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Recent Advances in CCS, CCU and CarbonTech: Feasible Solutions for Achieving Net Zero?

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Abstract

The paper discusses the role of Carbon Capture and Storage (CCS) and Carbon Capture and Utilization (CCU) in achieving a net-zero economy by 2050. It examines technological advancements in capturing and utilizing CO_2, including direct air capture and embedding CO_2 in concrete. With a focus on hard-to-decarbonize industries such as cement and steel, CCS and CCU are presented as fallback solutions where electrification through renewables is insufficient. The literature review highlights economic, policy, and societal factors impacting scalability. The paper assesses the role of carbon pricing, licensing and corporate partnerships in ensuring implementation. Key corporate solution providers in a nascent industry called CarbonTech such as Carbon Engineering and Climeworks are driving progress alongside corporate collaborations with large cap companies such as Microsoft and Shopify. Despite cost and scalability challenges, these technologies represent opportunities for reducing emissions while generating market value through CCU products.

Keywords: CCS, CCU, CarbonTech, Decarbonization, Net Zero, Hard to Abate Industries

Part I: Introduction, Research Objectives and Research Questions

Introduction

As the global community pursues a net-zero economy by 2050, innovative strategies are emerging to stabilize the climate. However, climate stabilization remains elusive as rising GHG emissions intensify, making the urgent implementation of decarbonization technologies like CCS and CCU critical alongside a roll-out of renewables. Nature-based solutions like reforestation are vital but insufficient to address current CO_2 emission rates at scale. If renewable energy deployment lags, CCS and CCU will be essential to achieving carbon neutrality by 2050. CCS deployment hinges on a high carbon price, as the paper will discuss below [1].

Carbon capture and storage as well as carbon capture and utilization (CCU)—the process of capturing CO_2 and converting it into valuable products like fuels or construction materials—offer promising solutions for reducing emissions in some industries[1]. In fact, The International Energy Agency (IEA) emphasizes the critical role of CCS and CCU in achieving net-zero emissions. In its Sustainable Development Scenario, the IEA projects that by 2030, over half of the CO_2 captured will come from retrofitted fossil fuel-based power and industrial plants, with the remainder from low-carbon hydrogen production[2].

The industry group 'CO_2 Value Europe' argue in a recent report that the potential impact of CCU technologies on emission reductions could be significant. Utilizing captured carbon as feedstock could reduce emissions in the chemical industry by 11%, in the transport sector by 7% through CCU fuels, and by 2% via mineralization in building materials[3].

The rise of companies focused on CCU signals a commercial push and a shift in how we address CO_2 mitigation [2, 3]. Despite some skepticism and citizen resistance (not-in-my-backyard), CCU advancements are progressing rapidly, transforming CO_2 into industrial feedstocks and positioning carbon as a resource that can generate revenue, rather than a waste product[4].

Rationale and Relevance

Finding new solutions for carbon-intensive industries is central to global decarbonization efforts [4]. As significant sources of emissions and hubs of innovation, industries hold the potential to drive essential climate action. This paper explores strategies such as Carbon Capture and Storage (CCS), Carbon Capture, Utilization, and Storage (CCU), and CarbonTech, focusing on their ability to mitigate emissions and transform CO_2 into valuable products. The paper highlights opportunities in these emerging technologies, which can accelerate the transition to a net-zero economy. The findings are relevant for policymakers, investors, and industry leaders seeking scalable solutions for decarbonization.

Research Objectives

- Analyze the effectiveness of Carbon Capture and Storage (CCS) technologies in mitigating emissions.
- Evaluate the potential of Carbon Capture and Utilization to transform CO_2 into high-value products and drive market adoption.
- Examine the economic, policy, and societal factors influencing the scalability of CCS and CCU solutions.

Research Questions

- How can Carbon Capture and Storage (CCS) and Carbon Capture and Utilization (CCU) technologies contribute to achieving a net-zero economy by 2050?
- What policy measures are needed for implementation, and to what extent do they represent viable solutions versus distractions in the broader decarbonization strategy?

Research Methodology

This study uses a qualitative case study approach, to examine technological solutions and selected corporate cases for reducing GHG emissions[6]. Thematic analysis was applied to identify patterns and themes across the literature review, the market research and these case studies [5, 6]. Additionally, a literature review was conducted to evaluate existing research on CCS and CCU[7].

To enhance the analysis, the study incorporates news stories, market news and industry reports as well as a discussion of pilot projects and demonstration facilities that offer insights into the real-world application of CCS and CCU solutions, as this field is a moving target. This is to ensure an assessment of scalability of the technologies [7].

The paper also uses descriptive analysis to present, discuss, and explain key concepts; this non-theoretical but descriptive approach is not a limitation, but a necessary step to contextualize the CCS and CCU technologies.

Part II: Defining Carbon Capture and Storage (CCS) and Carbon Capture and Utilization

Carbon Capture and Storage (CCS) – Increasing the Life Time of Power Plants

Carbon Capture and Storage (CCS) is a technology offering a new 'stabilization wedge' towards achieving a net-zero economy[8]. To think about the climate problem as a series of sectoral challenges that need a rapid upscaling of existing and viable solutions for upscaling is at heart of the stabilization wedges framework from 2004 [8].

While injecting CO_2 below ground into depleted oil fields for enhanced oil recovery is an established practice, the long-term storage of CO_2 remains a relatively new concept. Injecting CO_2 into depleted oil fields for enhanced oil recovery (EOR) is a well-established practice in the oil industry, with the first large-scale CO_2 capture and injection project initiated at Norway's Sleipner gas field in 1996[9].

CCS involves capturing waste carbon dioxide (CO_2) from substantial emission sources such as cement factories, industrial processes or coal-fired power plants [9]. The captured CO_2 is transported to an underground geological formation for storage, or in some cases directly captured and injected underground under the powerplant. CCS prevents it from entering the atmosphere and contributing to global warming.

The Rise of CCS

As of July 2024, the global carbon capture and storage (CCS) landscape comprises 50 operational commercial facilities, with an additional 59 under construction and 519 in various stages of development, totaling 628 projects in the pipeline. This represents a significant increase from 2022, when there were 30 operational facilities, 11 under construction, and 153 in development, amounting to 196 projects[10].

Most carbon capture projects are industrial, targeting hard-to-abate sectors like cement, steel, and fertilizer production[11]. This growth demonstrates confidence in CCS as a tool for climate change mitigation[12]. [10-12]. Table 1 provides a short overview of CCS technologies that is elaborated below:

Table 1: Technologies Included in Carbon Capture and Storage

Technologies	Characteristics
Direct Air Capture	Extracts CO_2 directly from the air using fans, requiring mass deployment for scale.
Point-Source Capture	Captures CO_2 at industrial sources; technology is mature and effective for carbontech.
Soil Sequestration	Retains carbon through specific farming practices.
Biochar	Converts biomass into CO_2-absorbing charcoal for soil storage.
Supercritical CO_2 Storage	Compresses CO_2 for underground storage.

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Point-Source Capture: Capturing CO_2 at the source where it is produced: mainly industrial smokestacks or at coal-fired power plants. Moreover, point-source capture has a proven operational record, established supply chains, and standardized processes, facilitating easier integration into existing industrial infrastructures. Diverse industries—steel, cement manufacturing and chemical production—can adopt point source capture solutions[13].

Direct Air Capture: Not connected to an existing power plant or an industrial site, giant fans suck carbon dioxide directly from the air where electricity is abundant such as in Iceland with its hydropower and geothermal sources. Direct Air Capture is the focus of companies like ClimeWorks and Carbon Engineering[14]. To affect climate change at scale this solution could possibly be rolled out at scale and costs must come down. But, if we observe what happened to the price of solar panels with a 80-90% decline over 10 years, then that is not unlikely [13].

Carbon sequestration or 'carbon storage,' is the short or long-term containment of carbon, mostly in the form of:

- **Soil sequestration:** These are practices that reward farmers for certain agricultural practices which retain agricultural carbon in the soil instead of cold combustion or other practices whereby carbon leeches into the atmosphere. Such farmer practices already exist and may include reduced tillage, cover cropping, and organic soil amendments, ultimately improving soil health, enhancing crop yields and improving soil resilience.
- **Biochar:** This approach is similar to soil sequestration and involves converting biomass into charcoal that captures CO_2. Bochar is produced by pyrolyzing biomass under oxygen-limited conditions, resulting in a carbon-rich material that, when incorporated into soil, can sequester carbon for extended periods. Its porous structure enhances soil fertility by improving nutrient retention and water-holding capacity, thereby supporting sustainable agricultural practices. This process sequesters carbon for centuries while reducing emissions from organic material decomposition[15, 16].
- **Supercritical CO2:** Supercritical CO_2 storage involves compressing CO_2 into a supercritical fluid—a state exhibiting properties of both liquids and gases—before injecting it into deep geological formations like depleted reservoirs or saline aquifers. At depths over 800 meters, high pressure and temperature maintain CO_2 in this state, allowing efficient storage[17].

Comparing CCS, CCU and CarbonTech

The terms CarbonTech and Carbon Capture, Utilization, and Storage (CCU) are related but not synonymous. CarbonTech encompasses a broad spectrum of technologies that transform captured carbon dioxide (CO_2) into valuable products, a concept also known as "carbon-to-value"[18]. This includes the conversion of CO_2 into fuels, building materials, plastics, and other industrial products [14-18].

In contrast, CCU refers to a suite of technologies that capture CO_2 emissions from sources like power plants and industrial facilities, followed by either storing the CO_2 underground or utilizing it in various applications[19].

The International Energy Agency (IEA) identifies CCU as a critical technology for reducing emissions from power and industrial sectors[20]. Despite its potential, global CCU adoption is limited, with few large-scale facilities in operation.

The primary obstacle for CCU is cost, which varies based on technology, transport, and storage methods. While currently expensive, CCU could become cost-effective in the long term compared to other carbon mitigation strategies[21]. Even so, optimistic projections estimate CCU will only account for 1.2% of global power generation capacity by 2040.

In less favorable scenarios, CCU adoption was previously projected to not scale significantly until 2050. However, recent developments show that CCU technologies are scaling much faster than anticipated (Global CCS Institute)[22].

The International Energy Agency (IEA) emphasizes that CCU technologies are essential for achieving net-zero emissions by 2050, particularly for decarbonizing hard-to-abate sectors like steel and cement, facilitating clean hydrogen production, and enabling atmospheric carbon removal (IEA). These advancements demonstrate the increasing role of CCU in global decarbonization efforts, underpinned by technological progress, corporate investment, and supportive policy frameworks[23].

The Role of Carbon Pricing for CCS to Scale

There are barriers to CCS adoption[24]. Carbon pricing is essential to CCS viability, particularly in hard-to-abate sectors like cement, chemicals and steel. Low carbon prices discourage investment, while higher prices incentivize adoption and scalability[25].

NGO Greenpeace claims CCS could double coal plant costs?[26] While natural-gas operations could remove carbon at a cost of around \$20 per ton, removing carbon from difficult-to-abate industrial processes like steel and cement production could cost around \$100 per ton. This disparity highlights the importance of carbon pricing mechanisms tailored to specific sectors. Without sufficient pricing to reflect the true environmental cost of emissions, investments in CCS remain economically unviable for industries with higher abatement costs, stalling progress in key areas critical for global decarbonization goals [19-22].

Higher carbon pricing incentivizes CCS adoption by internalizing the cost of emissions. However, high prices alone are insufficient. Targeted policies—such as subsidies, regulatory frameworks, energy support schemes, and streamlined CO_2 storage licensing—are needed to address economic and regulatory barriers. Without carbon pricing, CCS becomes economically unviable, increasing mitigation costs and slowing deployment [27]. A combination of robust carbon pricing and supportive policy measures is essential to scaling CCS for achieving climate goals[28].

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Table 2: Presents the Key Elements in the Discussion on CCS, CCU and Carbon Pricing

Key Element	Description
Barriers to CCS Adoption and Role of Carbon Pricing	Barriers include low carbon prices and uncertainties in CO_2 storage. Higher carbon pricing is essential for broader CCS adoption. Tailored pricing mechanisms for specific sectors, such as steel and cement, can drive CCS viability.
Cost Challenges in CCS and CCU Implementation	Costs vary significantly: $20/ton for natural gas operations vs. $100/ton for hard-to-abate industries like steel and cement. High abatement costs require robust carbon pricing and subsidies to make CCS investments economically viable.
Distinction Between CCS, CCU, and CarbonTech	CCS stores CO2 underground, while CCU adds utilization of CO2 for products; CarbonTech focuses specifically on creating marketable products from CO2.
Policy Tools for Scaling CCS and CCU	Carbon pricing remains crucial but must be complemented by subsidies, streamlined licensing frameworks for CO_2 storage, and co-benefits like energy support schemes to address economic and regulatory barriers.
Global Cooperation and Future Projections for CCU	CCU adoption remains limited due to costs and scalability issues; cooperation is critical for achieving global targets by 2050.

Part III: Corporate Partnerships and Innovation in CarbonTech: Bridging Startups and Established Players

Carbon capture, utilization, and storage (CCU) is rapidly becoming a focal point for companies aiming to align with net-zero targets. While the field is not yet a fully established ecosystem, it represents a dynamic and evolving network of partnerships between innovative startups and established corporations committed to reducing their carbon footprint. The commercial players in CCU are involved in CarbonTech, a new industry [23-16].

Market Trends in CarbonTech – a Sub-industry within CCU

The demand for net zero solutions is picking up. One driver is the pressure from institutional investors such as pension funds, asset managers, family offices, etc. who increasingly adopt stringent responsible investment policies that align with the Paris Agreement. When institutional investors do net zero alignment of their AUM they engage or exert proxy voting pressure on corporations they invest in to set more ambitious net-zero targets and near-term reduction targets. Corporations often consider their GHG initiatives central to their ESG strategy [27-30].

Net zero alignment among major investors is compelling companies to engage in partnerships. And collaborative efforts, such as joint ventures with clean technology firms or investments in sustainable supply chain practices, are becoming more common central. These actions not tend to align with investor demands for transparent and accountable decarbonization pathways.

Venture capital flows often signals emerging trends, and CarbonTech—which transforms excess CO_2 into valuable products—is increasingly attracting venture capital. CarbonTech companies convert CO_2 into usable products, aligning with the net zero goals of corporations like Microsoft and IKEA, which aim to achieve carbon neutrality or even negativity.

By repurposing harmful carbon, CarbonTech produces eco-friendlier materials. The largest market opportunities lie in fuels ($3.82 trillion), building materials ($1.37 trillion), and plastics ($0.41 trillion)[29].

According to the Circular Carbon Network's latest reports indicate that over 100 multinational firms are now investing in research and development (R&D) and engaging in carbon trading markets[30]. It is clear that corporate participation in CarbonTech initiatives has significantly increased. These collaborations are fostering the growth of the CarbonTech startup market, enabling startups to scale while providing corporates with innovative tools to meet their sustainability goals.

It is important to note that CCU and CarbonTech are related but distinct concepts. CCU encompasses the entire process of capturing CO_2 emissions and either storing or utilizing them. CarbonTech, on the other hand, specifically refers to technologies that convert captured CO_2 into marketable products, focusing on the utilization aspect of the process [31-35].

Therefore, CarbonTech can be considered a subset of CCU, emphasizing the creation of valuable commodities from CO_2. The market potential has spurred over 330 startups across 27 countries to develop products like synthetic fuels and building materials, with 62% founded since 2010[31]. In 2023, venture capital investment in carbon and emissions technology reached a record $17.7 billion, reflecting growing investor confidence amid global emission reduction efforts[32].

A Review of Startup Cases in the Subset of CCU, CarbonTech

Carbon Engineering

Startups are at the forefront of CarbonTech innovation, pioneering technologies to capture CO_2 and transform it into valuable products. For example, Canadian startup Carbon Engineering is

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advancing direct air capture (DAC) technology, which extracts CO_2 from the atmosphere and converts it into fuel[33]. The company's demonstration plant in British Columbia removes one ton of CO_2 from the air daily, showcasing the potential of DAC to achieve high carbon removal efficiency with a small land footprint.

Carbon Engineering's Innovation Centre, located in Squamish, British Columbia, is integral to advancing direct air capture (DAC) technology. Built in 2021, the facility focuses on validating new materials, processes, and technologies to reduce costs and improve efficiency. Research includes optimizing air contactor geometry and exploring novel technological pathways for DAC improvements, which may support the scalability and commercial viability of carbon capture solutions[34]. Such developments may add to the global toolkit for GHG reductions through technological and market-driven solutions.

Climeworks

Another leader in this space, Swiss company Climeworks, designs modular CO_2 collectors powered by renewable energy. Climeworks has raised over $100 million in financing and operates facilities that can remove and permanently store 90% of captured CO_2. Its scalable approach positions it as a key player in direct air capture, with applications ranging from industrial raw materials to permanent underground storage[35].

Climeworks specializing in the previously mentioned direct air capture (DAC) technology, has significantly advanced its operations and financial standing. In April 2022, the company secured an equity round of CHF 600 million (USD 650 million), marking a major milestone in the carbon removal industry[36]. This investment is intended to scale their DAC technology to a multi-million-ton capacity, facilitating the implementation of large-scale facilities [36, 37].

In December 2023, Climeworks entered into a 15-year agreement with Boston Consulting Group (BCG) to remove 80,000 tons of CO_2, underscoring its role as a leader in long-term carbon removal solutions[37]. Moreover, in October 2024, Climeworks partnered with Morgan Stanley to remove 40,000 tons of CO_2 by 2037, further solidifying its position in the novel CarbonTech industry[38].

CarbonCure

Concrete, a material integral to construction, accounts for 7-8% of global emissions annually[39]. Startups like CarbonCure are tackling this challenge by embedding captured CO_2 into concrete during production, reducing its carbon footprint. CarbonCure's technology is already in use at over 100 factories, demonstrating the potential for carbon-negative building materials to transform the construction industry. The cement industry, with limited pathways to decarbonization, is likely to remain the largest market for CarbonTech solutions. Innovations like CO_2-based calcium carbonate embedded in concrete could significantly lower emissions in a sector critical to global infrastructure development [38, 40].

Large Cap Corporates Are Partnering with CarbonTech Startups

Major corporations are increasingly partnering with CarbonTech startups to achieve carbon-negative goals. Companies like Microsoft, Amazon and Shopify are investing in innovative solutions that go beyond offsetting emissions, instead actively reducing their carbon impact.

Microsoft: Microsoft aims to offset its entire historical carbon footprint by 2030. Its initiatives include supplying eco-friendly fuel to Alaska Airlines and joining the Northern Lights project in Norway, which focuses on capturing and storing carbon emissions[40]. Microsoft has partnered with Climeworks to utilize Direct Air Capture for carbon removal. It is also exploring long-term storage agreements through the Northern Lights project, enhancing its focus on global carbon transport infrastructure.

Shopify

Shopify allocates $5 million annually through its Sustainability Fund, collaborating with startups like CarbonCure to integrate carbon offsets into customer purchases[41]. Shopify is also a founding member of Frontier, a $925 million advance market commitment to purchase permanent carbon removal by 2030. The initiative, which includes partners such as Stripe, Alphabet, Meta, and McKinsey, demonstrates Shopify's leadership in fostering scalable carbon removal technologies [40].

IKEA

IKEA is actively pursuing partnerships to integrate captured CO_2 into its manufacturing processes, opening new avenues for sustainable product innovation. As part of its commitment to becoming climate positive by 2030, IKEA is investing in renewable energy initiatives and working to reduce more greenhouse gas emissions than its value chain produces.

One new and notable collaboration is with LanzaTech, a carbon recycling company, to explore producing polypropylene (PP) plastic—a key material for products like SAMLA boxes and IKEA 365+ containers—using carbon capture and utilization (CCU) technologies. This process involves converting captured industrial emissions into ethanol and other raw materials through biological fermentation, showcasing the potential for sustainable materials in IKEA's product lines[42].

CarbonTech Is Not Yet an Ecosystem, But a Promising Framework

While these partnerships are picking up and will accelerate CarbonTech adoption, the field is not yet a fully developed ecosystem. Instead, it is an incremental framework where startups bring new solutions, and established players provide funding, expertise, quality assurance and critical feedback, and in the end ensure commercial access and a demand pull. The mutual benefits are clear: startups gain the resources to scale, while corporates secure innovative pathways to achieve their net-zero targets, as well as investor recognition of ambitions net zero efforts [41].

But as noted in the discussion on CCS earlier, creating a mature CarbonTech ecosystem will require greater policy support such

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as a higher carbon price, cross-industry collaboration, and a focus on addressing scalability challenges. Long-term investment and regulatory clarity are essential to move CarbonTech from an emerging framework to a global growth industry.

Table 3: Presents the Discussion on Corporations Advancing CarbonTech.

Key Element	Description
Rising Investor Confidence in CarbonTech	Record venture capital investments ($17.7B in 2023) highlight CarbonTech's potential to address climate challenges and create market opportunities.
Startups Pioneering CO_2 Utilization Technologies	Companies like Carbon Engineering and Climeworks lead direct air capture efforts, demonstrating scalable CO_2 removal with high efficiency.
Transforming Construction with Carbon-Negative Materials	Startups such as CarbonCure embed CO_2 into concrete, reducing emissions in a sector responsible for 7-8% of global carbon output.
Corporate Partnerships Driving Carbon Innovation	Corporations (e.g., Microsoft, Shopify) fund startups to develop solutions that actively reduce carbon footprints beyond offsets.
Evolving Framework for CarbonTech Collaboration	CarbonTech's ecosystem is still developing, with mutual benefits for startups (scaling resources) and corporates (innovative decarbonization solutions).

Conclusions

This paper has examined the evolving landscape of Carbon Capture and Storage (CCS), Carbon Capture, Utilization, and Storage (CCU), and CarbonTech through a structured literature review grounded in both qualitative and descriptive methods. By sourcing information from peer-reviewed journal articles, industry reports, magazines, and reputable web resources, this study aimed to provide a balanced and contextual understanding of the technological advancements, market dynamics, and policy frameworks influencing CCS, CCU, and CarbonTech.

The review highlighted that CCS, CCU, and CarbonTech technologies can play a significant role in achieving net-zero emissions by 2050, particularly for sectors that are challenging to decarbonize through renewables alone. The cement and concrete sector, contributing around 7–8% of global emissions, exemplifies how these solutions can help transform a high-emission industry into a more sustainable one. Innovators such as CarbonCure, Climeworks, and Carbon Engineering, supported by partnerships with multinational corporations like Microsoft and Shopify, demonstrate that carbon-based innovations are moving beyond theory and pilot projects toward tangible market opportunities.

Yet, these developments are not without challenges. Technologies need further refinement to reduce costs and enhance scalability. Effective carbon pricing, robust regulatory frameworks, and stronger incentives can accelerate adoption, while careful evaluation of storage integrity and environmental impacts will help maintain public trust. At the same time, thematic analysis revealed that global cooperation and capacity-building are essential. Harmonizing standards, fostering equitable funding mechanisms, and encouraging knowledge exchange between regions can help address infrastructure and affordability barriers.

The literature review suggests that CCS, CCU, and CarbonTech hold promise as components of a multifaceted net-zero strategy. By using descriptive and thematic analytical methods, and drawing upon a wide range of data sources for contextual intelligence, this research has provided a clearer understanding of how these technologies fit into the larger decarbonization narrative – but also highlight that this is a moving target. Corporations, startups and technologies are changing in this space.

However, it is worth considering whether novel CarbonTech players are complementary solutions to corporate strategies such as direct purchase agreements that back renewables adoption or ambitious energy efficiency measures. CarbonTech is at risk of becoming distractions in the larger decarbonization drive if overemphasized as standalone solutions. Towards a net zero world, we should not delay systemic and societal transitions to 100% renewables-based energy systems and fast electric vehicle adoption; let us just recall that as of 2023, approximately 40 million electric cars are in use worldwide, indicating that the vast majority of the global vehicle fleet—over 1.4 billion cars—are still powered by fossil fuels[43].

ESG officials in corporates may see these solutions as opportunities and risks within broader decarbonization strategies. While CSS, CCU and CarbonTech technologies may be necessary for hard-to-abate sectors like cement and steel, their viability depends heavily on scalable cost reductions, robust policy frameworks such as carbon pricing, and public trust in environmental safeguards.

The ultimate contribution of CCS, CCU and CarbonTech depends on the convergence of policy support, market uptake, technological improvement and cost reductions. These elements, working in tandem, can ensure that CCS, CCU, and CarbonTech evolve further - from useful concepts into a coherent stabilization wedge towards a net zero world.

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