential benefits warrant attention. Policies currently favour carbon capture and storage (CCS) over utilization and this imbalance, combined with limited market signals, could shape the depth and pace of CCU's development in the years ahead. Whether CCU proves to be a meaningful lever for decarbonization will depend on how stakeholders choose to create the right conditions for innovation, deployment and learning.

As momentum builds behind industrial decarbonization, CCU merits thorough, context-specific consideration. We invite stakeholders – including governments, industry, investors and researchers – to engage in a clear-eyed assessment of CCU's role within broader transition strategies. The challenge is to identify where CCU can deliver both climate and economic value, and how targeted support can accelerate that process as part of a larger set of strategies delivering more sustainable production and emissions management

The task is complex, but also full of possibility. With the right coordination, shared ambition and a willingness to test solutions, we can uncover where CCU truly adds value. By fostering open, evidence-based dialogue and clarifying the conditions required to scale up what works, decision-makers can ensure that choices around CCU are deliberate, informed and aligned with a sustainable industrial future.

Executive summary

CCU offers the potential to "defossilize" carbon-reliant industries – but for it to become viable, it requires supportive policy frameworks, patient capital and close collaboration across stakeholder groups.

Carbon capture and utilization (CCU) could present an opportunity for reducing emissions from industrial supply chains by converting captured CO_2 and other carbon-based emissions into valuable carbon-based products. CCU technologies therefore offer the potential to "defossilize" industries that rely on carbon feedstocks. A few re-use opportunities are already mature, such as urea production for use in fertilizers. Beyond this, there are technology pathways for reusing carbon in fuels, chemicals, construction materials and other pure-carbon products being developed with potential for climate benefits.

However, many applications of re-used carbon remain at pilot and demonstration scale and/or are commercially immature. Because these CCU technologies have attracted less attention than mature applications, this paper focuses on the challenges that innovators and first movers face, including their business strategies.

While CCU offers significant opportunities in theory, in practice nascent CCU technologies face many systemic barriers. This paper analyses three such barriers:

– **First, policy frameworks are fragmented and inconsistent** across jurisdictions and CCU pathways. This makes it challenging for first movers to see a reliable and significant market to support future scaling-up, deterring investment. Moreover, existing policies heavily favour sequestration over utilization and, in some cases, effectively create disincentives to invest in CCU.

– **Second, CCU companies face "valleys of death"** – as with many potentially important yet novel technologies. These are characterized by long development timelines, high capital requirements and immature business models lacking well-defined routes to revenue. These factors create barriers to conventional early-stage investment forms, such as traditional venture capital.

– **Third, successful deployment of CCU will require unprecedented cross-sectoral collaboration** – in most industrial supply chains – between CCU companies and incumbent industries. Partnerships can offer access to infrastructure, expertise and market channels to support the scaling-up of nascent CCU technologies. However, the inherent complexity of testing small-scale, first-of-a-kind technical solutions within large, mature, industrial complexes can impede collaboration. Beyond practical issues of technology integration, cross-industry collaboration also has an important role in advocacy and awareness raising.

This paper discusses the potential role that emerging CCU pathways could play in a sustainable industrial transition; it synthesizes community insights into systemic challenges across policy and finance; and it looks at the role of coordination across stakeholder groups. Findings are presented alongside strategic considerations for future CCU innovators and policy development needs.

1 State of play

Emerging CCU pathways have the potential to improve the sustainability of industrial activities while creating new value opportunities.

1.1 The role of carbon capture and utilization

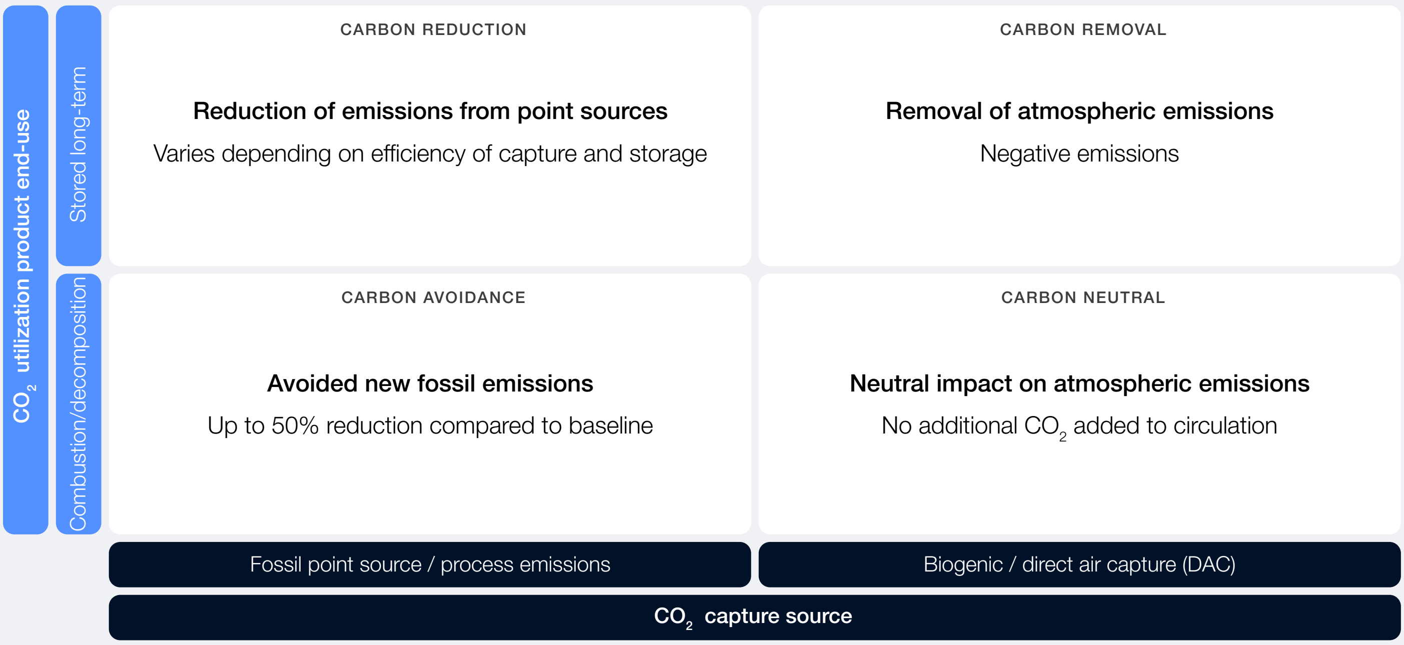
Note: technical terms used in this report are defined in a Glossary of terms at the end of this paper.

Carbon capture and utilization (CCU) has the potential to become a valuable lever in wider efforts to transition towards sustainable and circular economies. By converting captured CO_2 and other carbon emissions into carbon-based products, CCU can generate value from waste streams and potentially contribute emissions benefits. However, CCU pathways face significant barriers in the form of high costs, limited infrastructure and underdeveloped market frameworks.

With the exception of a few leading initiatives, CCU pathways currently receive limited policy support. In contrast, technologies that capture and permanently store carbon, such as carbon capture and storage (CCS), are attracting more policy and private sector investment. This can be explained in part by the relative simplicity of modelling CCS compared to CCU. Current climate models are unable to address the granularity of CCU, given the diversity of sectoral and geographical contexts, as well as the specific technologies, energy and feedstocks used.[1]

This paper follows the Intergovernmental Panel on Climate Change (IPCC) definition of CCU which describes it as carbon utilization within a product.[2] The paper also emphasizes CCU approaches that have yet to emerge at scale. Consequently, the role of CCU in enhanced hydrocarbon/oil recovery (EOR) or urea production is not discussed.

FIGURE 1 **Theoretical net emissions benefits under CCU scenarios**



Notes:
- Final emissions benefit will be dependent on full life-cycle emissions, including the emissions intensity of associated hydrogen and other co-feedstocks, processing emissions and product end-use.
- The two upper "stored long-term" categories are broadly equivalent to CCS.

Source: Wood Mackenzie analysis.[3]

By converting captured CO_2 and other carbon emissions into carbon-based products, CCU can generate value from waste streams and potentially contribute emissions benefits.

From an emissions perspective, CCU provides an opportunity to reduce emissions from industrial value chains, as well as emissions avoidance and carbon removal in some cases.[4] CCU can also promote broader adoption of carbon capture technologies. Carbon capture in isolation is not inherently productive and, without policy support, generally represents an added cost to conventional production.[5] However, in combination with utilization, there is an opportunity to offset these additional costs by introducing an additional revenue stream, potentially stackable with government subsidies.

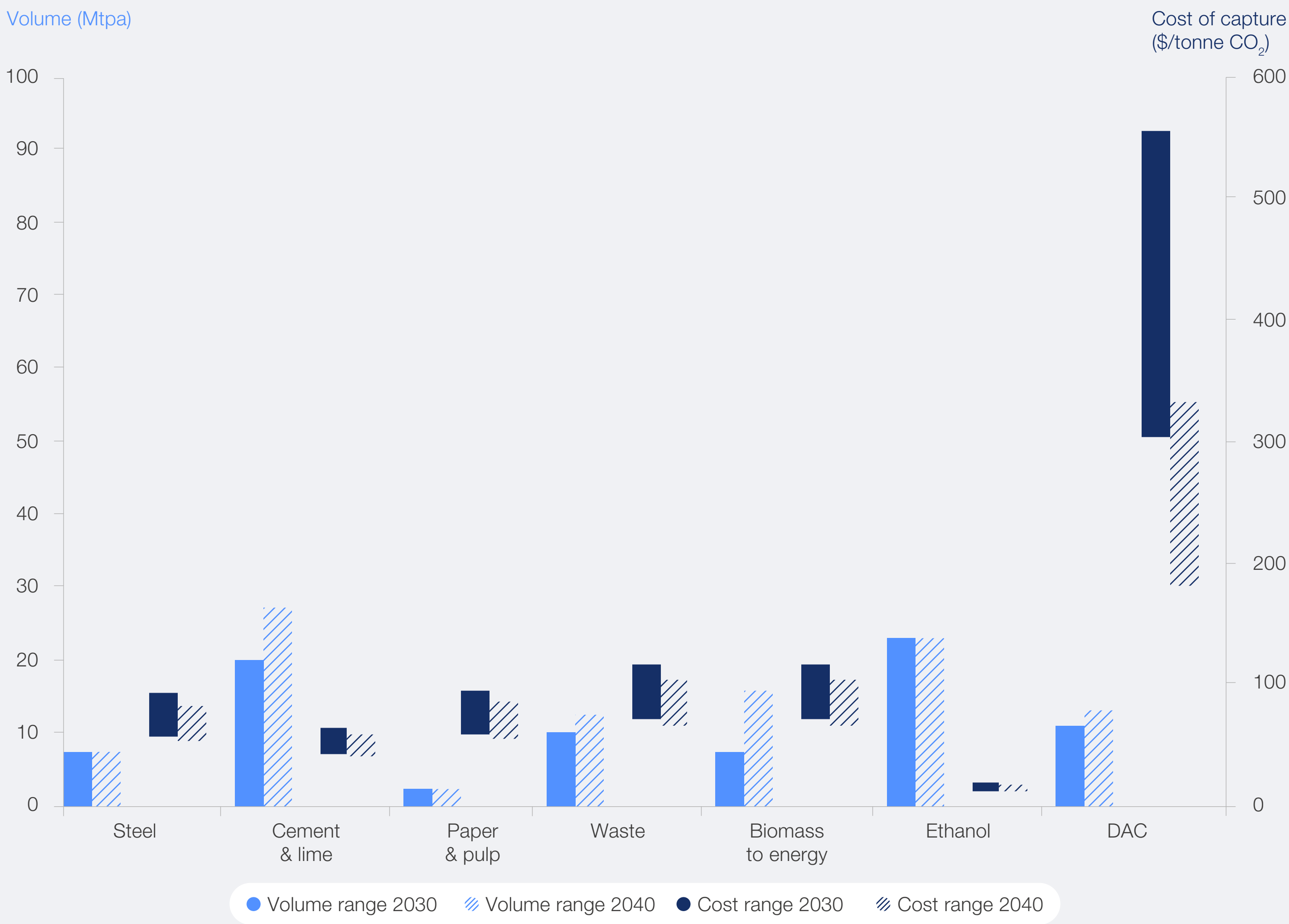
CCU is an emerging field and currently there are differing interpretations of emissions reduction benefits depending on life-cycle assumptions and baselines used.[6] As technology pathways and applications mature, the evidence base of greenhouse gas reduction will need to grow accordingly, as confidence in these outcomes will ultimately determine whether CCU is scaled up. Figure 1 represents a simplified distillation of outcomes, which all assume the use of decarbonized electricity and feedstocks.

The potential emissions benefits from CCU vary depending on the end-use of the utilization product, storage duration and carbon source. If fossil emissions are utilized for short duration products such as chemicals or fuels, the direct impact on net atmospheric emissions is modest, although it displaces an equivalent quantity of new fossil emissions that would have otherwise been created. In theory, this results in avoided emissions, compared to a scenario in which the fossil carbon was not reused; however, the extent of this will be dependent on the efficiencies of carbon capture and process of conversion to the final product.[7]

For capture and utilization that results in permanent storage of fossil carbon, the result is a reduction of emissions compared to business-as-usual, equivalent to CCS. Given their abundance, the use of fossil point source emissions could support the scaling-up of CCU technologies, providing economic as well as potential emissions benefits. However, claims of emissions benefits must be demonstrated with cradle-to-grave life-cycle analysis (LCA) and CCU must not be applied to extend the life of otherwise avoidable fossil emissions. For utilization to be net-neutral or carbon negative, biogenic and atmospheric emissions sources must be used as no additional carbon is added into circulation.[8,9,10]

Both the cost and availability of captured carbon emissions will influence the scalability of CCU applications (see Figure 2). Currently, atmospheric emissions are the most expensive and least abundant, with direct air capture (DAC) deployment in its infancy. More abundant emissions sources therefore have the potential to be near- to mid-term enablers of scale. This includes both point source emissions from industrial sectors with unavoidable emissions, such as lime production, waste, and paper and pulp, in addition to biogenic sources from ethanol, waste, biogas and bioenergy facilities.

FIGURE 2 | Current carbon capture capacity in development and cost estimates of global CCU-viable CO_2 sources



Notes:

– Mtpa = million tonnes per annum.

– Volume assumptions: 90% capture rate; biogenic and/or unavoidable emissions shown where possible.

– Cost assumptions: final investment decision (FID) two years before operation; based in USA; 1 Mtpa capacity; no transport and storage; no policy support; current technology (other than DAC); 2030 DAC costs reflect range of valued Wood Mackenzie DAC projects; 2040 DAC costs follow expected cost reduction trajectory.

Source: Wood Mackenzie Lens Carbon.

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Mtpa by 2050

Volume of CO_2 that must be utilized in line with IEA's Sustainable Development Scenario

Forecasting utilization volumes is challenging, given the diversity of CCU contexts and the extent to which CO_2 destined for sequestration could be reprioritized for feedstocks. Projections vary across studies, due to differing assumptions and scenarios – including the following:[11,12,13,14]

– In its 2019 study, the International Energy Agency (IEA) projected between 250 and 878 million tonnes per annum (Mtpa) of CO_2 utilization by 2060.[15]

– In its subsequent 2020 Special Report on Carbon Capture Utilisation and Storage, IEA projected that 189 Mtpa by 2030, 369 Mtpa by 2050 and 877 Mtpa by 2070 of captured CO_2 would have to be utilized in line with its Sustainable Development Scenario. This represents roughly 9% of all captured CO_2 within the scenario.[16]

– In 2024, the Oil and Gas Climate Initiative (OGCI) forecast that between 430 and 840 Mtpa of CO_2 could be utilized by 2040.[17]

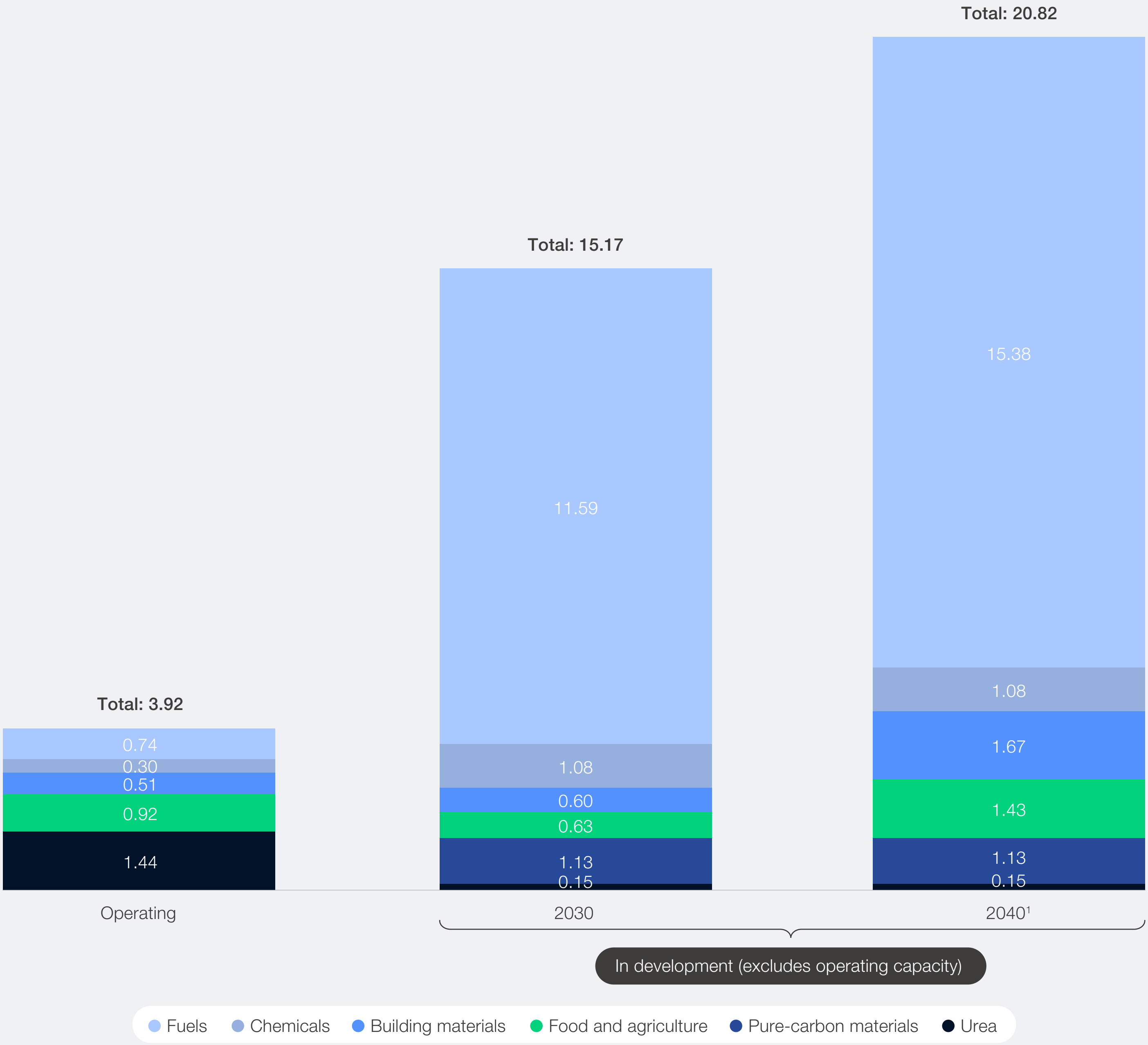
However, in contrast to these forecasts, the project pipeline of investments in CCU remains very low, due to systemic market barriers currently facing the sector, with only around 21 Mtpa in development to 2040 (see Figure 3).[18]

1.2 The current CCU project pipeline

Urea production is a mature market today, predominantly using CO_2 generated through steam methane reformation. A proportion of operating urea capacity, around 1.44 Mtpa, uses captured CO_2 from point sources as a feedstock (see Figure 3). Pilot- and demonstration-scale plants make up much of the remaining capacity, principally across fuel, chemical and building materials applications.

The current CCU project pipeline to 2040 indicates that planned investment is focused towards the production of fuels, which includes power-to-liquids sustainable aviation fuel (PtL SAF) and methanol, with lesser contributions from other chemicals, including ethylene and propylene (olefins), and construction materials.

FIGURE 3 **CCU capacity operating and in development, by final product type (Mtpa CO_2)**



Note:

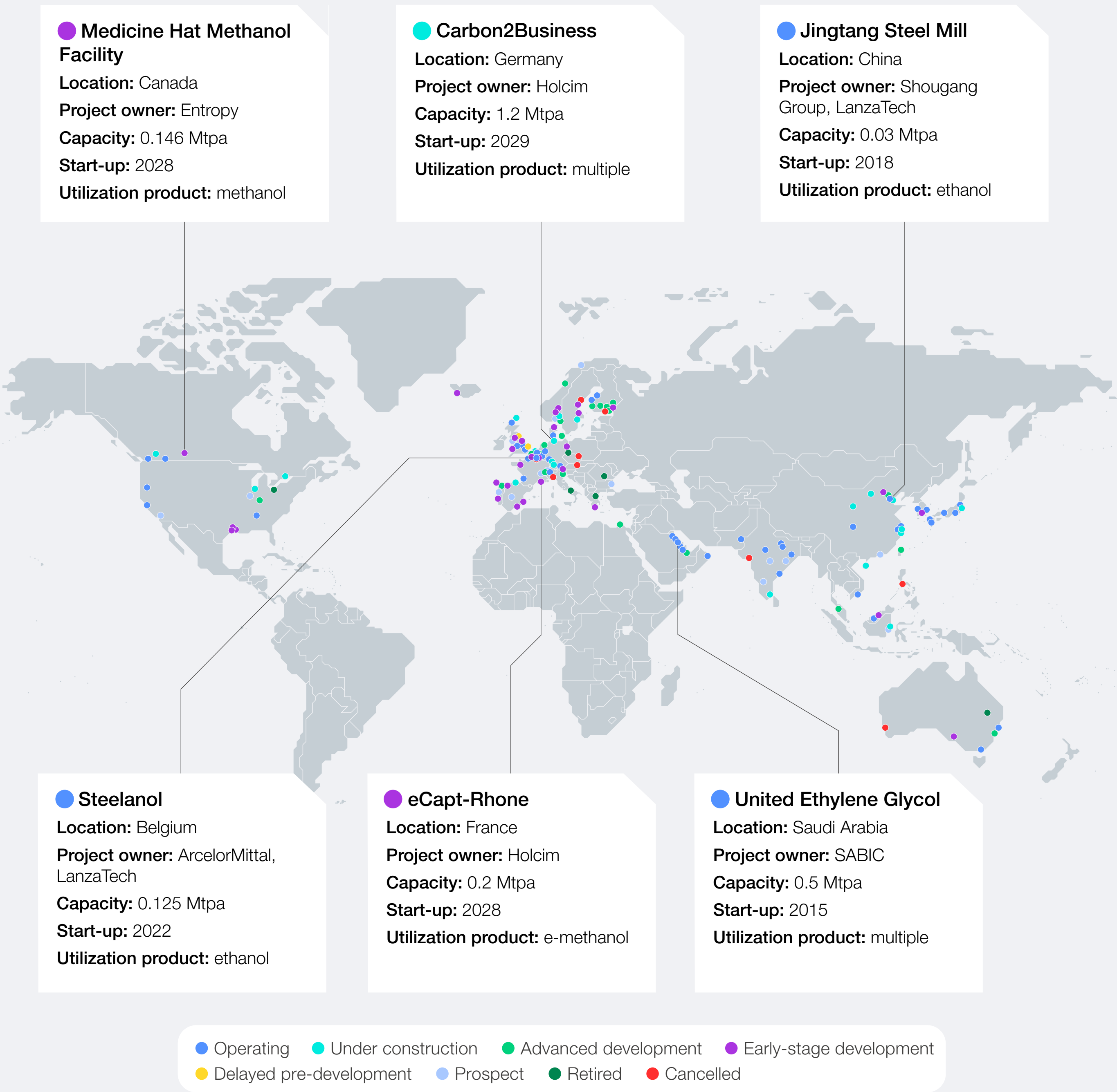
1. 2040 in-development capacity includes 2030 in-development capacity.

Source: Wood Mackenzie Lens Carbon.

Geographically, CCU activity is currently focused within regions which host existing commercially mature sectors and where funding mechanisms or regulatory frameworks enable first-of-a-kind projects, with concentrations of non-urea CCU at varying stages of development in Northern and Western Europe, the Gulf states, China, Australia, the US and Canada.[19,20,21,22,23,24]

Figure 4 shows the global distribution of CCU projects operating and in development up to 2040, colour-coded by development status. Enhanced hydrocarbon/oil recovery schemes (EOR) are excluded.

FIGURE 4 **Global distribution of CCU projects operating and in development to 2040**



Notes:

- Mtpa refers to mass of CO_2e utilized.
- Status definitions: under construction = FID taken; advanced development = in front-end engineering design (FEED) or advanced feasibility, working towards FID; early-stage development = project is announced and early feasibility work is underway; delayed pre-development = project has been delayed or suspended but restart is likely; prospect project = announced but undefined; retired = was operational but has ended; cancelled = announced but since cancelled.

Source: Wood Mackenzie Lens Carbon.

1.3 Utilization pathways

There is a range of emerging CCU pathways at different levels of technology readiness and addressable market potential (see Figure 5). Applications span agriculture, construction, fuel and chemicals manufacturing, as well as emerging next-generation materials such as graphene and carbon nanotubes. The relative scale of these applications in the coming decades will be driven by a combination of demand in end-use sectors, the rate of learning improvements and cost reductions in both CCU technologies and feedstocks such as low-carbon hydrogen.

Fuels and chemicals

Methanol represents a significant market opportunity, given the wide range of downstream applications across olefins, e-fuels and maritime transport. Current forecasts see e-methanol demand of around 40 Mtpa by 2050, out of a total 227 Mtpa of overall global demand.[25] This represents approximately half of overall low-carbon methanol production. There will be potential for this to grow further if e-methanol becomes the dominant production route; however it is competing against other low-carbon approaches.

Current forecasts see e-methanol demand of around 40 Mtpa by 2050, out of a total 227 Mtpa of overall global demand.

Bioethanol/e-Ethanol may present a significant, but comparatively lower, market opportunity as demand for gasoline is expected to decline in the coming decades. The technology exists at near-commercial scale today, with LanzaTech already producing at sites around the world. SAF-producing pathways benefit from existing policy support, particularly in Europe with mid-term growth potential.

Use of e-methane could play a similar role to alcohols as a feedstock in chemical and plastic applications, as well as in fuel applications. e-Methane benefits from opportunities to leverage existing infrastructure, as well as its potential as a "drop-in" replacement for fossil methane.[26]

Demand for olefins will be substantial by 2040, with the Chinese market being a primary driver. Projecting forward to 2040, global demand for ethylene and propylene derivatives could be as high as 519 Mtpa.[27,28] However, steam cracking is currently modelled to provide the majority of associated production capacity. Market penetration of CCU into the olefins sector will require cost reductions in catalytic CO_2 hydrogenation and/or electrochemical CO_2 conversion pathways, as well as methanol and ethanol synthesis feeding into alcohol-to-olefin routes.[29]

Regardless of pathway, the feasibility of all CCU-derived hydrocarbon production will be strongly influenced by the cost and availability of renewable electricity, low-carbon hydrogen and CO_2.

Building materials

The use of CO_2 in building materials, specifically CO_2-treated aggregates and CO_2-cured concrete, are near cost-competitive today, with significant growth potential. Global markets for these materials already exist at scale and are forecast to grow to over 100 Gt across concrete and aggregates by 2040.[30] Only a portion of this demand is likely to be realized by CO_2-treated products and, in

FIGURE 5 | **Summary of emerging CCU pathways, maturity and cost comparison**

	Technology pathway	Theoretical market opportunity (2040)[1]	Conversion technology maturity[2]	**Cost of final product with carbon oxide conversion,** relative to conventional, non-CCU production[3]
Fuels and chemicals	**Methane**		Methanation	2 to 2.5x
Fuels and chemicals	**Methanol**		CO_2 catalysis; Reverse water gas shift; CO_2 electrolysis; Plant co-feed	1.2 to 1.5x
Fuels and chemicals	**Ethanol**		Gas fermentation	N/A (used as intermediate)
Fuels and chemicals	**Olefins**		CO_2 catalysis; Alcohol-to-olefins; CO_2 electrolysis	1.5 to over 2.5x
Fuels and chemicals	**Fuels**		CO_2 catalysis; Fischer-Tropsch; CO_2 electrolysis; Alcohol-to-fuel	1.5 to over 2.5x
Building materials	**CO_2-treated aggregates**		Carbonate mineralization	1.0 to 1.4x
Building materials	**CO_2-cured concrete**		CO_2-injection	1.5 to 1.7x
Pure-carbon materials	**Carbon nanotubes**		Molten salt electrolysis	N/A
Pure-carbon materials	**Electrochemical materials** incl. graphite		Molten salt electrolysis	N/A
Pure-carbon materials	**Carbon black**		Molten salt electrolysis; Methane pyrolysis	N/A

Notes:

1. Based on expectations of total target market size in 2040 (not specific to CCU). Quarter segments reflect 1-4 scale. 1 = low growth potential; 2 = mid/large-scale growth potential, but with contingencies or limitations; 3 = large-scale growth potential in 100's Mtpa; 4 = widespread, gigatonne-scale opportunity.

2. 1 = lab scale; 2 = small pilot scale; 3 = industrial-scale demonstration; 4 = implementable at commercial scale today.

3. Cost multiples assume use of cheap feedstocks ($2/kg for H_2, $100/tonne for CO_2) to highlight relative costs of conversion technologies.

Source: Wood Mackenzie Lens Carbon.

the case of CO_2-treated aggregates specifically, will be limited by the availability of waste material feedstocks. CO_2-treated building materials may also represent long-duration carbon sinks, creating opportunities to charge product premiums and sell removals credits if biogenic or atmospheric CO_2 is sequestered.[31,32,33] However, final life-cycle emissions are highly impacted by transportation and processing emissions, particularly if freshly mined materials are used in place of waste materials.[34]

Pure-carbon materials

Innovative start-ups are developing technologies for the conversion of CO_2 into carbon-based materials such as carbon nanotubes and graphite. In the case of graphite, current demand sits at 6 Mtpa increasing to ~8.6 Mtpa by 2040, driven by growth in the batteries market.[35] Moreover, geostrategic imperatives could accelerate regional production development as the US and European Union (EU) prioritize supply chain diversification.

1.4 World Economic Forum UpLink start-ups

The nascency of CCU markets creates a valuable role for innovative start-ups that can drive technological innovation and pilot emerging commercial models. The companies highlighted in Table 1 below demonstrate a cross-section range of CCU approaches being developed, all of which won the World Economic Forum Uplink CCU challenge and represent promising pathways for carbon conversion technologies.

TABLE 1 **Winners of the World Economic Forum Uplink CCU challenge**

Fuels and chemicals

Company	Technology	Product	TRL
Dioxycle	COx electrolysis	e-Ethylene from COx inputs	TRL 5
eChemicles	CO_2 electrolysis	CO and e-Ethylene	TRL 5
EnaDyne	Plasma catalysis	C1-C4 chemicals	TRL 5
Oxylus Energy	CO_2 electrolysis	e-Methanol	TRL 5
D-CRBN	Plasma catalysis	CO_2 conversion to CO	TRL 6
Icodos	Absorption-desorption	e-Methanol	TRL 6
Nanjing Gasgene	Gas fermentation	C3-C12 bulk chemicals, sustainable aviation fuel (SAF), animal feed protein	TRL 5

Pure-carbon materials

Company	Technology	Product	TRL
Up Catalyst	Molten salt carbon capture and electrochemical transformation (MSCC-ET)	CO_2 to carbon-based materials for energy storage, composites, coatings	TRL 5

Direct air capture + H_2

Company	Technology	Product	TRL
Parallel Carbon	Carbonate formation + pH swing	$CO_2 + H_2$	TRL 5
Greenlyte	Absorption-desorption	$CO_2 + H_2$	TRL 5

Building materials

Company	Technology	Product	TRL
Carbon to Store	Electrochemistry + chemical processing	Building materials from carbonation of alkaline wastes	TRL 5

Notes:
TRL = technology readiness level (scale from 1-9, where 9 is a fully proven and deployed technology); COx = carbon oxides (CO or CO_2); Cx-Cy chemicals = various carbon-based chemicals containing x or y number of carbon atoms.

2

Policy barriers

Policy frameworks for CCU are emerging globally, but are currently fragmented, volatile and favour sequestration over reuse.

> If governments wish to deploy CCU, regulatory support will be required to enable first movers to bear early risks and establish self-sustaining markets.

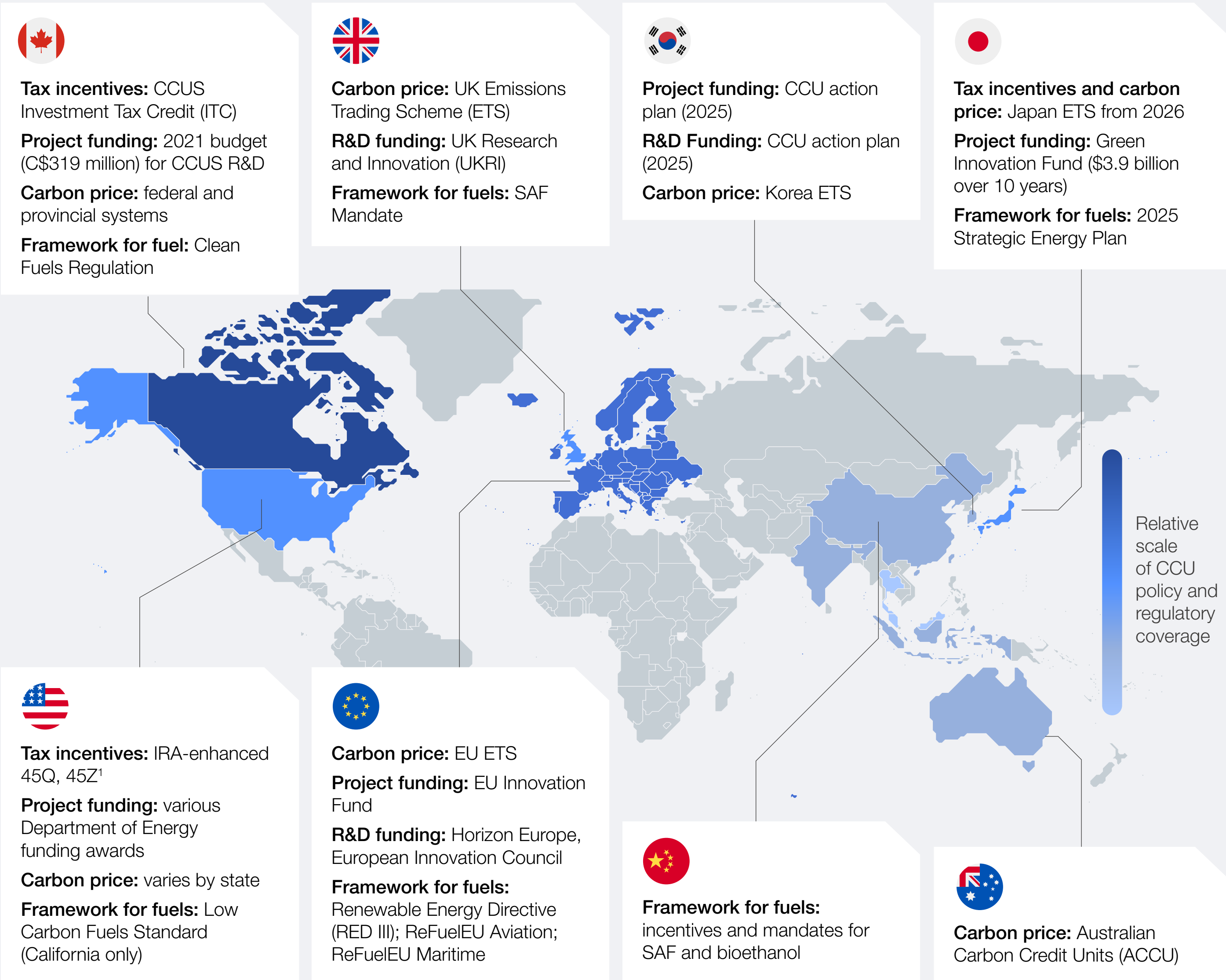
Scaling-up CCU depends on enabling policy and regulatory frameworks. Most emerging CCU pathways cannot currently compete on price with conventional production approaches without incentives and support. Additionally, the first-of-a-kind nature of many of the technologies presents a fundamental challenge to financing, due to the unfamiliarity of financiers with these new approaches. This creates a chicken and egg dynamic in which perceptions of technological risk, upfront cost and immature end-markets for CCU products prevent investment in the demonstration and scaling-up that could start to mitigate these barriers. If governments wish to deploy CCU, regulatory support will be required to enable first movers to bear early risks and establish self-sustaining markets.

However, the global CCU policy environment today is fragmented, inconsistent and often conflicting. Sequestration is favoured over reuse, though the absence of an effective global carbon price broadly undermines deployment of capture. This has introduced uncertainty among innovators and a perceived lack of policy credibility among investors. Existing frameworks are also regionally specific, leading to concentrations of CCU initiatives in certain jurisdictions. This has the potential to limit the global scale-up of CCU technologies, as well as increasing the impact of any policy instability.

2.1 The state of CCU policy

The regions with CCU policy frameworks and regulatory coverage are shown in Figure 6, together with relevant examples. The map is not exhaustive.

FIGURE 6 **Global distribution of CCU-relevant policy frameworks**



Notes:

1. Refers to US Inflation Reduction Act (IRA), sections 45Q (carbon oxide sequestration tax credit) and 45Z (clean fuel production tax credit).

Source: Wood Mackenzie Lens Carbon.

North America

The US tax code is a leading driver of CCU investment, particularly section 45Q of the Inflation Reduction Act (IRA), which provides a tax credit for CO_2 captured and either utilized or stored. Under the IRA in 2022, the value of the utilization credit was first increased from \$35 to \$60/tonne for utilization of point source CO_2 and \$35 to \$130/tonne for atmospheric CO_2.[36] The IRA also introduced direct pay and transferability provisions, which have been helpful for projects in raising capital. Further to this, the 2021 Infrastructure Investment and Jobs Act (IIJA) introduced capital support for DAC hubs (\$3.5 billion) and hydrogen hubs (\$8 billion), as well as a suite of CCUS-related research programmes.[37]

Political and regulatory volatility has contributed to a sense of heightened risk around US climate subsidies among investors.

However, much of this funding has since been withdrawn.[38] In 2025, the "One Big Beautiful Bill" further amended 45Q, bringing tax credits for utilization in line with those for sequestration: $85/tonne CO_2 from point sources and $180/tonne from DAC. Furthermore, the 2025 changes brought forward inflation adjustment by one year, starting in 2027.[39] The 45Q credit pays out to operators over 12 years provided construction starts before 2033.[40] While the final bill has enhanced the position of carbon utilization under 45Q, the preceding political and regulatory volatility has contributed to a sense of heightened risk around US climate subsidies among investors.

In Canada, the federal government provides a CCUS Investment Tax Credit (ITC), introduced in 2024 via the Income Tax Act. The scheme provides a tax credit covering between 37.5% and 60% of eligible capital costs up to 2030, depending on technology. From 2031 and 2040, the ITC rates will be halved and from 2040 phased out completely.[41] Canada has also implemented Clean Fuel Regulations (CFR), under which e-fuels projects can generate credits worth on average C$133.20/tonne.[42] On a provincial level, the Alberta Carbon Capture Incentive Program (ACCIP) also provides grant funding of 12% of eligible capital costs for CCU projects which permanently sequester CO_2.[43]

Europe

The EU regulatory environment is composed of a range of measures which have been introduced and revised over time. The result is a complex system of fragmented regulation, where member states have also implemented their own national-level frameworks. Overall, the EU's CCU ambition is integrated with CCS and carbon dioxide removal (CDR) through the Industrial Carbon Management Strategy. The strategy outlines the EU's intention for CO_2 to become a traded commodity within the single market by 2040. It envisions that 280 Mtpa CO_2 will need to be captured by 2040, of which one third (~92 Mtpa) could be utilized.[44]

The EU's regulatory levers currently focus on three delivery areas: the EU Emissions Trading System (EU ETS), e-fuel supply mandates and innovation support. The EU ETS currently only allows for carbon stored permanently in products to be counted against carbon price obligations, creating a level of incentive for carbonated aggregates and concrete. An upcoming EU ETS review in 2026 is expected to consider a number of changes which could enable CCU. This includes considering charging at the point of emission to atmosphere (rather than point of capture), whether to recognize non-permanent CCU and whether to include CDR.[45]

The EU's e-fuels measures focus on increasing the cost of counterfactual fuels to drive demand for CCU-derived alternatives. The Renewable Energy Directive (RED III) is the principal EU renewable fuels policy, which includes specific mandates and rules for e-fuel use across the bloc. At a minimum the regulation requires that

FIGURE 7 **Penalty calculation under ReFuelEU Aviation regulations**

Source: Wood Mackenzie Lens Hydrogen.

Regulation will lead to competitive CO_2-derived SAF from 2040 onwards, but it will be high cost and will remain largely driven by the cost of green hydrogen production.

1% of all fuels used in transport by 2030 should be RFNBO (renewable fuels of non-biological origin), which includes e-fuels. The RED regulation currently allows for industrial point source CO_2 to be utilized, but specifies post-2040 that all CO_2 feedstock for e-fuels must come from atmospheric or biogenic sources to be considered as avoided.[46] Given the relatively small volumes of biogenic and atmospheric CO_2 expected to be available by 2040 in comparison to point source capture, concerns have been raised about the feasibility of this clause.

The EU has also introduced the FuelEU Maritime and ReFuelEU Aviation regulations, which draw on the RED sustainability criteria. The ReFuelEU Aviation regulation sets out PtL SAF (e-SAF) quotas from 2030, which rise to 35% by 2050. Penalties for non-compliance are levied on fuel suppliers per tonne of fuel below quota, at a rate of twice the difference between references prices for conventional aviation fuel and e-SAF. Reference prices for 2024 are equivalent to $8,348/tonne of e-SAF (10x conventional) and $796/tonne of conventional aviation fuel (see Figure 7).

Analysis shows that the regulation will lead to competitive CO_2-derived SAF from 2040 onwards, but it will be high cost and will remain largely driven by the cost of green hydrogen production.[47] For the shipping sector, the FuelEU Maritime regulation specifies that should RFNBOs remain lower than 1% in the shipping sector by 2031, a sub-quota of 2% will apply from 2034.[48]

The EU's framework for innovation provides support from early-stage innovation to commercial scale. This includes the Horizon Europe research fund, the Innovation Fund for near-commercial scale, first-of-a-kind climate innovation projects and the European Innovation Council (EIC), which provides broad financial and advisory support across a range of subject areas and technology readiness levels (TRL).[49,50]

Asia

Policy frameworks for CCU across Asia are in early stage, with China, Japan and the Republic of Korea as frontrunners. Japan's CCU strategy is set out in its 2025 Strategic Energy Plan. The focus areas are e-chemicals, e-fuels and minerals, with commercialization targets starting from 2040 onwards. Japan's Green Innovation Fund has been established to support these early projects, with a budget of $3.9 billion over 10 years.[51] The fund is currently supporting a range of demonstration projects at a base in Hiroshima, utilizing CO_2 from a coal gasification facility. In addition, Japan has started early cross-border collaborative work on CO_2 accounting, as well as other international initiatives. Longer-term policy frameworks are in development and the country is preparing to implement a Green Transformation Emissions Trading System GX-ETS from 2026.[52] The GX-ETS is expected to include CO_2 mineralization, creating an incentive for CO_2-treated building materials, although the specific methodology remains under discussion.

In 2025, the Republic of Korea launched its CCU action plan, aimed at accelerating R&D in chemical and biological CO_2 conversion, as well as mineral carbonation. Initially, this will involve designating and operating CCU "strategic research labs" and launching a flagship CCU project. In the longer term, more detailed regulations specifying standards and certification of CCU technologies, products and enterprises will be developed.[53]

2.2 How policy could support CCU

Financial incentives for adoption

Direct subsidies, carbon prices and consumption mandates could all play a role in offsetting cost and driving demand for CO_2-derived products.

To date, the CCU sectors that have seen the most scale are those most able to generate revenue in isolation. The core challenge for emerging pathways, particularly for fuels and chemicals, remains the substantial cost hurdles. Direct subsidies, carbon prices and consumption mandates could all play a role in offsetting cost and driving demand for CO_{2}-derived products.

Incentives that are technology-agnostic have been particularly effective in driving investment. Specifically, the broad applicability of the US's 45Q tax credit to capture carbon for the purpose of reuse has enabled access to financing where technology risk is a barrier to traditional debt financing. The increase in utilization credit price in 2025 could result in a further boost to CCU investment. However, continued investment would require certainty of mechanisms post-2033.

In contrast, the EU's prioritization of storage, while critical for emissions mitigation, has created a disincentive for CCU – because the EU ETS levies costs on CCU in all cases except when it results in permanent sequestration. Consequently, the large upfront capex for the equipment to capture and convert CO_2 – plus the requirement to pay a carbon price (by surrendering EU ETS emissions allowances or by covering the cost for the CO_2 provider) – create a major disincentive for CCU, compared to emitting.

The EU ETS could be an enabler of CCU if it provided a commercial incentive for products with a wider range of storage durations.

Some innovators are taking steps to avoid this, for example by prioritizing CO_2 sources that do not require the surrender of allowances. Nevertheless, the EU ETS could be an enabler of CCU if it provided a commercial incentive for products with a wider range of storage durations. Content mandates, similar to the mechanisms introduced for SAF, could also help support investment in e-chemicals pathways.

Stakeholders have put forward proposals to classify utilization products according to their carbon storage duration or potential to displace fossil carbon, such as the Global CO_2 Initiative's Track 1 and Track 2 definitions (see Box 1). While product classifications would need to be accompanied by robust LCA, differentiated carbon pricing could incentivize utilization products that, despite falling short of permanent sequestration, could still deliver emissions reductions. For example, nuanced classifications that recognize the different emissions mitigation potential of different end products could complement considerations linked to feedstock source. This should be based on internationally recognized and standardized LCAs for CCU.[54,55,56,57]

BOX 1: Track 1 and Track 2 utilization product definitions could help to target policy incentives

The Global CO_2 Initiative has developed definitions of Track 1 and Track 2 CCU products which are differentiated by storage duration. The classification is intended to provide clarity for policy-makers and financiers when assessing support for CCU developments.

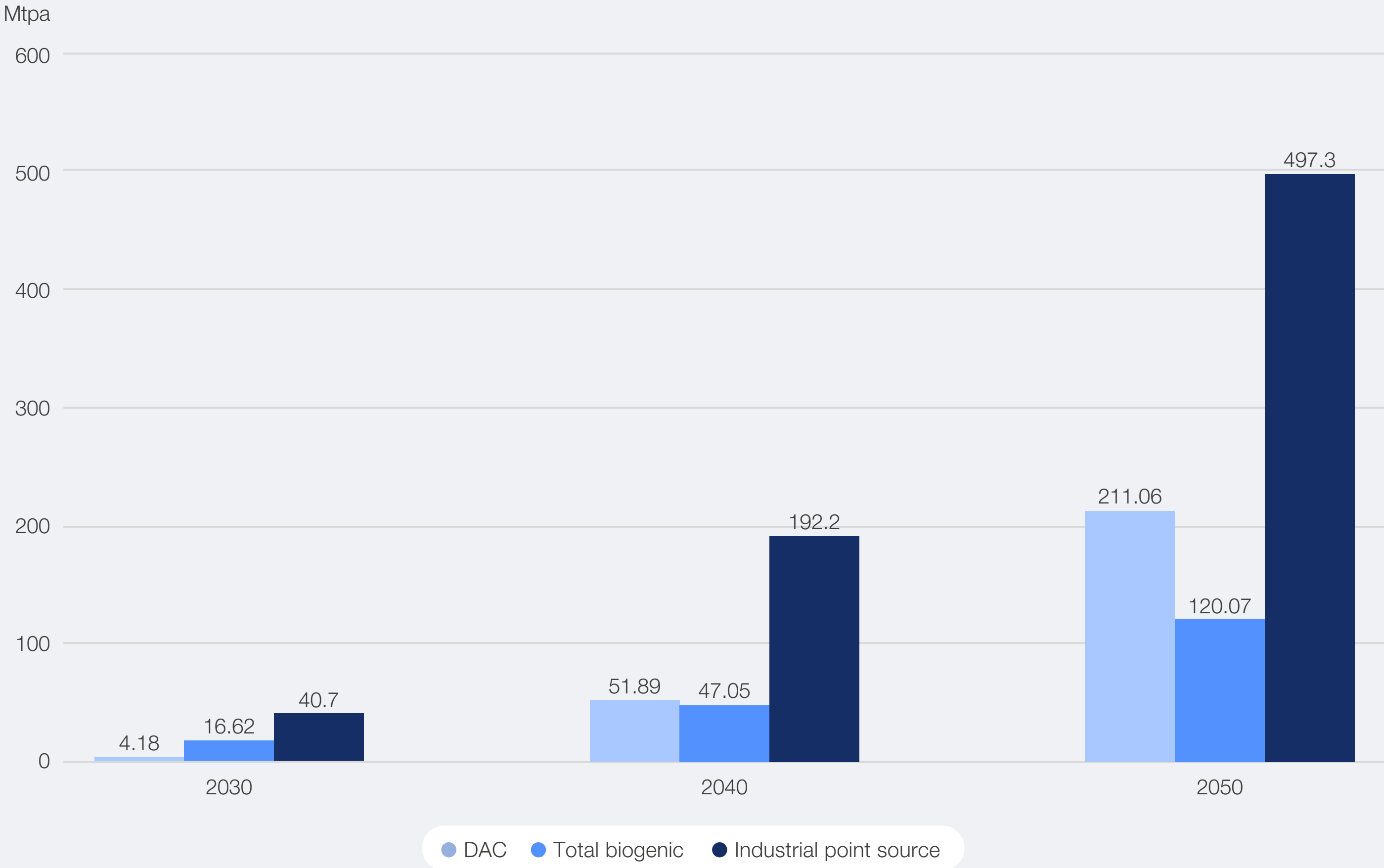
Track 1 CCU products: these are defined as removing CO_2 for at least 100 years, if not permanently. In practice, Track 1 products are broadly equivalent to storing CO_2 underground (CCS), for example: CO_2-treated construction materials (e.g. aggregates, pre-cast concrete). Track 1 products currently receive the most support globally, given the ease of integration into existing subsidy and carbon pricing regimes.

Track 2 CCU products: these release CO_2 back into the atmosphere within fewer than 100 years, through use or decomposition (e.g. fuels and chemicals with storage duration measured in months to decades). While the climate benefits of such products are limited compared to long-term sequestration, Track 2 products can displace virgin fossil carbon in circulation or be carbon neutral, depending on the emissions source.

Source: Global CO_2 Initiative.[58]

Moreover, in the near- to mid-term, it will generally be cheaper to capture concentrated CO_2 rather than dilute atmospheric sources. Until 2040, CO_2 volumes from industrial point sources are expected to be significantly more abundant than combined atmospheric and biogenic sources (see Figure 8). Point source capture could theoretically enable capture at lower cost and help unlock investment at scale, assuming long-term price signals are applied. However, beyond capture cost, the final cost of CO_2 as a feedstock will depend on the balance of policy costs, incentives and its value to the provider.

FIGURE 8 | CO_2 capture capacity outlook to 2050, by CO_2 source



Notes: Relative share of CO_2 capture capacity expected in 2030, 2040 and 2050 across CO_2 sources. Biogenic comprises both BECCS and ethanol. Industrial point source is the sum of cement, steel, refining and chemicals.

Source: Wood Mackenzie Lens Carbon.

Creating credibility

The cost of capital is very sensitive to perceptions of policy risk or bankability of a subsidy offering. This is particularly important for CCU projects as they are effectively high-risk, long-term infrastructure investments with high upfront capital requirements. Early innovative projects therefore seek to identify jurisdictions with the right combination of credibility and adequate incentives.

Commitment to direction and consistency across policy areas is therefore key. Without this, novel CCU projects can quickly become unfinanceable. For example, despite an initial boom in US investment in 2021 and 2022, investment is now challenged by political risk following withdrawal of federal climate tech funding and volatility around 45Q. This contrasts with Canada, which is increasingly viewed as an attractive region by financiers of CCU projects, due to the perceived stability of its ITC offering. In addition, financiers are growing less confident in backing companies which rely on single incentives for viability. Instead, they are looking for projects that can take advantage of numerous levers, so the failure of one does not derail the project. Some innovators, particularly those with multiple products or value propositions, are better able to strategically manage perceptions of policy risk (see Box 2).

For the foreseeable future, certain jurisdictions with the right combination of scaling-up opportunities and credible policy environments will remain areas of focus. This is a challenge for start-ups seeking to identify sites to host demonstration projects, as suitable countries with credible and supportive policy environments may differ from their current base. While there is a balance to be struck by considering the location of their team, engaging with global companies for scaling-up opportunities can provide optionality. Such geographical diversification can also be a route to mitigating against policy risk.

> “ Canada is increasingly viewed as an attractive region by financiers of CCU projects, due to the perceived stability of its Investment Tax Credit.

BOX 2: **Carbon To Stone benefits from public procurement demand signal**

The top innovator from the Forum's UpLink programme, Carbon To Stone, has experience navigating political risk and has benefited from standards set by public sector procurement in supporting scale-up of CCU. Carbon To Stone is a leading start-up developing reactive CO_2 capture and mineralization technology which generates carbonated material using alkaline waste materials combined with point source or atmospheric CO_2 capture, for use as low-carbon or carbon neutral building materials.

Being able to make a policy-independent, value-driven pitch to prospective customers can be a valuable tool for start-ups in navigating a shifting political environment. In this case, being able to position themselves as a company specializing in waste upcycling, rather than carbon capture, has been a useful strategy.

Carbon To Stone's story highlights the role public sector procurement can play in driving demand among prospective customers. For example, under their Buy Clean Concrete Guidelines, the government of the State of New York requires that purchases of construction materials meet defined sustainability criteria.[59] This has led to increasing interest in low-carbon and carbon neutral building materials, with new customers among concrete suppliers driving new business for Carbon To Stone.

Source: Wood Mackenzie, expert interview with Carbon To Stone.

Standards and public sector procurement

Beyond direct mandates, the public sector has the capacity to drive standards through procurement and other forms of offtake agreements.

Product classification could be a valuable lever for driving market interest in CCU-derived alternatives to conventional products. Being able to credibly demonstrate emissions intensity improvements can be a market differentiator for products that are uncompetitive on price. Opportunities to tie such classifications to consumption or emissions-intensity mandates for end-use sectors will enhance this further. This could include minimum standards for emissions-derived and DAC/biogenic carbon within carbon-based products.

Beyond direct mandates, the public sector has the capacity to drive standards through procurement and other forms of offtake agreements. The public sector is the leading buyer of many CCU-relevant products, in particular construction materials and fuels. By requiring that these materials come with certain environmental product declarations, incumbent industrial suppliers will be increasingly incentivized to invest in low-carbon options to remain competitive.

2.3 Considerations for addressing policy barriers

To address and navigate the policy and regulatory barriers described above, the following enabling actions are recommended for key stakeholder groups.

First movers – navigate policy and political risk

While the wider policy and regulatory environment is largely beyond innovators' sphere of influence, the following strategic approaches could help mitigate associated risks:

- Aim to establish operations in regions with the right combination of credible incentives and political stability.
- Where possible, target regions which can provide multiple policy levers to draw on, providing redundancy and improving financing appeal.
- Aim to pursue geographical diversification as a means of mitigating policy risks where practical.
- Engage with the public sector as a prospective offtaker to identify and comply with potential product requirements.
- Ensure that pitches to investors highlight the commercial value of the product independent of alignment to policy ambitions.
- Ensure that the technology will be financially viable when operating at scale, without subsidy.

Policy-makers and regulators – address perverse incentives and expand support

- Work with the scientific community to develop consensus on the range of mitigation opportunities presented by different CCU pathways and CO_2 sources. Identify a preferred industry-standard CCU LCA methodology.

- Draw on an industry-standard LCA methodology to create regulatory clarity for emerging products, including classifications or standards.

- Introduce credible and technology-agnostic incentives. Established mechanisms such as contracts for difference (CfD) can be utilized to provide sufficient stability to enable project financing.

- Consider the role of carbon pricing regimes in accounting for the diversity of emissions benefits arising from CCU products that do not result in long-term sequestration, informed by LCA.

- Develop incentives for emissions-derived carbon use in chemicals manufacturing that can unlock investment and drive demand. This could include recycled carbon content mandates within products, as well as CCU product blending into conventional product markets.

- Work with industry and sector associations to identify and address perverse incentives, to ensure that CCU projects are not subject to additional regulatory hurdles that business-as-usual practices do not face.

- Leverage product standards in public procurement to drive demand for CO_2-derived products.

- Expand CCU R&D funding to accelerate technology maturation.

- Ensure that CO_2 transport infrastructure is designed with all industrial carbon management applications in mind – including CCS, CCU and CDR.

3 Financial barriers

CCU start-ups currently face financing challenges due to long development timelines, high capital requirements and immature business models.

Innovative CCU technologies face a distinct set of financing challenges that hinder their path to commercial viability. These challenges stem from long development timelines, high capital intensity, fragmented policy support and an immature market structure. As a deep tech sector,[60] CCU technologies typically progress through extended R&D cycles and require significant funding to demonstrate and scale up. At each stage of this innovation curve, the risk-return profile shifts, presenting unique barriers to capital access and misalignments with investor expectations.

The result is a series of "valleys of death" — funding gaps that arise during transitions from research to pilot, pilot to demonstration and demonstration to full-scale deployment. Overcoming these requires patient, risk-tolerant capital and more strategic alignment between technology development and financial ecosystems.

3.1 Investment trends in CCU

Investment in CCU companies has increased sharply since 2020. Fuels, chemicals and intermediates have seen the greatest increase in investment across all pathways.

Investment in CCU companies has increased sharply since 2020 (see Figure 9). Fuels, chemicals and intermediates have seen the greatest increase in investment across all pathways. Investment in technologies for producing CO_2-treated building materials has also increased since 2021, but still lags behind other emerging pathways.

US-headquartered companies continue to dominate CCU investment flows, with a surge in 2022 (likely driven by expansion of the 45Q tax credit and capital grant funding under the IIJA) that significantly improved the economic viability of carbon capture projects.

Since 2023, regional investment flows have diversified, with European and Canadian CCU developers capturing increased market share. In Europe, this shift has coincided with the implementation of RED III, which has created new incentives and greater policy clarity for carbon utilization in fuel applications. The trend underscores the growing importance of regional policy frameworks in shaping investor confidence and capital allocation. While the US retains a leadership position, regulatory certainty in Europe and Canada is enhancing their competitiveness (see Figure 10).

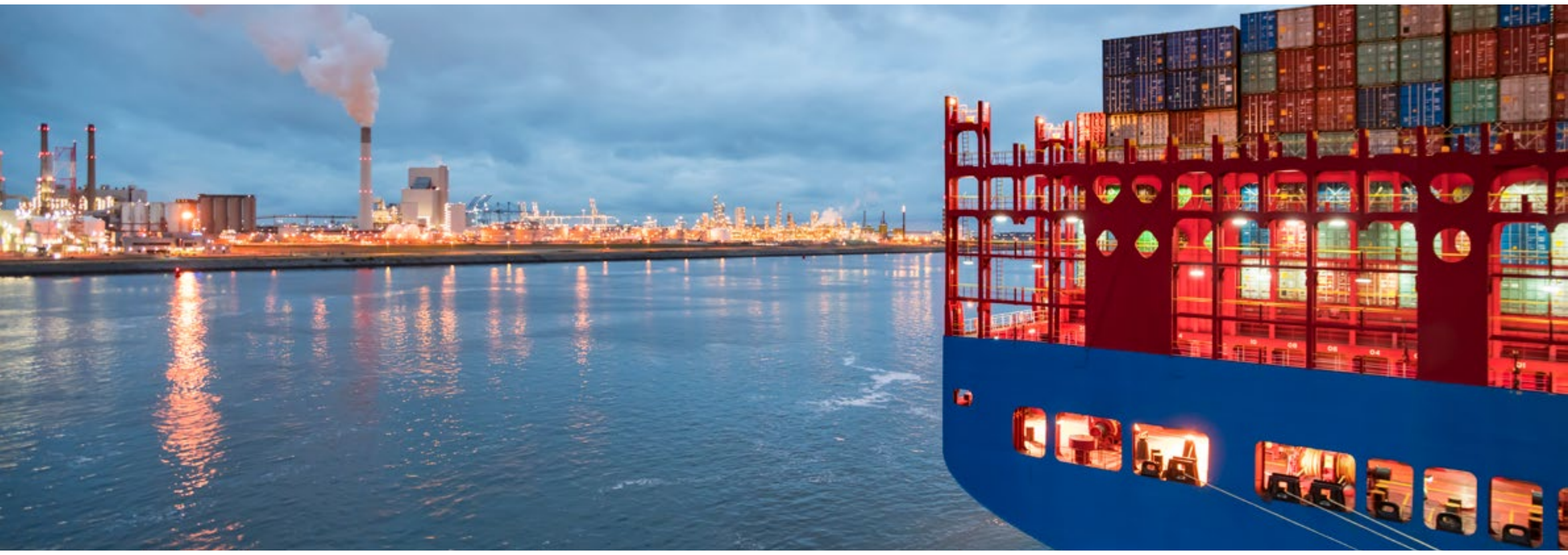
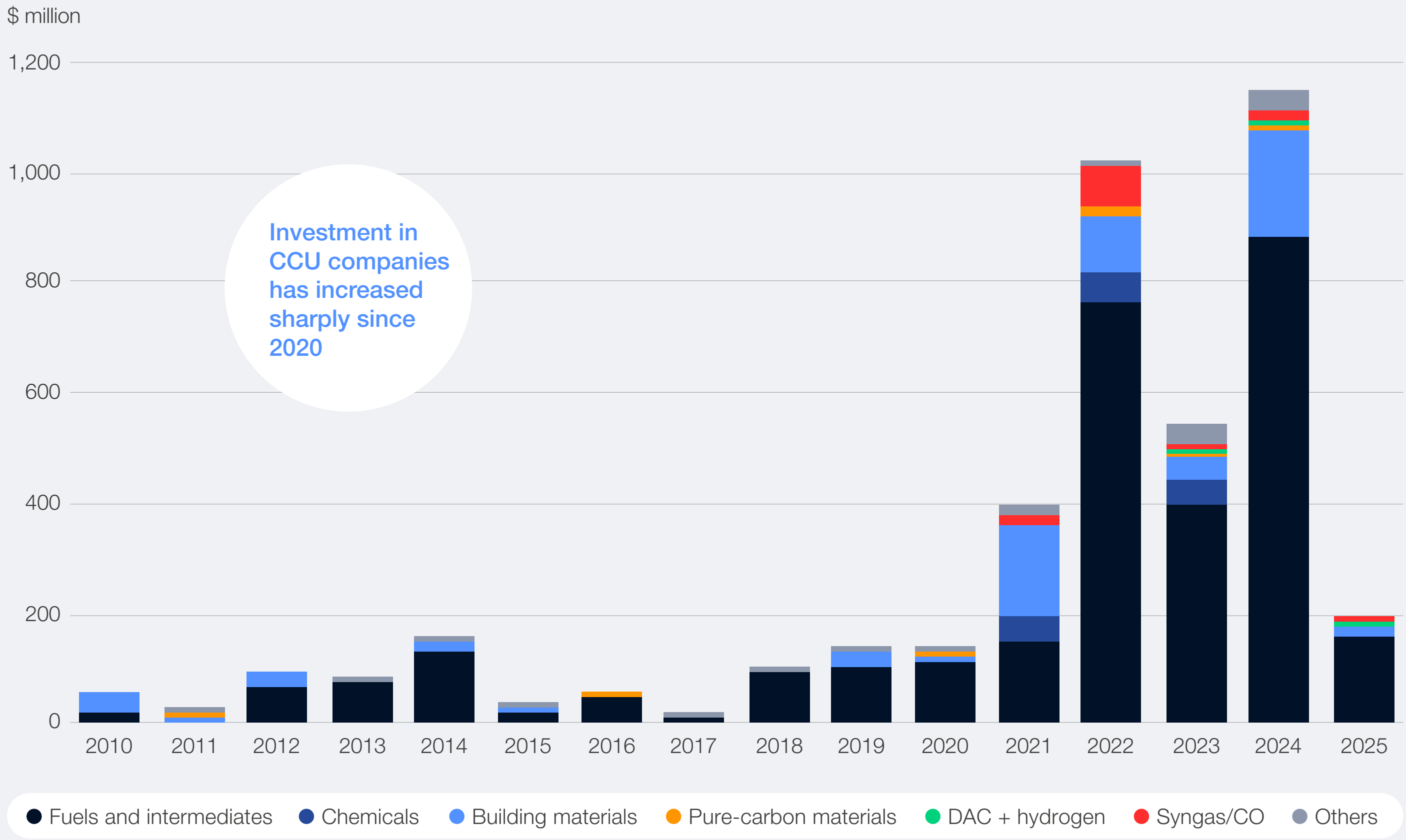
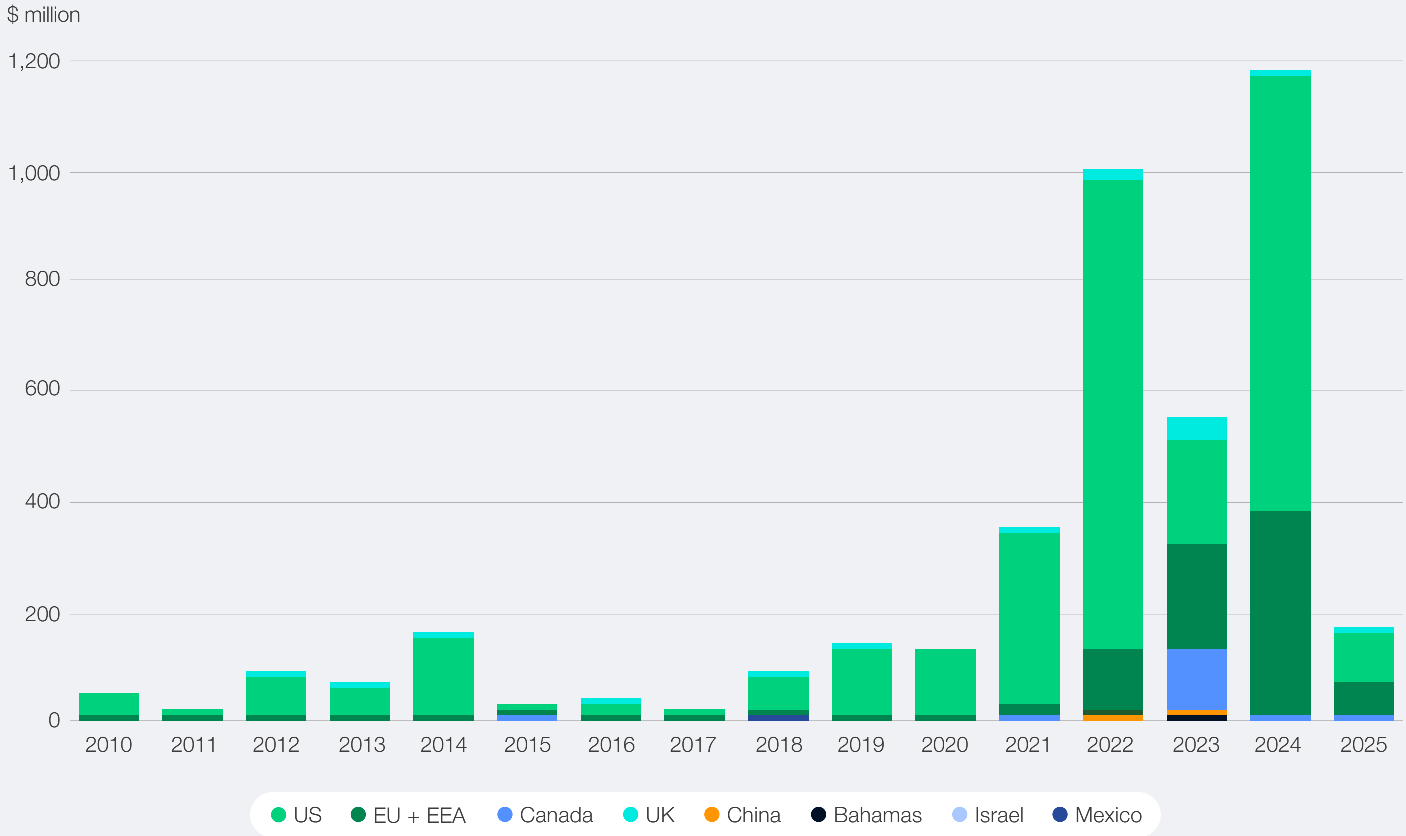


FIGURE 9 | **Investment in CCU companies, by utilization product and region (2010-2025)**

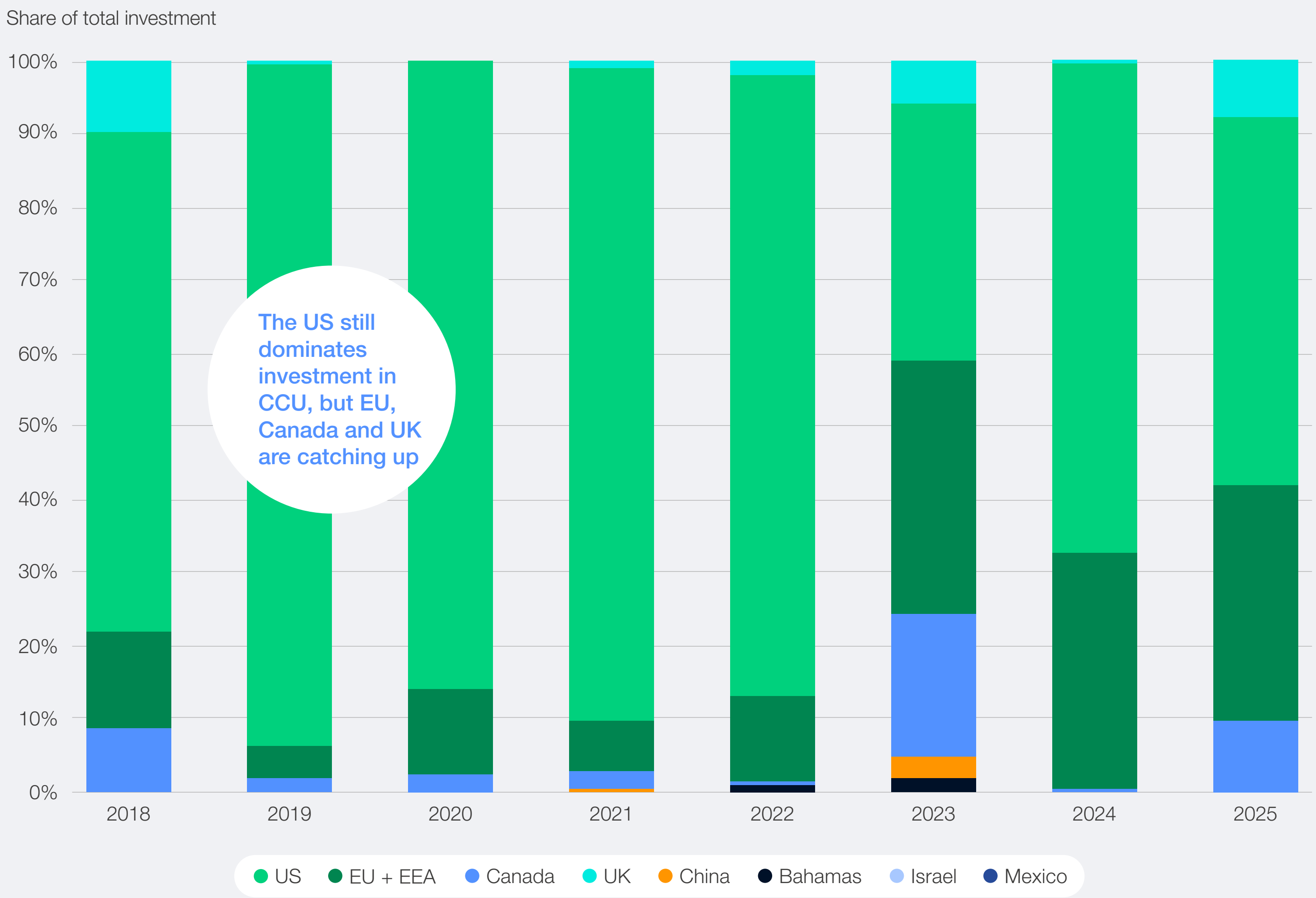




Notes: Others include bicarbonate, biochar, energy storage, fertilizers and proteins.

Source: Wood Mackenzie Lens Carbon, data provided by Dealroom (2025).

FIGURE 10 | **Investment in CCU companies, relative share by region (2018-2025)**



Note: Countries refer to location of company HQ.

Source: Wood Mackenzie Lens Carbon, data provided by Dealroom (2025).

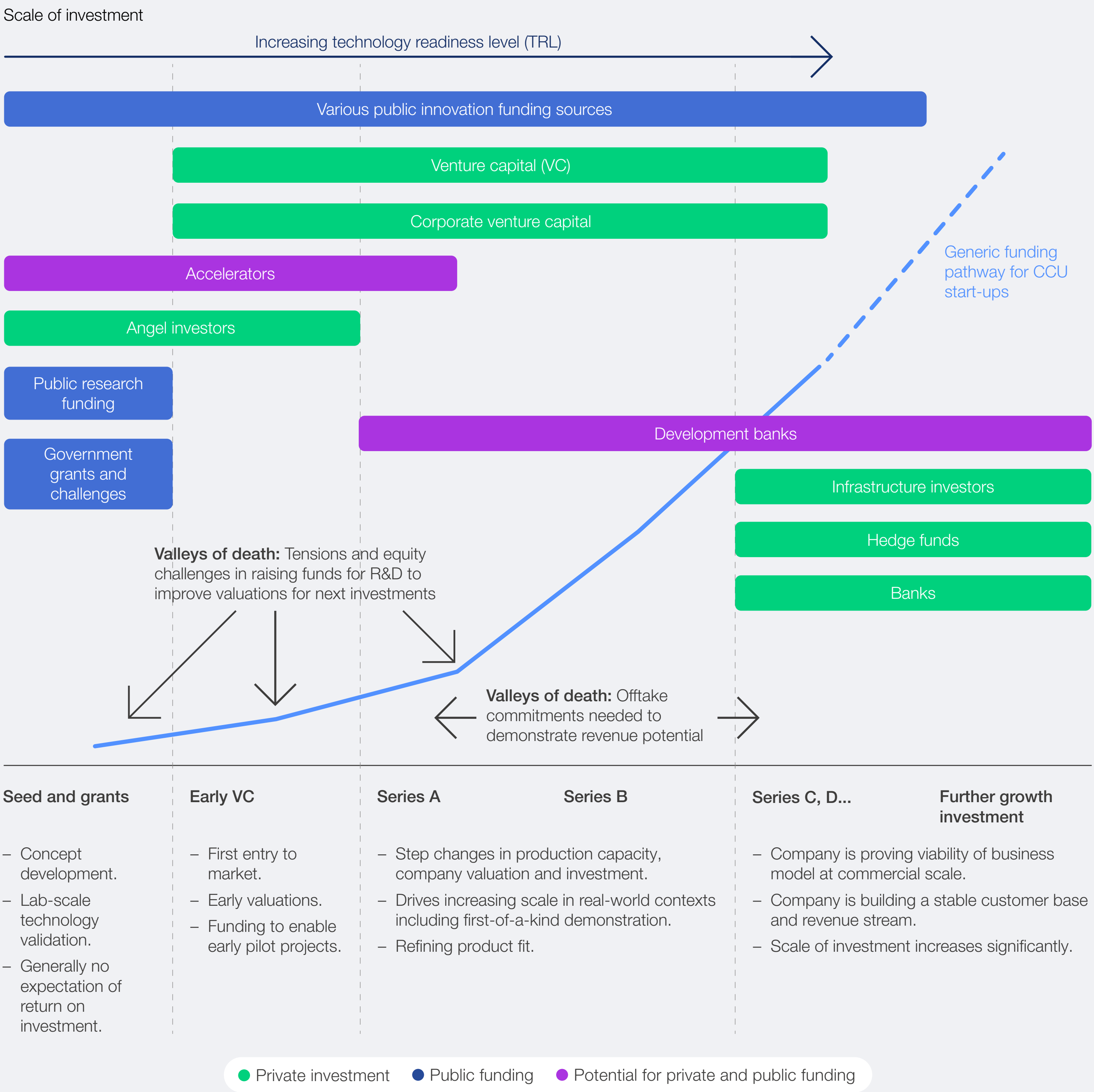
3.2 Financial barriers and enablers along the innovation curve

A funding gap often emerges when transitioning from research validation to industrial pilot development: the first valley of death in the CCU life-cycle.

Each stage of CCU technology development – early research, pilot testing, demonstration and commercial deployment – presents a distinct set of financial challenges. These stages differ in capital intensity and cost of capital, as well as types of investors and risk profiles. As CCU technologies develop they encounter successive valleys of death, where funding gaps can stall progress despite technological promise. Mapping these barriers along the innovation curve helps identify where targeted interventions from both private and public actors would be most effective in supporting start-ups and first-of-a-kind technology deployments (see Figure 11).

Figure 11 gives an illustrative generic overview of the funding pathway for CCU start-ups, the roles of different investors at different funding stages and key valleys of death. Real-world journeys along this curve vary according to specific technology and company. Additionally, while the relationship is not exact, each funding stage can enable incremental increase in technology development (TRL) and scale, from early R&D, pilots and demonstrations up to full commercial deployment.

FIGURE 11 | **Illustrative overview of the innovation curve, role of investors and valleys of death**



Source: Wood Mackenzie Lens Carbon.

Early-stage R&D: de-risking the unknown

At the lowest technology readiness levels, CCU innovation, like any technology innovation, is exploratory and commercially unvalidated. Development timelines are unpredictable and technical outcomes are uncertain, making this phase risky for most conventional investors.

As a result, CCU start-ups depend on public research grants, philanthropic capital and challenge-led R&D competitions to establish scientific credibility and generate proof of concept. However, a funding gap often emerges when transitioning from research validation to industrial pilot development: the first valley of death in the CCU life-cycle, where limited venture appetite meets growing capital requirements.

Funding sources that tolerate uncertainty, offer longer investment horizons or reduce dilution pressure can create much-needed breathing room.

Pilot stage: the "early equity trap"

Building and operating pilot facilities introduces significantly higher capital demands, with limited short-term commercial returns. Given ongoing technology risk and long time horizons for revenue, many investors require disproportionately large equity stakes to justify early-stage backing.

This dynamic, known as the early equity trap, has led some start-ups to give up an excessive share, potentially 50% or more during pilot fundraising. While this may enable progress in the short term, it often undermines longer-term viability by deterring future investors and risking founder displacement.

To overcome this, patient capital becomes essential. Funding sources that tolerate uncertainty, offer longer investment horizons or reduce dilution pressure can create much-needed breathing room. Emerging models, such as Tencent's CarbonX Program (see Box 3), provide structured pathways to de-risk early pilots and improve downstream financing options.

BOX 3

Tencent CarbonX Program aims to bridge early valleys of death

Tencent's CarbonX Program is designed to accelerate the commercialization of CCU technologies, particularly those that can be integrated into consumer products.[61]

The programme aims to bridge the valley of death between academic research and early-stage industrial pilots by providing bridging support to selected research teams and start-ups, enabling them to accelerate first-of-its-kind pilots in real-world industrial settings and establish a new CO_2-to-chemicals-to-products value chain.

Start-ups selected for the programme can access:

- Catalytic grant funding of up to several million US dollars.
- Mentorship and technical support from Tencent and its partners.
- Pilot deployment funding, including coverage of the "green premium", so that industry partners can test products at no additional cost.
- Supply chain integration, enabling research teams and start-ups to validate their technologies in operational settings.

CarbonX Program works closely with a wide network of ecosystem partners, including major consumer brands and industrials, with the intention of supporting the development of sustainable supply chains and enabling real-world testing of low-carbon innovations. The programme also works with a range of investment partners who may consider making equity investments when appropriate, to support the growth of the start-ups and commercialization of emerging technologies.

Source: Wood Mackenzie, expert interview with Tencent.

A persistent mismatch exists between public sector decision-making timelines and the fast-paced fundraising needs of early CCU companies.

In parallel, the public sector plays a structurally distinct enabling role at this stage. First-of-a-kind technology deployments face a multidimensional risk profile, including technical, regulatory, market and integration barriers, that private investors often struggle to assess or price. Public funders are better positioned to absorb this uncertainty, taking a strategic and long-term view that aligns with climate, innovation and economic policy goals.

Instruments such as public equity investments, loan guarantees, first-loss mechanisms and co-investment structures can help de-risk pilot-stage technologies and crowd in private capital. Public institutions can also aggregate technical expertise, supporting due diligence for unfamiliar or complex technology classes. Notable examples include the EIC, which blends grant and equity-based funding to scale deep tech innovation across the EU (see Box 4).

Development finance institutions, such as the European Investment Bank and the Asian Development Bank, offer concessional loans, venture debt and large-scale grant funding to offset high capital intensity. However, a persistent mismatch exists between public sector decision-making timelines and the fast-paced fundraising needs of early CCU companies. Better alignment is needed to prevent promising technologies from being delayed by funding bottlenecks.

BOX 4 | European Innovation Council integrates public research funding and equity investment

The European Innovation Council (EIC) was established under the EU's Horizon Europe programme.[62] With a budget of €10.1 billion (for the period 2021-2027), it supports game-changing innovations throughout project life-cycles from early-stage research to proof of concept, technology transfer and the financing and scale-up of start-ups and SMEs. A unique feature of the EIC is that it provides funding for individual companies through both grants and investments. The investments currently take the form of direct equity or quasi-equity investments and are managed by the EIC Fund.

The EIC works with programme managers (PMs) – subject matter experts who are responsible for developing visions for technological and innovation breakthroughs in their fields of expertise. PMs actively manage portfolios of EIC-funded projects to advance these strategic visions, facilitating stakeholder collaboration to translate concepts into commercial reality. They also identify potential challenges for emerging technologies and disruptive innovations. To date, there have been several CCU-relevant challenge areas, including on solar-to-X and waste-to-value devices.

Source: Wood Mackenzie, expert interview with EIC.

Demonstration stage: proving commerciality

At the demonstration phase, CCU technologies must demonstrate feasibility scale, by integrating into real-world systems and generating revenue streams independent of government grants. However, this is often constrained by high upfront capital expenditure and insufficient demand certainty.

Capital expenditures for demonstration plants are typically factored into company valuations as depreciation, which may negatively affect investor perception of commercial viability. In parallel, many early projects struggle to present convincing offtake commitments and demonstrate the evidence of revenue potential that investors are seeking.

Therefore, securing credible offtake agreements, even if short-term or contingent on milestones, can de-risk investment and unlock capital. Programmes such as the World Economic Forum's First Movers Coalition (FMC) have demonstrated how aggregate demand from large buyers can send strong market signals. FMC offtake commitments now represent annual reductions of 31 MtCO_2e by 2030.[63]

For long-duration storage products, pre-purchase agreements for emissions removals can also help to fund deployment ahead of delivery.[64] These offer a form of patient offtake that allows producers to bridge short-term capital needs while retaining long-term value.

Commercial deployment: scaling-up strategically

Closer to commercial deployment, most first-of-a-kind projects face the challenge of competing with fossil incumbents in price-sensitive markets. While the products they offer are often chemically identical, they tend to carry a green premium during initial production rounds, limiting adoption in the absence of cost reductions.

Successful scaling-up requires strategic business models that reduce cost exposure, align with infrastructure investors and unlock new deployment mechanisms. One approach is the build-to-operate model, where the CCU company assumes early project risk in exchange for anchor offtake. As cost curves decline and technologies mature, licensing becomes a viable alternative, allowing scale without heavy capital outlay.

Geographic decoupling mechanisms such as book-and-claim can further reduce cost and risk and support demand. These allow low-carbon production in optimal regions, where clean energy and feedstocks are abundant, while enabling green credit claims elsewhere. Book-and-claim initiatives are attracting growing attention for enabling SAF demand, but could be applied to other CCU-derived products.

Crucially, at early stages it is important to anticipate the risk appetite of future scaling-up partners, including engineering, procurement and construction (EPC) firms and infrastructure investors. Even when CCU developers perceive additional scale as low-risk, their partners may not. Addressing these perceptions early improves the likelihood of securing project finance and attracting commercial-scale debt.

3.3 Considerations for addressing financial barriers

To address the barriers outlined across the innovation curve, the following enabling actions are recommended for key stakeholder groups.

Early-stage CCU companies – strategic positioning and capital planning

CCU companies must play an active role in shaping their funding trajectory – for example:

- Avoid early equity dilution by diversifying capital sources early, including patient and non-dilutive instruments.
- Demonstrate credible offtake through conditional or milestone-based agreements, even at demonstration scale.
- Pursue smart market entry strategies, avoiding early exposure to price-sensitive commodity markets where green premiums are unsustainable.
- Design for scale by anticipating the risk perceptions of future partners such as EPC firms and infrastructure investors.
- Utilize licensing and book-and-claim models to reduce capital exposure and unlock regional opportunities.

Private investors – de-risking and market signalling

Private investors, including venture capitalists, corporates and infrastructure funds, can:

- Tailor investment approaches to the TRL stage, with early-stage VCs focusing on technical milestones and late-stage investors demanding revenue validation.
- Participate in blended finance models where risk is shared with public or philanthropic actors (e.g. first-loss mechanisms, loan guarantees).
- Signal market intent through patient offtake, forward contracts or early equity commitments that can catalyse co-investment.
- Develop and expand both public and private patient capital vehicles which can help to bridge early funding gaps for CCU companies.
- Support book-and-claim initiatives to help developers realize locational cost savings and reduce cost hurdles.
- Identify mechanisms or approaches to address investment barriers associated with unavoidable upfront capital outlay. Where this cannot be achieved by private finance, public sector funders could play a greater role in de-risking investment.

Corporates and buyers – demand creation and scaling-up partnerships

Large industrials and downstream buyers have a unique ability to:

- De-risk supply chains by entering into offtake agreements or hosting pilot operations, reducing scale-up friction for early-stage companies.
- Join purchasing coalitions to aggregate demand and set credible benchmarks for future procurement.
- Support market formation and enable cost reductions through book-and-claim systems.
- Co-invest or incubate technologies that align with long-term sustainability strategies.

Public sector and development banks – de-risking and system stewardship

Governments and public finance institutions could consider the following to help scale up CCU:

- Support the introduction of book-and-claim initiatives.
- Establish public-sector procurement mandates for CCU-derived products to drive demand.
- Provide catalytic capital at early stages, including grant-to-equity mechanisms (e.g. EIC) and concessional debt (e.g. European Investment Bank – EIB, Asian Development Bank – ADB).
- Design risk-sharing instruments, such as loan guarantees, milestone-based grants and results-based financing.
- Act as aggregators of technical and market intelligence, helping reduce due diligence costs and align risk assessments across the finance chain.
- Align decision timelines with the faster-paced reality of venture-backed start-ups to avoid bottlenecks.

4 Cross-sectoral collaboration

Cross-sectoral collaboration provides opportunities to aggregate expertise, as well as coordinate risking sharing and advocacy activities.

CCU creates new forms of sustainable industrial symbiosis between industrial producers and end-users. As an emerging and diverse sector, no single institution typically possesses a complete range of expertise and resources required to deliver CCU projects independently. This places an emphasis on collaborative working, cross-sectoral thinking and partnerships to trial new technologies, overcome market barriers and identify new value propositions.

4.1 Leveraging collaboration to realize growth

Although start-ups and pilot-scale technology deployments cannot replace value chain steps wholesale, working with industry incumbents in viable applications creates anchor opportunities from which they can begin to scale up. By integrating into existing industrial value chains, CCU innovators can access infrastructure, expertise and market channels, while incumbents can explore potentially transformative sustainability solutions (see Box 5). Establishing the right collaborative partnerships to test technologies in real-world contexts can enable first deployments and scale-up. If successful, these development partnerships can evolve over time into commercial relationships, although they may require further work to overcome practical and interorganizational challenges.

BOX 5: **ArcelorMittal and LanzaTech's Steelanol collaboration proves CCU at scale but runs into regulatory challenges**

LanzaTech and ArcelorMittal teamed up over a decade ago on the Steelanol project at ArcelorMittal's Ghent steelworks. Unique in Europe, this project converts blast furnace gases – containing CO, CO_2 and H_2 – into ethanol for fuel and materials. This initiative has offered ArcelorMittal an exploratory step towards their 2050 net-zero target and allowed LanzaTech to scale up their gas fermentation technology in Europe.

The collaboration began with small-scale mobile unit tests. Following their success, the partners moved to a large-scale demonstration, supported initially by Horizon 2020 funding from the EU. This grant helped the partners navigate the engineering phase of their plant.

Regulatory hurdles arose, particularly with fuel certification challenges under what was then RED II regulation, because the blast furnace gas was not biogenic. As a solution, the Torero project was born, generating bio-coal onsite to inject biogenic carbon back into the process. This development helped certify the ethanol as an advanced biofuel, unlocking further financial support from the European Investment Bank.

A pivotal achievement for LanzaTech and ArcelorMittal was the inclusion of a new fuel category under the revised RED II regulation – known as recycled carbon fuels (RCF). RCFs describe carbon-based fuels made from non-intentionally produced waste streams, offer another certification pathway under EU legislation.

Unexpected regulatory shifts, however, complicated the sale of bioethanol, deviating ArcelorMittal from its initial business projections of using biogenic off-gases from the Torero project. Additionally, RCF production faced challenges due to penalties reflecting the carbon intensity of local power grids, directly affecting environmental LCA outcomes for the produced ethanol.

ArcelorMittal's substantial investments, supported by a €10 million Horizon 2020 grant and a loan from the EIB, aimed to set a sustainable industry standard. However, the evolving regulatory landscape continues to pose financial risks and could stifle the investments and innovation needed to meet the EU's climate targets. In June 2025, ArcelorMittal publicly urged EU authorities to swiftly address these issues to maintain the viability of the Steelanol and Torero projects.

Looking ahead, the partnership plans to diversify by leveraging its ISCC+ certification for sustainable chemicals and exploring ethanol markets outside the EU, including sustainable aviation fuels. This approach aims to mitigate the potential setbacks from the EU's challenging regulatory environment and maintain the momentum towards sustainable industrial innovation.

Source: Wood Mackenzie, expert interviews with LanzaTech and ArcelorMittal.

Sites and strategies to mitigate scale-up risk

The ideal demonstration site and scaling-up strategy will depend on the CCU pathway and target market opportunity. For example, start-ups producing CO_2-treated building materials require access to local sources of feedstocks and/or offtake. Developing flexible deployment models, such as container-based "hardware-as-a-service" approaches, can help to better target dispersed industrial sites and reduce costs associated with transporting materials. In other settings, such as pathways targeting chemical industry supply chains, the ability to achieve relevant scale quickly is a core driver. In this instance, scaling-up niches can be found where there is the right combination of local infrastructure and abundant low-carbon feedstocks.

At the early stage, CCU projects can face offtaker risk as they are reliant on only a few or even a single customer. Innovators are targeting sites which have multiple end-uses for utilization products to help mitigate this risk. For example, CCU technologies producing sustainable feedstock gases for chemical industries are particularly well placed to fill this niche. However, for other pathways, trialling technology deployments in different industrial contexts simultaneously may be the best route to diversifying offtake (see Box 6).

BOX 6 **enaDyne has leveraged feedstock and infrastructure opportunities to drive scale**

enaDyne is a leading CCU start-up which has developed a novel plasma catalysis technology to convert CO_2 and methane to various short-chain hydrocarbons with a range of downstream applications. Strategic site selection has been a crucial scaling-up lever for enaDyne's technology. Biogas plants in Germany were valuable initial targets for the business, due to a pre-existing combined CO_2 and methane gas stream, as well as sustainable electricity from co-generation facilities. Additionally, in the context of reducing subsidies in Germany, there has been demand for valorization of outputs streams among biogas players, presenting a valuable demonstration and scaling-up opportunity for enaDyne.

The business is now forming partnerships with incumbent industrial players to valorize off gases – also composed of CO_2 and methane – and to abate harmful PFAS emissions. This creates immediate economic value for the incumbent partners and sets the stage for expansion within this production niche. With the technology proven in this context, the next step for the company is driving growth to deploy at the scales at which these legacy industrial players operate.

Source: Wood Mackenzie, expert interview with enaDyne.

Building credibility and relationships with industry incumbents

Incumbent industrials generally operate legacy businesses with longstanding, proven engineering practices and production processes. As a result, they can be reluctant to take on risk associated with unfamiliar technologies. This can be exacerbated by communication challenges, as novel solutions may draw from emerging technology areas which legacy industrials have little exposure to. The result can be protracted timelines to conduct due diligence before a decision is made on whether to partner on a CCU trial. Such slow decision-making presents a significant obstacle to start-ups, which operate on timelines of months to days, given their commitments to venture capital investors.

Slow decision-making presents a significant obstacle to start-ups, which operate on timelines of months to days, given their commitments to venture capital investors.

Leveraging opportunities to demonstrate credibility helps CCU technology developers to unlock working partnerships with incumbent industrial companies. Establishing a relationship early during the R&D stage can be particularly effective at accelerating the timeline towards deployment, as initial barriers arising from a lack of familiarity are overcome early. Furthermore, as incumbent development partners can often be future customers, their involvement provides practical insights on integration needs and market fit that can be incorporated early on. Taking advantage of industry-sponsored public and private research funding programmes can be a route to establishing these connections.

Partnering with individual veterans from the target industry can also provide valuable mentorship and facilitate access to industry incumbents. The challenge here lies in identifying and recruiting relevant and motivated mentors, who can be hard to come by. Start-ups that have done so successfully have often leveraged professional networks, but there may be a role for third-party organizations to broker connections between innovators and prospective mentors. Start-ups have also employed multistakeholder networks of academic, industrial and commercial experts to help guide technology and business development – enabling demonstration and scaling-up opportunities.

4.2 The role of multi-stakeholder collaborations

There are significant uncertainties around how future value chains will evolve as CCU pathways scale up. By taking a collaborative rather than competitive approach, companies are working to validate and realize commercial market opportunities for CCU.

Creating market opportunities

Cross-industry networks are emerging which seek to build links between incumbent industrial sectors, technology developers and end users to identify project opportunities (see Box 7). In some cases, consumer brands are also driving demand from the end-user side.[65] Although specific offtake arrangements to date have tended to be bilateral and limited, this is indicative of a growing interest in supply chain sustainability.

BOX 7

TBM to accelerate commercial deployment through cross-industry networks

TBM is a Japanese start-up developing and commercializing CCU technology through strategic partnerships. The company has optimized a process to produce high value-added, CO_2-derived calcium carbonate that can be used for TBM's unique product, CR LIMEX. This product is a new material made mainly from calcium carbonate, combined with resin as a binder, which can be used for both interior and exterior building materials, as well as various plastic fittings – thereby fixing CO_2 for the long-term in an economically viable way. TBM collaborates with multiple upstream and downstream CCU technology companies across the world, including the CO_2-emitting industry, CCU technology companies, converters and end-users of CR LIMEX.

To accelerate the commercialization of its CCU projects, TBM established the resource recycling council (RRC), which now numbers 2,415 members, as a platform for cross-industrial collaboration. The directors and members of RRC include companies and organizations engaged in the steel, energy and construction sectors, in addition to municipalities, ministries and carbon recycling associations – all of whom are all enthusiastic about resource circularity and CCU. Utilizing this robust network, TBM has connected with construction industry players and other corporations looking to reuse their emissions, creating partnerships that are planning to launch CCU projects together, accelerating commercial deployment and de-risking the scale-up of CCU technology.

Source: Wood Mackenzie, expert interview with TBM.

" Collaborative efforts to mitigate risk or redistribute costs could unlock deployment opportunities to apply CCU technologies which benefit the whole value chain.

From an infrastructure perspective, collaboration can also unlock economies of scale through demand aggregation. For example, CCU projects at pre-commercial scale usually generate small volumes of product compared to established industrial production; meanwhile, downstream processing infrastructure and equipment has been optimized to operate at full commercial scale, often at orders of greater magnitude. Active coordination between companies can help bridge scale imbalance through the combination of outputs into pooled processing batches to improve the economics.

Managing risk through public and private collaborations

High capital expenditure requirements for CCU technology and associated infrastructure create a level of risk that is hard for certain industries to overcome. This proves particularly acute for low-margin sectors such as cement and steel, where abundant opportunities exist to valorize feedstocks or reduce carbon intensity through CCU approaches. Collaborative efforts to mitigate risk or redistribute costs could unlock deployment opportunities to apply CCU technologies which benefit the whole value chain.

The public sector plays an important role in managing this type of risk, through supporting research and development (see Box 8), funding to back specific projects (Box 5), and facilitating shared infrastructure solutions that enable economic viability for multiple participants. In the carbon sequestration sector, there are precedents for government funding for anchor coalitions and underwriting for shared infrastructure that has enabled CCS value chains to emerge. While there are important distinctions between CCS and CCU, examples such as Norway's Northern Lights project demonstrate the potential for public private partnerships in delivering high-risk, infrastructure-led carbon management projects.[66]

BOX 8

Public sector funding in Japan helps foster development partnerships between industry and researchers

Japan's Green Innovation Fund (GIF) is a leading example of how public sector funding can help de-risk and accelerate CCU technology development. The fund has a budget of $3.9 billion over 10 years targeted towards recycled carbon fuels and chemicals, cement/concrete, bioconversion and capture technologies.

The quasi-governmental New Energy and Industrial Technology Development Organization (NEDO) manages the GIF, including supporting a CCU-specific R&D and demonstration base at Osakikamijima, Hiroshima. The centre was established in 2019 and is anchored around the Osaki CoolGen coal gasification plant, which supplies CO_2 to surrounding demonstration facilities. The Hiroshima base brings together universities and industrial companies, including Mitsubishi, Kajima and Nippon Steel, for joint demonstration projects to bring CCU technologies to maturity.

Source: Wood Mackenzie, expert interview with GIF.

Raising awareness of CCU's potential

Negative perceptions associated with carbon-based technologies may be contributing to a wider lack of awareness of the economic and sustainability potential provided by CCU pathways. Coordinated messaging has a role to play, from communicating fundamentals to non-specialists, through to highlighting specific regulatory barriers to policy-makers. From an advocacy perspective, CCU companies individually struggle to highlight regulatory barriers due to their limited political visibility compared to large incumbent industries. Regional industry associations have emerged as key focal points for research and communication activities for CCU.[67,68] Leading commercial CCU collaborations have also had success in advancing regulatory development (Box 5).

4.3 Considerations for cross-sectoral collaboration

Practical considerations and actions for cross-sectoral collaboration between first movers and wider stakeholders across the CCU ecosystem are proposed below.

Early-stage innovators – establishing strategic partnerships

- Identify prospective sites with the infrastructure, low-carbon feedstocks and offtake potential required to realize scaling-up potential.
- Consider opportunities to diversify offtake at demonstration stage to reduce offtaker risk.
- Leverage opportunities to demonstrate credibility with legacy industries in order to establish development and scaling-up partnerships, including recruiting industry veterans to bridge cultural divides.
- Establish multistakeholder advisory groups to aggregate technical and commercial expertise to inform business development and open market channels.
- Engage early across the supply chain to overcome communication challenges, anticipate technical requirements and accelerate decision-making.
- Enable economies of scale in downstream processing through aggregating product output between aligned CCU projects.
- Participate in cross-industry networks that aim to advance CCU pathways and overcome market barriers.

Corporates and industry incumbents – acting to enable scale

- Leverage public funding to resource CCU technology identification and feasibility studies in support of sustainability goals.
- Work with emerging innovators to identify mutually beneficial development and scaling-up opportunities, including hosting demonstration projects onsite.
- Establish and/or participate in sector-specific or broader cross-industry networks to enable new project opportunities and to engage in coordinated advocacy.

Public sector – structures to de-risk collaboration

- Support the introduction of open-source research, development and demonstration facilities which can be co-funded by corporates to bring together the academic sector and industrial players to advance technology development.
- Open sources of funding to de-risk R&D and enable legacy industrials to invest time in technology identification and feasibility assessment.
- Draw on lessons from support of industrial clusters and CCS value chains to fund and de-risk anchor coalitions for CCU deployment.

5 Ways forward

CCU could play a role in the defossilization of industrial supply chains – if supported by concerted action to validate approaches, unlock investment and overcome market constraints.

CCU presents an opportunity to transition to a more sustainable consumption model, in which captured carbon can substitute for virgin fossil carbon or be stored within materials.

The carbon atom remains a fundamental building block across the economy, underpinning a spectrum of industrial products from plastics to chemicals and fuels. Currently, demand for liquid hydrocarbons as petrochemical feedstocks alone is expected to grow from around 17 million barrels per day in 2025 to around 26 million by 2050.[69] As long as consumer demand exists for carbon-based products, it can be expected to contribute to demand for fossil hydrocarbons and associated emissions.

CCU presents an opportunity to transition to a more sustainable consumption model, in which captured carbon can substitute for virgin fossil carbon or be stored within materials. In this way, "defossilization" could complement decarbonization measures such as electrification and fuel switching. CCU could present an economic opportunity by creating new sources of revenue from the valorization of waste streams. This would make CCU a valuable lever for low-margin, emissions-intensive industrial sectors and a potential market differentiator for downstream consumer brands.

Based on the evidence outlined in this paper, this final chapter presents next steps that would enable broader adoption of CCU.

5.1 Building credible and durable market signals

If policy-makers wish to see deployment of CCU technologies, they must commit to stable and long-term incentives. The impact of political and regulatory volatility has been apparent across leading jurisdictions.

The main challenge is that a mature market does not currently exist for CCU-derived products relevant to defossilization. Significant cost hurdles currently undermine the demand needed to drive investment; and these hurdles can only be overcome through deployment to realize technology improvements and economies of scale. Industrial companies on the whole are willing to make a transition to more sustainable operations, but they cannot be expected to bear unmanageable risks and costs. This places the emphasis on policy incentives to level the early-stage playing field and allow first movers to compete in markets with fossil alternatives. However, with the exception of a small number of leading initiatives, global policy frameworks for CCU are insufficient to drive uptake.

If policy-makers wish to see deployment of CCU technologies, they must commit to stable and long-term incentives. The impact of political and regulatory volatility has been apparent across leading jurisdictions. As highlighted previously, the revocation of US federal funding under the IIJA, as well uncertainty surrounding the IRA's 45Q mechanism, has negatively impacted investor confidence. In the EU, RED III CO_2 source mandates, while well-intentioned, continue to introduce adverse incentives for CCU approaches, which have been compounded by regulatory volatility. To a degree, innovators along the innovation curve are able to navigate uncertainty in the short term, for example through geographic diversification and by leveraging multiple revenue streams. However, in the medium- to long-term, the public sector holds ultimate responsibility for establishing the enabling conditions for a self-sustaining market for CCU products.

Regulatory frameworks should incentivize CCU while ensuring emissions reductions are realized by industry-standard, cradle-to-grave LCA. This approach could also extend to existing carbon pricing frameworks to account for the varying emissions benefits of shorter duration products, provided they consider product end-of-life. This could help to address functional disincentives and additional regulatory burdens facing CCU deployment compared to business-as-usual practices. Demand-side incentives such as ReFuelEU show promise for fuels pathways and applying similar content mandates to other CCU sectors, such as chemicals, could provide valuable drivers of demand. Framing enabling policies that can reduce the costs and accelerate the growth of directly related sectors, such as DAC and low-carbon hydrogen, will prove critical for CCU adoption. Beyond direct measures, lessons can be learned from the catalytic impact that public sector procurement has had on CCU products.

5.2 Driving deployment in an immature market

Private sector investors should consider alternative ways of reflecting capital in project valuations, beyond depreciation, to reflect its necessity.

Many CCU technologies are at a relatively nascent stage of development, and technology developers, particularly start-ups, face challenges in simultaneously driving performance improvements while maturing their business models. Mechanisms are needed to help decouple technology development from business growth. Governments can establish programmes which de-risk early technology development, as demonstrated by programmes of the European Innovation Council (EIC) and Japan's Green Innovation Fund (GIF). While these models differ in practice, they both underwrite technology development costs and focus cross-sectoral expertise on incubating potential commercial applications.

As they advance up the innovation curve, the onus is on technology developers to ensure they plan carefully to diversify funding sources, while avoiding early equity traps and unsustainable market entry points. However, other market participants can take steps to mitigate financing gaps. There is a need to expand patient funding vehicles to better reflect deep tech development timescales and capital requirements, following the example of Tencent and the EIC.

Overcoming the capital challenge requires expanding specific risk-sharing mechanisms that involve public sector actors, such as first-loss mechanisms and loan guarantees. However, private sector investors should also consider alternative ways of reflecting capital in project valuations, beyond depreciation, to reflect its necessity. Other systems for finding cost reductions, such as book-and-claim initiatives, should be supported by motivated corporates.

Ultimately, projects cannot attract financing unless there is demonstrable revenue generation potential. Offtake agreements are therefore critical, even if conditional or short-term. Start-ups can build these into early-stage development partnerships with motivated incumbent industrials, potentially leveraging public research and development mechanisms where possible.

Procurement mandates from public purchasers, usually the largest purchasers of goods and services, will also send stable demand signals. There is also a role for private players with longer-term market creation ambitions to take a patient offtake approach which aggregates demand. These agreements can support bridging funding for technology developers and create a demand signal for investors.

5.3 Collaboration and governance

> Industrial cluster decarbonization can provide a model for CCU ecosystem collaboration.

Scaling-up CCU is a transdisciplinary exercise that brings together non-traditional technology and market expertise. Such collaborations, in addition to a need to drive awareness of the opportunities and market barriers, have incentivized cross-industry partnerships at project, sector and supply chain level. Therefore, while markets mature, collaborative partnerships can be expected as the default model for CCU project deployment. In addition, there will be an ongoing need for awareness-raising across stakeholder communities. Establishing new networks or leveraging existing ones to communicate shared messages to policy-makers and other market players can enable this.

Fostering a broader culture of industrial collaboration beyond the first, pioneering partnerships may require a more formalized approach to engendering trust and transparency. Emerging governance models underpinning wider industrial cluster decarbonization can provide a model for CCU ecosystem collaboration. A common theme across industrial cluster governance is the coalescence of stakeholders around a shared vision that champions transparency and joint coordination, underpinned by private, public or blended finance. These models work to ensure public participation in deployment and focus on aggregation of demand and resources.

Given that CCU is another emerging form of industrial symbiosis, there are clear commonalities with the industrial cluster experience. There are already direct parallels with emerging CCU initiatives such as GIF, or the Brightlands Circular Space in the Netherlands, a public-private R&D collaboration focusing on the circular economy.[70] For later-stage commercial deployments, governments should build on experiences with industrial clusters to create a public funding-led approach to anchor infrastructure, akin to CCS value chain deployments. In this way, capital outlay can be de-risked while creating trusted spaces to underpin transparency and realize economies of scale through aggregated demand for infrastructure.

In summary, the insights gathered through engagement with stakeholder groups has highlighted key roles for advancing CCU towards a self-sustaining market, both independently driven and in collaboration (see Figure 12).

FIGURE 12 **Illustrative summary of stakeholder roles that could support self-sustaining markets for CCU**

	Strategy and R&D focus (Current stage)	Deployment and market formation (mid-term)	Self-sustaining market (long-term)
Public sector	▲ – Develop policy strategy and standards – Identify regulatory barriers – Provide resources to de-risk R&D	▲ – Deploy commercial incentives – Establish product standards – Sustain R&D support – Leverage procurement to support demand	● – Reduce subsidies – Maintain and refine product standards
Innovators	▲ – Lead R&D – Engage early with incumbents – Participate in cross-industry networks	▲ – Lead R&D – Broaden market fit – Advocate via cross-industry networks	▲ – Maintain drive for scale and efficiency – Broaden sectoral application
		Innovators & incumbents collaborate on first-of-a-kind projects	Innovators & incumbents collaborate on nth-of-a-kind projects
Incumbents	▲ – Support R&D – Engage with policy development – Participate in cross-industry networks	▲ – Lead R&D – Broaden market fit – Advocate via cross-industry networks – Support book-and-claim initiatives	▲ – Maintain drive for scale – Reduce reliance on subsidies – Prioritize cost reductions
Financiers	● – Develop patient capital vehicles	▲ – Develop patient capital vehicles	● – Deploy traditional investment vehicles

▲ Driving change ● Preparation/participation

Conclusion

CCU could open up new markets, enhance industrial resilience and provide climate benefits – if given strong public sector support, clear demand signals and innovative finance models.

While pioneering activity driven by innovators, first movers and early incentives has built some momentum in recent years, CCU remains a nascent and evolving field. The absence of appropriate market frameworks means that CCU approaches have yet to find a significant role in industrial production. This may be explained by the diversity of contexts in which CCU could play a role, the complexity of integration into existing climate models, as well as the early-stage nature of many technologies involved. Greater confidence in CCU outcomes will develop as technologies mature, though this can be accelerated through the standardization of life-cycle assessments to drive consensus on emissions potential.

Although CCU represents a different kind of challenge for policy-makers, this paper's findings highlight the central importance of the public sector in leading this activity. Ultimately it will be for policy-makers to determine what role CCU should play in their transition strategies. If policy-makers wish to incentivize CCU, these findings highlight the importance of a twin-track approach:

– First, de-risking innovation and R&D can help drive performance improvements while enabling financiers and projects developers to become more familiar with CCU approaches.

– Second, creating supportive and predictable market environments can enable promising CCU approaches to become competitive against incumbent production routes.

At a company scale, the findings of this paper provide useful learnings for other first movers. In particular, the experience of start-ups and early-stage innovators in overcoming financing challenges and valleys of death can be valuable for informing market entry strategies and business planning for others in this space. However, it is equally clear that other corporate and financial stakeholders can also take concerted action to reduce friction for project developers, through establishing clear demand signals and innovative finance models.

An ongoing challenge will remain the sector's ability to coordinate efforts and increase market familiarity with CCU technologies. In this, cross-sector alliances and shared infrastructure could reduce risks, aggregate demand and accelerate learning.

If CCU is incentivized it could open up new markets, enhance industrial resilience and provide climate benefits. Through deployment at increasing scale, the evidence base for policy can be expanded, industries can identify value opportunities and financiers can better assess potential investments. We invite stakeholders to engage in an open, evidence-based assessment of CCU, to ensure that future choices about its role are deliberate, informed and aligned with long-term climate and industrial goals.

Glossary

The following is a list of common terms used in this paper and an explanation of their intended meaning.

Atmospheric carbon – carbon derived from the atmosphere, usually obtained through direct air capture of CO_2.

Biogenic carbon – carbon released from the combustion or decomposition of biomass or products derived from biomass.

Captured CO_2 – CO_2 recovered from air or emissions sources through carbon capture technologies.

Carbon dioxide removal – removal and permanent storage of carbon dioxide from the atmosphere.

Carbon oxides (COx) – umbrella term for CO and CO_2. Both can be used in CCU.

CCU-products:

- **Fuels** – materials combusted for the purpose of generating heat, e.g. methane.
- **Intermediates** – materials produced for conversion into more complex chemicals. Compounds such as methane, methanol and ethanol can be used as both fuels and intermediates.
- **Chemicals** – materials produced for use in final product which is not specifically produced for combustion, e.g. ethylene and propylene.
- **e-fuels/e-chemicals** – a subset of CCU fuels and chemicals synthesized from captured CO_2 and green hydrogen.

Cradle-to-grave life-cycle analysis – evaluation of the effects a product has on the environment over the entirety of its life.

Direct air capture – a form of carbon capture technology which captures CO_2 directly from the atmosphere.

Emissions avoidance – displacement or prevention of greenhouse gas emissions otherwise expected to be generated.

Emissions reduction – reduction of emissions from existing emissions sources through change in activity, such as application of new technologies.

Fossil point source – industrial or power sector sources of emissions from the use of fossil fuels.

Long-duration storage – sequestration of carbon within a solid medium for periods of centuries.

Net neutral – no overall addition or removal of CO_2 from the atmosphere from a given activity.

Process emissions – industrial emissions arising from industrial processes that do not involve the use of fossil fuels.

Valorization – creation or enhancement of the economic value of materials.

Contributors

Project leads

John Ferrier
Senior Research Analyst CCUS, Wood Mackenzie

Tim van den Bergh
Lead, Climate Tech Innovation, World Economic Forum

Additional contributors

Mhairidh Evans
Vice President, Global Head of CCUS Research, Wood Mackenzie

Catherine Horseman-Wilson
EMEA CCUS Lead, Wood Mackenzie

Anis Nassar
Manager, Materials Systems, World Economic Forum

Volker Sick
Professor of Advanced Energy Research, University of Michigan

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Parallel Carbon

Saskia Bruysten
Carbon Equity

Freya Burton
LanzaTech

Lorenzo Chiavarini
Dealroom

Bashir Dabbousi
Saudi Aramco

Carina Faber
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Shravant Gadikota
Carbon To Stone

Vera Grim
Federal German Ministry of Research, Technology & Space

Philip Hahn
enaDyne

Tokuro Hatori
TBM

Florian Hildebrand
Greenlyte Technologies

Csaba Janáky
eChemicles

Emilie Kaern
World Economic Forum

David Kearns
Global CSS Institute

Jan Mertens
Engie

Harrison Meyer
Oxylus Energy

Carlota Ochoa Neven du Mont
Extantia

Viktoria Nikulshyna
Holcim

Sebastian Pohlmann
UP Catalyst

Sarah Saltzer
University of Stanford

Célia Sapart
CO_2 Value Europe

Gill Scheltjes
D-CRBN

Wim van der Stricht
ArcelorMittal

David Strittmatter
ICODOS

Aruna Subramanian
SABIC

David Victor
University of California

David Wakerley
Dioxycle

Hao Xu
Tencent

Mai Yaguchi
Ministry of Economy, Trade and Industry of Japan

Jamila Yamani
Salesforce

Xu Yang
Nanjing Gasgene

Production

Jean-Philippe Stanway
Designer

Jonathan Walter
Editor

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World Economic Forum
91–93 route de la Capite
CH-1223 Cologny/Geneva
Switzerland

Tel.: +41 (0) 22 869 1212
Fax: +41 (0) 22 786 2744
contact@weforum.org
www.weforum.org