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Putting the U in CCUS: Overview of emerging pathways in carbon utilisation

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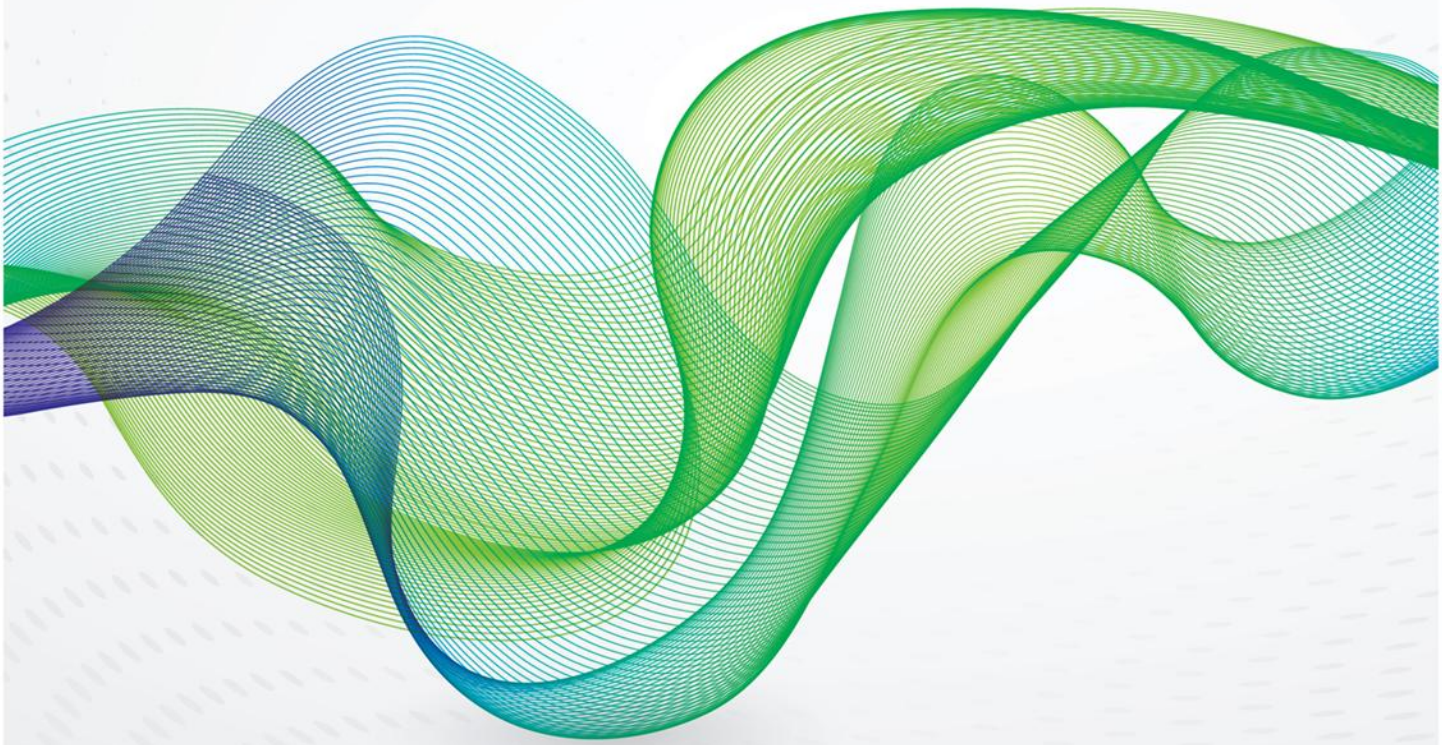
Putting the U in CCUS: Overview of Emerging Pathways in Carbon Utilisation



OIES Paper: CM11

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Introduction

The push to limit the increase in global temperatures to 1.5°C above pre-industrial levels by 2100 has focused efforts on reducing unabated fossil fuel usage, primarily by deploying renewable energy in electricity generation and improving energy efficiency. This has led to significant strides in both areas. Renewable energy's share of the global electricity mix increased from 18% in 2000 to 32% in 2024[1], while global energy efficiency improved by nearly 30% over the same period[2]. However, the same period saw strong population growth in emerging economies that make up the so-called 'Global South'. Aided by rapid industrialisation in these areas, total energy usage increased by 54%[3]. These realities have led to increased support for other approaches to achieve carbon neutrality. Key among these are carbon dioxide removal (CDR) and carbon capture, utilisation and storage (CCU and CCS) technologies in hard-to-abate sectors that are critical to maintaining economic growth sectors, like cement, steel and petrochemicals.

CDR involves the removal of carbon from the atmosphere for permanent storage, and a variety of technologies are being developed to advance this idea. These include direct air capture and storage (DACS), bioenergy with carbon capture and storage (BECCS), soil carbon sequestration and reforestation[4]. Globally, almost all CDR is achieved through reforestation. New technologies, including DACS and BECCS, contribute only 2 $MtCO_2$/year or 0.1% of the total CDR volume[5]. The main reasons for this difference are the cost and scale of deploying technology-based CDR, especially the energy required to capture atmospheric CO_2. Additionally, the capture points are only part of the network required to deliver full value. Logistics in the form of CO_2 transport – pipelines or ships – are critical, as are the availability and proximity of depleted hydrocarbon reservoirs for permanent storage of CO_2.

In contrast to CDR, carbon capture and storage (CCS) involves the capture of CO_2 from point source emitters, typically large industrial facilities where fossil fuels are combusted to generate heat and electricity; or produce hydrogen, cement, steel and ammonia. Like BECCS and DACS, the captured CO_2 is transported for permanent storage. With existing CCS networks – including some or all of capture, transport, and storage – being developed by firms involved in fossil fuel extraction or usage, environmental pressure groups have generally challenged its long-term value as an effective way of achieving meaningful emissions reductions[6]. However, the need to accelerate carbon neutrality, combined with the relatively higher level of maturity of some CCS technologies compared to CDR, suggests that existing CCS transport and storage networks can play a role in de-risking CDR technologies. At a high level, this would involve the location of atmospheric and bioenergy capture plants (more likely the former) near CO_2 pipelines, significantly offsetting the cost of building an entire DACS and/or BECCS system, while leveraging proven storage, transport and/or utilisation pathways.

While the focus of both CDR and CCS is on permanent sequestration, it is not always practical (for logistical or geographical reasons) or economic to sequester CO_2. The utilisation of CO_2 as a feedstock – displacing fossil carbon alternatives - is one that is gaining increased traction. This builds on more mature and accepted uses such as in food or beverages, or equally mature but more disputed uses, such as for enhanced oil recovery (EOR). CCU is one of the more mature approaches to carbon neutrality, yet simultaneously one of the least understood or categorically defined. This paper intends to provide a broad-based overview of CCU, as well as a deeper dive that will incorporate scalability, market dynamics and enabling regulatory frameworks for emerging technologies. Finally, the role that CCU plays in the larger carbon management landscape will be explored along with an assessment of what may lie ahead, including opportunities and challenges.

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[1] IEA. 2024. *Share of renewable electricity generation by technology, 2000-2030*, IEA, Paris Link, Licence: CC BY 4.0
[2] IEA. 2024. *Global annual improvement in primary energy intensity, 2000-2024, and by IEA scenario, 2022-2030*, IEA, Paris Link, Licence: CC BY 4.0
[3] Ritchie, Hannah et al. 2020. *Energy Production and Consumption*. Link
[4] US Department of Energy. 2024. *Carbon Dioxide Removal.* Link
[5] University of Oxford Net Zero Climate. 2024. *Carbon Dioxide Removal.* Link.
[6] Laville, Sandra. 2023. *Why carbon capture and storage will not solve the climate crisis any time soon.* Link.

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Background

CCU is increasingly gaining ground as a multipurpose lever in global decarbonisation efforts. In the broadest sense, it involves the conversion of captured carbon into a usable product while either eliminating or reducing the amount of carbon that would otherwise have been emitted from a conventional fossil fuel to produce that product. While this is a generally accepted view of carbon utilisation, there are nuanced interpretations that can lead to significant differences in how certain pathways are viewed and the fiscal and regulatory support provided to these pathways in a carbon-constrained world. This is important in the context of the cost required to build out carbon capture at the scale required to make a meaningful impact on global carbon neutrality efforts. Carbon capture on its own does not have a business case, but CCU can potentially make one for scaling the industrial point capture of CO_2 and commercializing pathways for transport. In some ways, this mirrors the scaling of CCS/CCU transport and storage as a potential enabler of BECCS and DACS.

The American University[7] considers CCU to be completely distinct from both CCS and CDR due to the short-term nature of its storage (compared to CCS) and its recycling, not removal, of carbon (compared to CDR). Based on this definition, the American University considers CO_2 in cement to be CDR (if biogenic or atmospheric), not CCU, because of the long-lived nature of cement. On the other hand, they consider EOR to be CCU but its claims to carbon neutrality or carbon reduction are challenged on the basis that the emissions created from the combustion of oil from EOR processes are greater than those generated by the original sequestration. The Oil and Gas Climate Initiative (OGCI) views CCU as any captured carbon that is reused for a purpose other than its original one[8]. By focusing on this circular approach, they consider EOR to be a viable pathway, along with CO_2 stored in concrete and other potential longer-term uses of carbon. Unlike the American University, the OGCI emphasizes the difference between pathway (i.e. CCU or CCS) and climate impacts, such as carbon removal, carbon reduction and carbon neutrality.

Dziejarski et al. suggest that CCU technologies like EOR and CO_2-cured concrete are a combination of CCS and CCU and should be designated accordingly[9]. The cyclical approach they proposed suggests that irrespective of how the carbon was captured, if it is combined with energy and reagents to create or process an industrial product, it is utilised carbon. Even if CO_2 is released after product usage, in a circular model, the ability to capture those emissions remains and maintains the integrity of the circularity. They suggest defining direct air carbon capture and utilisation (DACCU) separately from CCU, if required to drive a focus on investment in the former rather than the latter, but do not see this changing how the carbon is utilised. This view of CCU is aligned with the carbon utilisation pathways suggested by Ekemezie and Digitemie[10], who considered CCU from industry, from air and from bioenergy as equivalents in their potential to boost agricultural production or provide synthetic fuels, particularly in emerging economies. In their paper, Mertens et al. consider the source of CO_2 to be immaterial if it is a hard-to-abate sector since the utilized carbon will result in the reduction of life-cycle emissions[11].

Beyond the definitions of CCU, CO_2 has high thermodynamic stability, which means that significant amounts of energy are required to convert it into fuels or chemicals, which can be used in industrial processes. Mertens et al. view the generation of energy for this conversion as the main challenge that needs to be resolved for most utilisation pathways to be scalable[12]. The use of renewable energy is the

[7] American University. 2025. *Fact Sheet: Carbon Capture and Use*. Link
[8] Oil and Gas Climate Initiative. 2024. *Carbon capture and utilization as a decarbonzation lever.* Link
[9] Dziejarski, Bartosz et al. 2023. *Current status of carbon capture, utilization, and storage technologies in the global economy: A survey of technical assessment*. Fuel. 342. 127776. 10.1016/j.fuel.2023.127776.
[10] Ekemezie & Digitemie. 2024. *Carbon Capture and Utilization (CCU): A Review of Emerging Applications and Challenges*. Engineering Science & Technology Journal. 5. 949-961.
[11] Mertens, Jan et al. (2023). *Carbon capture and utilization: More than hiding CO_2 for some time.* Joule, Volume 7, Issue 3, 442 - 449
[12] ibid

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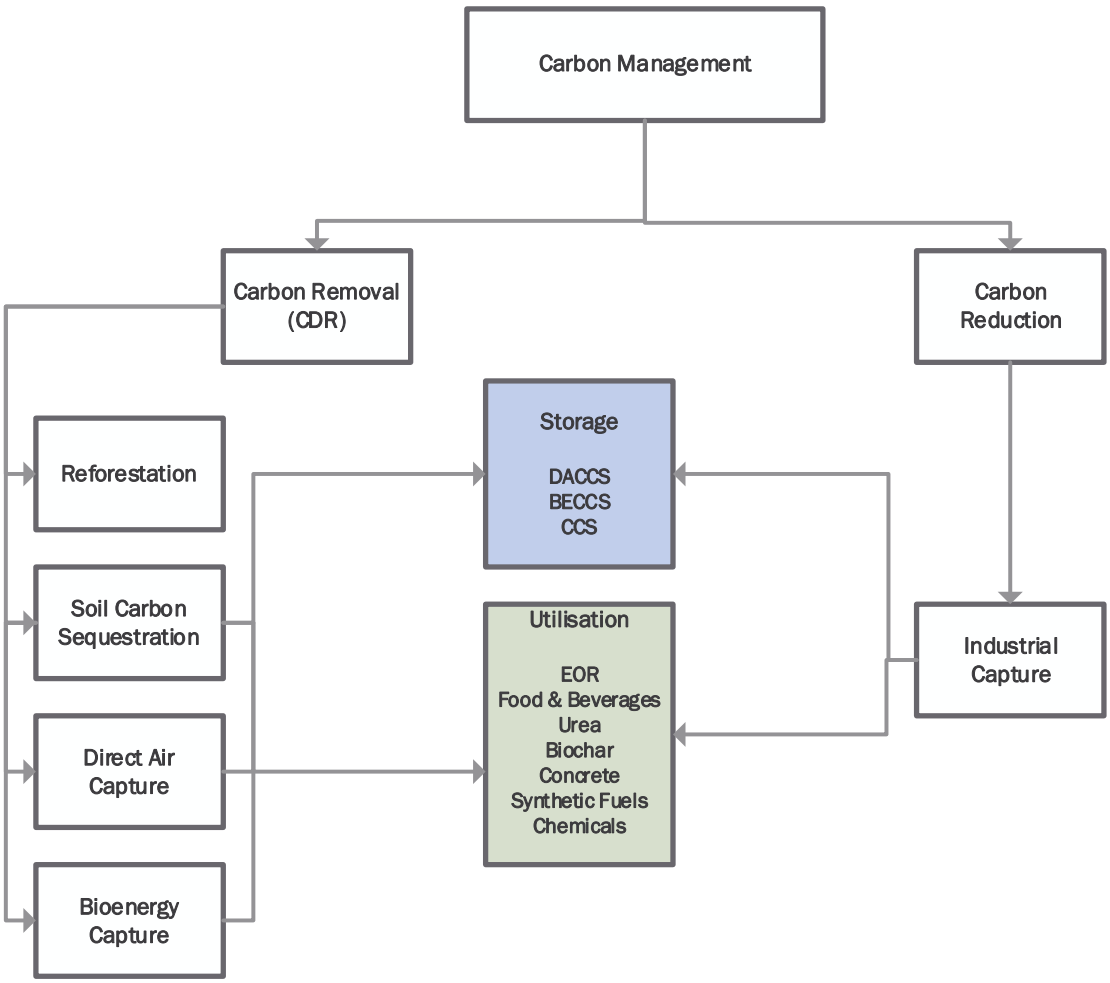
ideal solution, but is currently characterized by high costs as well as variability, factors which can prevent scale in line with the net zero targets of most major economies. Options to address this include using sunlight for photochemical reduction of CO_2 as well as hydrogen-generated electricity as an energy carrier for CO_2 transport infrastructure, but these are not efficient, are limited in terms of pathway applicability and are not yet proven at scale[13]. Further, even in cases like the conversion of CO_2 to carbonates, which is exothermic (energy-releasing), there is no current technology that can capture that waste heat and recycle it within the same – or an adjacent - process[14]. The availability, cost and reliability of large-scale renewable energy for electricity generation stands out as the biggest requirement that can enable viable CCU pathways.

Figure 1: Overview of Carbon Management Pathways



Focusing on which pathways and conversion mechanisms can drive progress on carbon neutrality, Gabrielli et al. argue for utilisation efforts to focus on DACCU but acknowledge that CCU from fossil sources can result in substantial emissions reductions relative to the current state[15]. These reductions

[13] Leonzio, Grazia and Shah, Nilay. 2024. *Recent advancements and challenges in carbon capture, utilization and storage*. Current Opinion in Green and Sustainable Chemistry, Volume 46, 100895. Link

[14] Mertens, Jan et al. (2023). *Carbon capture and utilization: More than hiding CO_2 for some time.* Joule, Volume 7, Issue 3, 442 - 449

[15] Gabrielli, Paolo et al. (2020). *The Role of Carbon Capture and Utilization, Carbon Capture and Storage, and Biomass to Enable a Net-Zero-CO_2 Emissions Chemical Industry*. *Industrial & Engineering Chemistry Research* **2020** *59* (15), 7033-7045. Link

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depend in large part on whether CCU is viewed as a standalone means of achieving carbon neutrality or whether it is seen as a parallel pathway to CCS and DACCS. In their 2017 paper on the role of CCUS in mitigating climate change, Mac Dowell et al. insist that if CCU is not seen as a single tool, considering its impact on emissions reduction is estimated to be less than 1% of the total volume required to be sequestered by 2050[16], then it offers potential for hard-to-abate sectors and is an enabler for other carbon management pathways. Based on further exploring CCU technologies and pathways with a view to understanding their readiness and applicability, this paper will define a CCU pathway as one which involves the *conversion or injection of CO_2 into products which have an economic value, the use of which results in lower-life cycle emissions than if CO_2 had not been utilized*. This view is represented in Figure 1. In addition, the utilized CO_2 should either be in long-duration storage or any emissions associated with its use can otherwise be captured and re-used for other CCU processes.

A Note on Mature Carbon Utilisation Pathways

The vast majority of contemporary CO_2 utilisation occurs in the urea (57%), EOR (34%) and food/beverage (6%) sectors[17]. These are relatively mature segments, however in the case of urea and the food industry, while there is utilisation of CO_2, there is no corresponding long-duration storage as the CO_2 escapes into the atmosphere once it is utilised. It should also be noted that while these volumes comprise the majority of utilisation today, from an absolute growth perspective, these segments are not expected to make a significant contribution to carbon capture volumes once the emerging pathways mature[18].

Injecting CO_2 into depleted hydrocarbon reservoirs for EOR has occurred for half a century, primarily in the United States, resulting in increased oil production and the long-duration storage of the injected CO_2. Its maturity as a CO_2 utilisation pathway is partially offset by the emissions associated with combusting the extracted oil, leading to geopolitical differences in its recognition as a climate mitigation pathway. While EOR is supported by the 45Q legislation in the United States, albeit at a lower level than CCUS and DAC, it is excluded from similar carbon management investment tax credits in Canada. There are some markets with no EOR penetration today which have vast potential for CO_2 storage via EOR, including Nigeria, Angola, Venezuela and several oil producing countries in the Middle East[19]. Currently, these jurisdictions have almost no EOR development with noted gaps in the availability of pipelines and other transport logistics, as well as a lack of enabling political and regulatory backing. Concerns about declining investment in oil exploration, combined with steady or moderately increasing demand, may drive governments to focus on developing this area further to unlock new barrels at lower costs[20]. If global acceptance of EOR as a viable emissions reduction or avoidance tool is obtained, EOR has the potential to be recognised as the most significant CO_2 utilisation pathway. In a modelled scenario, the overall contribution of CO_2-EOR to the overall CO_2 mitigation challenge of 160 $GtCO_2$ between now and 2050 can be as high as 8% when combined with CO_2 storage. However, it should be noted that this is only economically viable where the cost of EOR does not exceed 45% of the per barrel cost of oil[21].

[16] Mac Dowell, N. et al. (2017). *The role of CO_2 capture and utilization in mitigating climate change*. Nature Clim Change **7**, 243–249. Link
[17] IEA (2019), *Putting CO2 to Use*, IEA, Paris Link
[18] Mac Dowell, N. et al. (2017). *The role of CO_2 capture and utilization in mitigating climate change*. Nature Clim Change **7**, 243–249. Link
[19] US Energy Department. 2011. *What is Carbon Utilization?* In Focus - Carbon Capture & Storage. Link
[20] Ibid
[21] Mac Dowell, N. et al. (2017). *The role of CO_2 capture and utilization in mitigating climate change*. Nature Clim Change **7**, 243–249. Link

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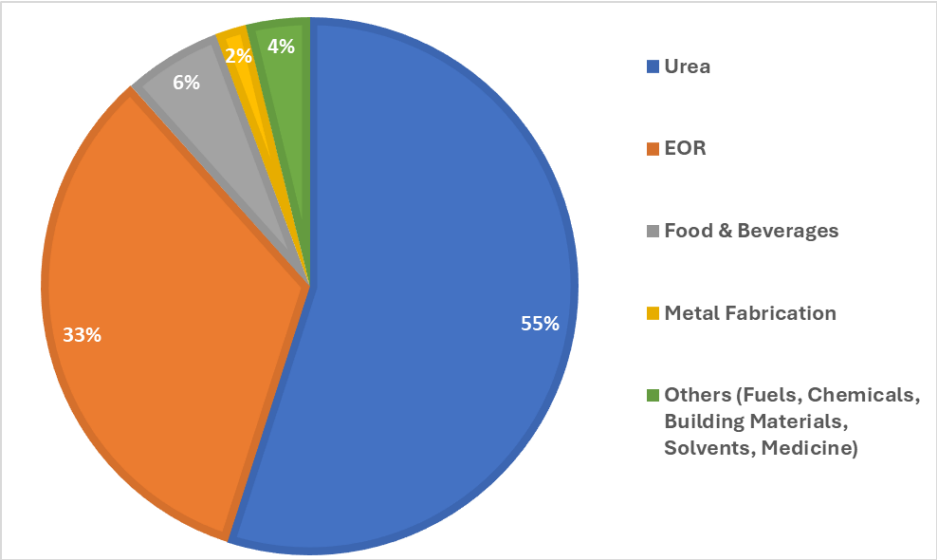
Figure 2: CO2 Utilisation (2023): Mature & Emerging Pathways

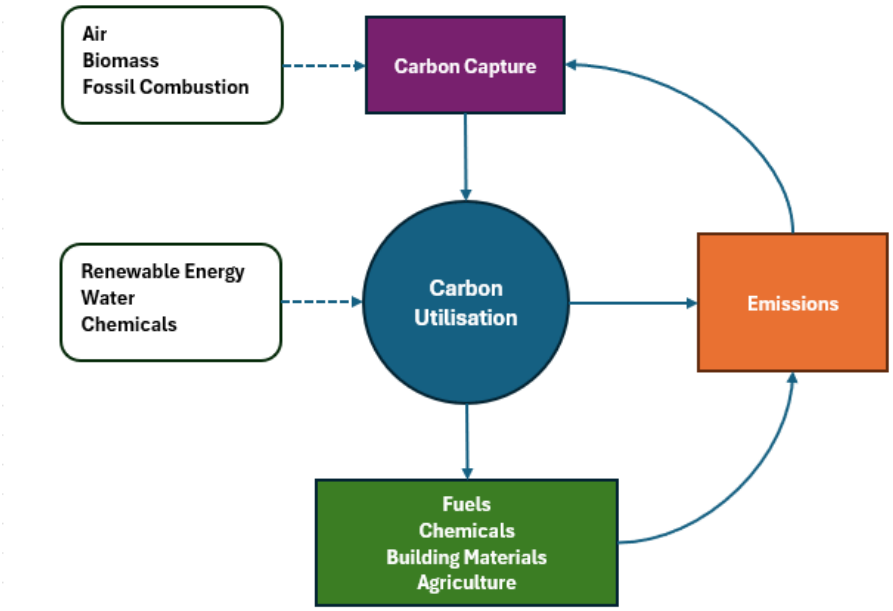


Source: IEA

A Review of Emerging CCU Pathways & Technologies

Emerging CCU pathways in hard-to-abate sectors include biochar/carbonates, building materials, synthetic fuels, and chemicals/polymers. For the identified sectors, cogent definitions will be provided along with technological readiness, costs, scalability and the demand and supply dynamics which can impact their economic feasibility. A review of relevant enabling policies – by geography and sector – will also be undertaken in a bid to support a broader understanding of the opportunities and limitations in advancing CCU maturity globally. Figure 3 highlights the inputs into the capture and utilisation processes, along with the potential for any emissions from the utilisation process and end-use to recaptured to achieve a carbon-neutral life cycle.

Figure 3: CCU Lifecycle and Emerging Utilisation Pathways



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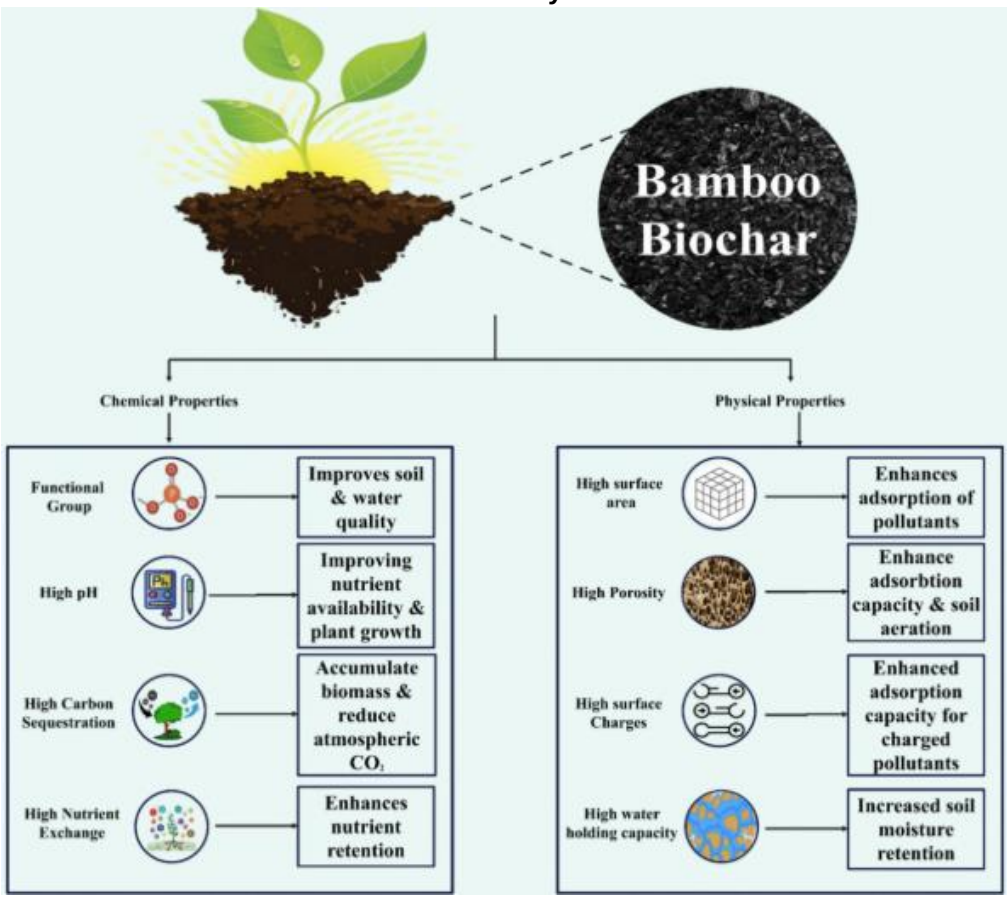
Biochar & Agriculture

Overview & Technology. The use of CO_2 in agriculture as a soil enhancer is an understated one. CO_2 captured from point-sources or DAC can be converted into carbonates and biochar, for injection into soil structures to improve their yields while acting as a relatively stable sequester of carbon[22]. These two benefits have been highlighted as resulting in a life cycle impact that is potentially carbon-negative when stabilizing decaying organic plants that would otherwise emit CO_2[23]. Biochar is created from biomass through the process of high temperature pyrolysis under inert conditions. After this, the biochar is either activated by physical means (steam, CO_2) or chemical means (potassium hydroxide, zinc chloride). The activation process creates larger pore volumes while retaining the structure of the biochar, creating stable pockets for long-duration CO_2 residence[24]. This attribute of biochar also makes it a viable option as an absorbent for use in the industrial point source capture of CO_2, with the added benefit that spent biochar used for capture can be repurposed in agricultural settings to enrich the soil.

Figure 4: Biochar as a Multi-Beneficial CCU Pathway



Source: Kumar, Ansari, Awarkar et. al.[25]

[22] Ekemezie & Digitemie. 2024. *Carbon Capture and Utilization (CCU): A Review of Emerging Applications and Challenges*. Engineering Science & Technology Journal. 5. 949-961.
[23] Levitan, Dave. 2010. *Refilling the Carbon Sink: Biochar's Potential and Pitfalls*. Yale Environment 360. Link
[24] Zhang, C et al. 2023. *The Application of Biochar for CO_2 Capture: Influence of Biochar Preparation and CO_2 Capture Reactors*. Industrial & Engineering Chemistry Research *62* (42). Link
[25] Kumar, T., Ansari, S.A., Sawarkar, R. *et al. Bamboo biochar: a multifunctional material for environmental sustainability*. Biomass Conv. Bioref. (2025). Link

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Scalability & Adaptability. In contrast to other utilisation pathways, the energy requirements and complexity required for biochar are relatively low, minimizing significant barriers to commercial scale. Unlike the other pathways, the use of biochar – depending on source - can be considered both carbon-reducing and carbon removal (CDR). This increases the relative social acceptance and likelihood that its climate potential can be achieved. Due to its porosity when activated either physically or chemically, biochar can store large amounts of CO_2, with the potential to reduce global emissions by up to 2.2 $GtCO_2$ annually[26]. This potential is enabled by the global availability of biochar, and the diversity of its applicability, including CO_2-rich biochar from point source capture being deployed as soil enrichers that also trap carbon from organic material, or simply using 'raw' biochar directly in the soil with the same agricultural benefits. Additional benefits that extend beyond carbon removal, such as potential support for ecosystems that are under water stress, make biochar not only environmentally viable, but also environmentally stabilising[27]. Despite the vast potential of biochar as a CO_2 utilisation pathway, its success is dependent on the porosity of the biochar, with high pore volumes associated with enhanced CO_2 capture capacity and wider pores producing the opposite effect.

Costs & Enabling Policies. The feedstock availability and energy conversion costs for biochar make it a cost-effective carbon removal lever. Estimated costs are up to US$179/$tCO_2$, which compares very favourably to an average of US$388/$tCO_2$ for other CDR options. This cost profile was based on 52kt CO_2 being utilised annually, or 0.005% of the potential market size for biochar[28]. Cost learning, both volumetrically through the buildout of pyrolysis plants as well as broader technology deployment in carbon capture, can be expected to reduce those costs significantly. Incorporating biochar development into the suite of options available for carbon removal credits will help increase the funding available to support this scaling, while providing purchasers with a high impact CDR option that has allied benefits. An increase in the amount of biochar produced is also likely to support CCS growth, given biochar's utility in the capture process. There are concerns about biochar's potential to displace existing food systems, with crops grown purely for their biomass potential[29]. This concern can be offset through regulatory policies that incentivize the maintenance of existing land use with the burden of proof on biochar suppliers to demonstrate that the biochar is additive, not subtractive.

Supply & Demand. Biochar has the potential to be produced anywhere in the world, with ready feedstock availability and relatively simple processing needs. This makes it an option for most countries, whether the need is greater food security, combating natural disasters like floods and drought; or simply increasing harvest volume and quality. The risks previously identified with the potential for food production to be displaced by the cultivation of crops specifically for biochar production can change supply dynamics as this is more likely to occur in relatively industrialised countries. Additionally, this displacement could divert funding from the use of biochar in emerging economies, eroding some of the allied benefits that have positioned biochar as the most significant source of CDR. Demand for biochar is likely to be led by agricultural economies, although their needs are likely to be met through local supply. Demand for biochar credits, as with most emissions-reduction or removal credits will be led by industrialised economies, and specifically by sectors that are unable to mitigate their emissions directly or have hard-to-abate emissions.

Building Materials

Overview & Technology. CO_2 used to cure concrete or as construction aggregates provides a pathway for both utilisation and long-duration storage through a process known as CO_2 carbonation. While the storage is generally considered permanent, the conversion process also means that the CO_2 can be considered utilised when handled this way. Concrete is one of the most consumed materials in the world,

[26] Moya, Berta. 2023. *Biochar is carbon removal's jack of all trades. Here's why*. World Economic Forum. Link
[27] Stegenta-Dąbrowska, et al. (2024). *Effective Carbon Dioxide Mitigation and Improvement of Compost Nutrients with the Use of Composts' Biochar.* Materials 17, no. 3: 563. Link
[28] Moya, Berta. 2023. *Biochar is carbon removal's jack of all trades. Here's why*. World Economic Forum. Link
[29] Levitan, Dave. 2010. *Refilling the Carbon Sink: Biochar's Potential and Pitfalls*. Yale Environment 360. Link

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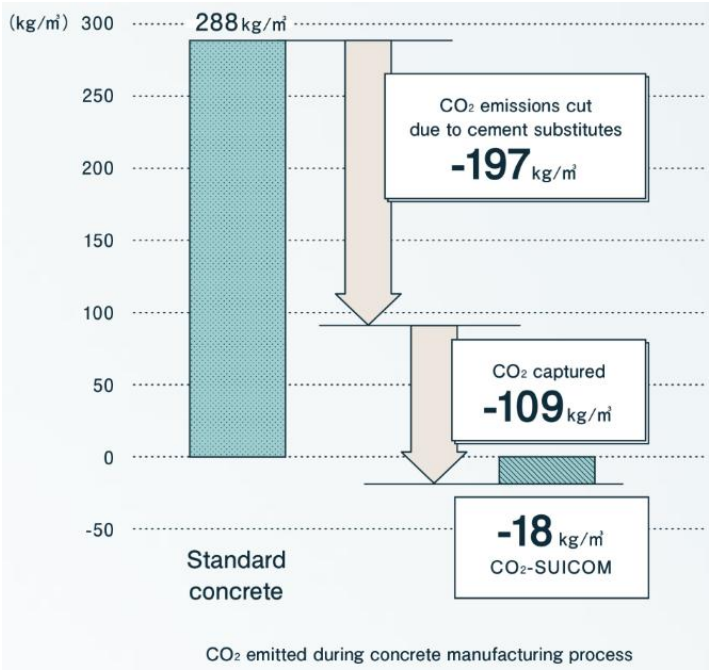
behind only water, and the manufacturing process generates almost 8% of global CO_2 emissions[30]. These emissions result from the combustion of fossil fuels – coal or natural gas – to produce the heat required for separation and production; as well as the chemical reactions that convert limestone and clay to concrete. There is evidence that CO_2 converted into mineralized carbonates within concrete results in a structure which is more durable and stronger than conventional concrete[31]. Key to this is the ability to inject gaseous CO_2 into a concrete slurry early in the process - prior to the mixture setting - otherwise the opposite effect is achieved, and the structure becomes unstable and weaker[32]. Where the injected CO_2 is captured from the combustion process or the air and the source of electricity is renewable, it is possible to significantly reduce the carbon emissions associated with the life cycle and even potentially obtain carbon-neutral concrete (Figure 5).

Figure 5: Carbon-Negative Concrete Leveraging Substitutes, Capture and Utilisation



Source: Kajima Corporation

Scalability & Adaptability. Based on conventional cement production, the calcination of limestone to produce calcium oxide accounts for 60% of the CO_2 emissions associated with the life-cycle process. Combusting natural gas and coal to heat up the cement kilns accounts for the remaining 40%[33]. Introducing carbonated CO_2 into the process, assuming all else remains constant, is estimated to result in emissions reductions of up to 32%. Using decarbonised electricity and heat, this reduction can be up to 40% of the lifecycle emissions irrespective of the CO_2 source[34]. Concrete produced this way can displace up to 25% of the volume of conventional concrete in standard Portland cement without adverse

[30] Stefaniuk, Damian et al. (2023). *Cementing CO_2 into C-S-H: A step toward concrete carbon neutrality*. PNAS Nexus, Volume 2, Issue 3. Link

[31] Ekemezie & Digitemie. 2024. *Carbon Capture and Utilization (CCU): A Review of Emerging Applications and Challenges*. Engineering Science & Technology Journal. 5. 949-961.

[32] Fu, X., A. Guerini, and D. Zampini. 2024. *Storing CO2 while strengthening concrete by carbonating its cement in suspension*. Nature. Link.

[33] Lee, Christine Wei-li. 2024. *UCLA engineers develop scalable process to decarbonize cement production*. UCLA Science + Technology. Link.

[34] Strunge, Till, Phil Renforth, and Mijndert Van der Spek. 2022. *Towards a business case for CO2 mineralisation in the cement industry*. Nature. Link

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effects on physical properties such as hardness, strength and water usage[35]. In 2020, 45 billion tons of construction aggregates and 25 billion tons of concrete were produced; a baseline case sees CO_2 utilisation as high as 4 gigatons per year by 2050 with a 10% penetration of the concrete and aggregates market[36]. Further, the displacement of conventional concrete in the process can result in an additional profit of €32/ton of cement sold according to one developed scenario[37]. Taking these together, the injection of CO_2 into the precast concrete and construction aggregates could result in an annual value of up to €100 billion globally.

Costs & Enabling Policies. Achieving the projected value of injecting CO_2 into concrete is dependent on a few factors, including the previously discussed optimal ratio of carbonated CO_2 in the concrete mix. Compared to conventional concrete manufacturing, the full lifecycle costs associated with carbon capture and transport, along with the additional processing costs are higher for concrete produced this way compared to conventional concrete. In a production plant where the electricity and heat costs are decarbonised, or where carbon capture originates from DAC, these costs are even higher. Overall, the cost of manufacturing CO_2-cured concrete is expected to range from €100-€150/ton[38]. Pathways to reducing these costs and improving the economics include carbon pricing, with avoided CO_2 credits traded on carbon markets. Any such pricing will need to be competitive enough such that concrete manufacturers preferentially choose to incorporate carbonated CO_2 into their processes. Setting minimum carbonation content requirements is another approach policymakers could take, and this is likely to not only increase adoption but also support the reduction of other costs along the CO_2 value chain. Existing fuel regulations in several jurisdictions, where minimum ethanol and fatty acid methyl ester (FAME) content is required in gasoline and diesel, respectively, are models that can support the economic and regulatory basis for this approach.

Supply & Demand. The demand for precast concrete and construction aggregates is expected to increase to over 150 billion tons in 2050, an increase of almost 300% compared to 2020. These volumes are incompatible with Net Zero scenarios and other emissions reduction targets announced by most signatories to the 2015 Paris climate agreement and others like it, without significant CO_2 abatement. Despite the potential market size, the additional processing complexity of injecting CO_2 combined with the need for proximal carbon capture or transported CO_2 is likely to limit the growth of this segment. Even within countries that have carbon management programmes, including carbon pricing or emissions trading systems, the economics of CO_2-cured concrete are not favourable where the source of CO_2 is far away from the utilisation point. Since carbon pricing is the largest factor in profitability, it is expected that profitability will depend on the existence (and price level) of a carbon market. In general, the demand for CO_2 carbonation in the manufacturing of concrete and construction aggregates is likely to be driven less by corporate or policy mandates and more by the ready availability of relatively inexpensive CO_2. The creation of CCUS hubs, where transport networks have an offtake system, has been linked to the emergence of this market.

Synthetic Fuels

Overview & Technology. Liquid synthetic fuels are non-fossil fuels that have been identified as low-carbon or carbon-neutral options for hard-to-abate sectors, particularly long-distance road transport and aviation. Synthetic fuels involve the production of synthetic gas (syngas) from the catalytic conversion of hydrogen with either biomass gasification or anaerobic digestion, as well as directly through biomass pyrolysis and fermentation. Increasingly, synthetic fuel research and development is focused on electro-fuels (e-fuels) where CO_2 is synthesised with hydrogen to produce methanol and ethanol[39]. Processes

[35] Ibid
[36] Sick, Volker, Gerald Stokes, and Fred C. Mason. 2022. *CO2 Utilization and Market Size Projection for CO2-treated Construction Materials*. Frontiers in Climate. Link
[37] Strunge, Till, Phil Renforth, and Mijndert Van der Spek. 2022. *Towards a business case for CO2 mineralisation in the cement industry.* Nature. Link
[38] Ibid
[39] The Royal Society. 2019. "Sustainable synthetic carbon based fuels." Link.

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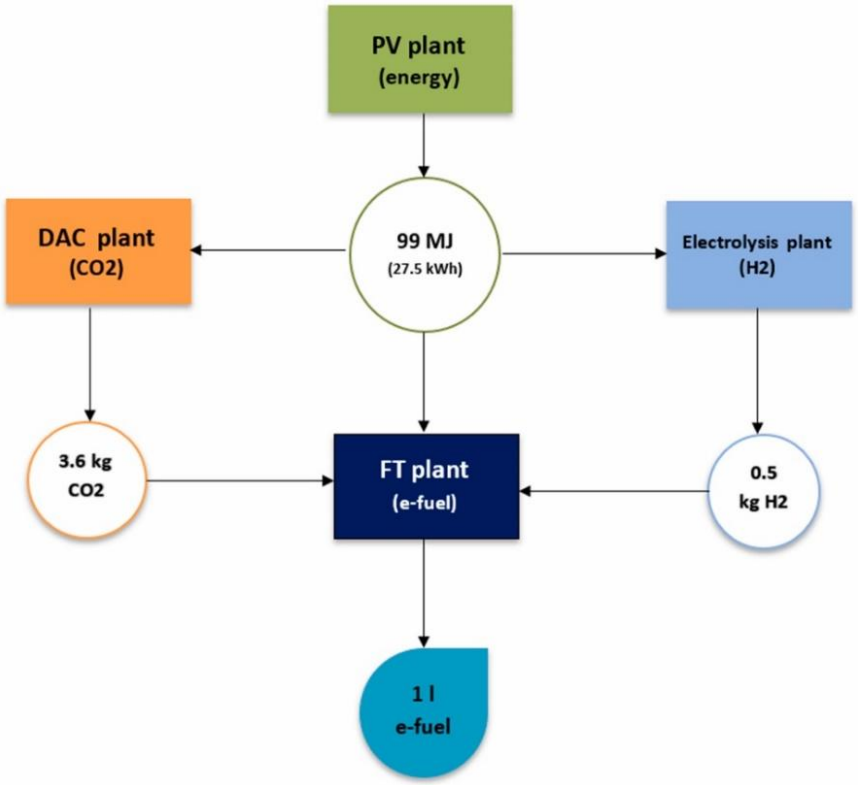
exist to convert methanol and other synthetic fuels to gasoline, including Exxon-Mobil's Methanol to Gasoline (MTG) process, as well as the Fischer-Tropsch Synthesis. These processes are considered mature and commercially viable, with the production of methanol rated at the highest technological readiness level (TRL 9)[40]. Other e-fuels such as e-kerosene and e-methane have lower technological readiness, but several pilot plants are being developed to demonstrate their readiness, particularly in the EU[41]. These fuels are attractive because they can leverage existing fuel infrastructure and with some modifications, conventional engines. Although synthetic fuels emit CO_2 during combustion, the amount emitted is equivalent to the amount that was utilized in production. Thus, synthetic fuel can be carbon-neutral (if the carbon is biogenic or atmospheric) or low-carbon, particularly if renewable energy is used for electricity. Figure 6 shows the renewable energy, hydrogen and captured CO_2 (via DAC in this case) requirements to produce one litre of e-fuel.

Figure 6: Energy & CO_2 Requirements to Produce 1L of E-Fuel



Source: D'Adamo, Idiano et. al. (2024)

Scalability & Adaptability. For the e-fuel to be considered carbon-neutral, the converted hydrogen must be produced through electrolysis from renewable energy sources and the CO_2 should be obtained through DAC or BECC. However, it is important to note that the production of e-fuel is energy-intensive, with an estimated energy penalty of up to 50% just for DAC alone. This does not include the vast amounts of energy required to produce hydrogen, especially using electrolysis. Altogether, the combined process of producing carbon-neutral methanol from CO_2 involves the energy input of up to 60GJ/tonne of methanol compared to an output of 20GJ/tonne[42]. A perfectly designed system would not only involve DAC with green hydrogen but would also co-locate the hydrogen production plant with

[40] Dziejarski, Bartosz et al. (2023). *Current status of carbon capture, utilization, and storage technologies in the global economy: A survey of technical assessment*. Fuel. 342. 127776. 10.1016/j.fuel.2023.127776.
[41] The Royal Society. 2019. "Sustainable synthetic carbon based fuels." Link.
[42] Mac Dowell, N. et al. (2017). *The role of CO_2 capture and utilization in mitigating climate change*. Nature Clim Change **7**, 243–249. Link

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variable renewable energy generation linked to long-duration storage[43]. The combination of leveraging excess peak power and balancing that load using stored energy can help reduce the energy penalty associated with carbon-neutral e-fuel production. Low-carbon e-fuels are less carbon intensive than carbon-neutral e-fuels, with the difference being primarily in the energy requirements of DAC compared to industrial CO_2 capture, with the latter having an energy penalty of approximately 20%[44]. Utilizing blue hydrogen (produced from gas- or coal-fired power plants with carbon capture) to produce e-fuels reduces the energy penalty substantially but is carbon-additive. As a means of demonstrating that the technologies are viable, 'blue' e-fuels are a potential intermediate step to scale fully sustainable e-fuels. It is also worth noting that, driven by fuel mandates in aviation and shipping sectors, the e-fuels market can contribute to a significant proportion of the CO_2 utilisation market.

Costs & Enabling Policies. The amount of energy required to produce e-fuels leads to a significant cost premium compared to conventional fuels. The levelised cost of producing e-fuel at a modelled plant in Europe using variable renewable energy, with DAC-derived CO_2 was estimated to be average €3.1/L, significantly higher than the average of <€1/L for refined fossil fuels[45]. These estimated prices make e-fuels relatively uncompetitive at the present time but are likely to be revised downward in the future, with lower renewable electricity prices and technology scaling. There is an inherent assumption that the price of fossil fuels will remain constant, but this is not guaranteed given geopolitical tensions and adverse climate change that can lead to price shocks. The combination of these downward pressures on renewable energy costs and upward pressures on fossil fuel pricing can unlock the potential for e-fuels to displace conventional fuels, but the largest impact on cost is likely to be policy-driven. Enabling policies, including subsidies and investment backing, will be required to accelerate the competitiveness of e-fuel pricing, like the policies adopted to enable the commercialization of battery-electric vehicles (BEVs). In addition, carbon-neutral e-fuels require both renewable energy generation with long-duration storage, so other policies supporting investment in green hydrogen production as well as decarbonisation of the electricity grid will be required in tandem.

Supply & Demand. Unlike conventional fossil fuels, e-fuels can – in theory – be produced anywhere in the world. A combination of cost and the availability of cheaper alternatives suggests that deep penetration of the overall liquid fuels market will be both limited and localized. Demand is likely to be driven by countries and jurisdictions which are net energy consumers with an appetite to displace liquid fuels in long-distance transport and aviation, particularly those with legislated requirements to be carbon neutral by 2050. This includes the EU and the UK as well as large markets like China. Specific US states where carbon pricing schemes have been implemented, like California and Oregon, are also expected to be at the forefront of e-fuel adoption. While e-fuels can be supplied from anywhere in the world, major suppliers are likely to be in countries with high demand for liquid fuels which also have established CO_2 networks (capture, transport) and renewable energy generation. This co-location of renewable energy and CO_2 supply will be required to support scaling, management of energy production costs and ready access to customers.

Chemicals

Overview & Technology. Along with synthetic fuels and building materials, the third major utilization pathway for converted CO_2 is the manufacturing of chemical intermediates and polymers. Chemical intermediates are not finished products but are produced during a chemical reaction and utilized in a subsequent process step. Intermediates that can be derived from CO_2 include formic acid, which is used as a chemical reducing agent; olefins, which are used to manufacture plastics and aromatics, used in consumer goods manufacturing. Methanol, previously discussed as a synthetic fuel, can also be used

[43] Ihejirika, Nnaziri. 2023. Assessing Carbon Capture and Storage and Clean Hydrogen Acceleration Under the US Inflation Reduction Act. *Oxford Institute for Energy Studies*. OEF Issue 138. Link

[44] Soeherman, Jimmy K. et al. (2023). *Overcoming the Entropy Penalty of Direct Air Capture for Efficient Gigatonne Removal of Carbon Dioxide*. ACS Engineering Vol 3, Issue 2. Link

[45] D'Adamo, Idiano et al. (2024) *Environmental implications and levelized cost analysis of E-fuel production under photovoltaic energy, direct air capture, and hydrogen*. Environmental Research, Volume 246, 2024, 118163. Link

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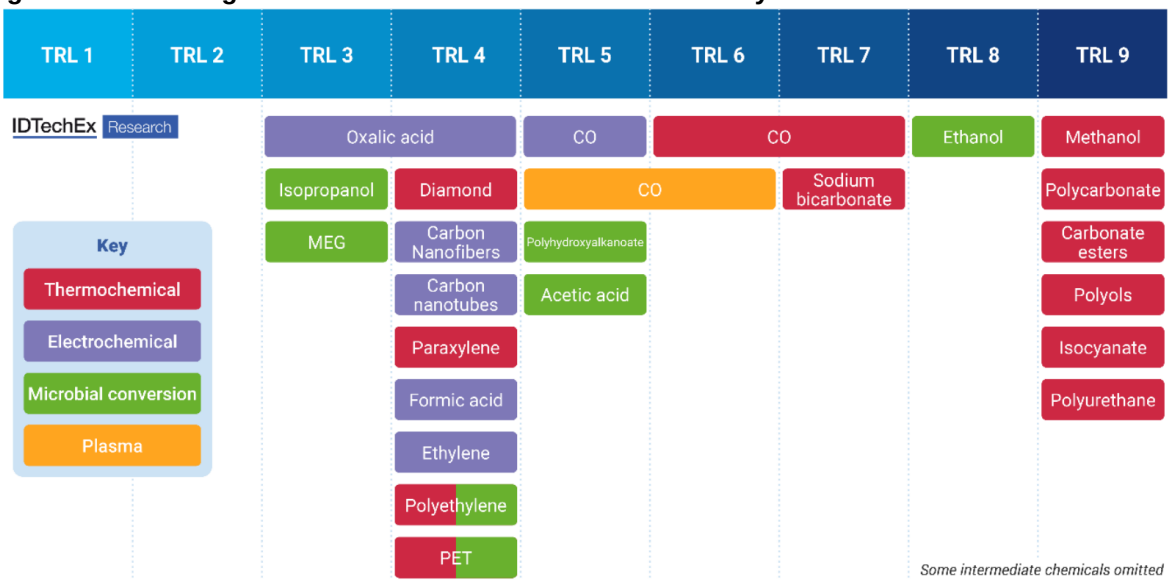
as an intermediate in the production of polymers and plastics. The technological readiness of these chemicals covers a wide range, but in general their production via CO_2 conversion is relatively early stage in comparison to synthetic fuels and building materials[46]. From a carbon accounting perspective, this utilization of CO_2 can result in the direct reduction of emissions associated with the combustion of fossil fuels. Currently this process requires electrolysers, which tend to consume large amounts of electricity inefficiently. In addition to using electricity generated from renewable energy sources, the development of low-temperature electrolysers leveraging electrochemical processes can bring this utilization pathway closer to carbon neutrality[47]. It should be noted that these are further behind in technological readiness than thermochemical processes (Figure 7).

Figure 7: Technological Readiness of CO2 Utilisation Pathways for Chemical Production



Source: Eve Pope (2024)

Scalability & Adaptability. The chemicals industry directly contributes up to 2% of global CO_2 emissions, or about 1Gt CO_2 annually[48]. Unlike synthetic fuels and building materials, the amount of CO_2 used in the conversion process is relatively high, with direct conversions from CO_2 to chemicals such as acetic acid, ethanol and formic acid using water and electricity only[49]. The thermochemical processes normally required for these are energy intensive, meaning that deep abatement of these emissions using CO_2-derived chemicals and polymers in the short-term is likely limited to those chemicals or intermediates that can be produced without large amounts of processing, or need for energy-intensive hydrogen[50]. Despite the energy intensity, the relative process simplicity means that economic viability for both direct-to-use chemicals like ethanol and more complex plastics like polyethylene and PET can be high even when derived from CO_2. It is estimated that the market size for this segment will increase from US$3B in 2024 to as much as US$40B in 2045[51], with reductions in annual emissions of up to 12000 Mt CO_2 by 2050[52].

[46] Dziejarski, Bartosz et al. 2023. *Current status of carbon capture, utilization, and storage technologies in the global economy: A survey of technical assessment*. Fuel. 342. 127776. 10.1016/j.fuel.2023.127776.
[47] Harmon, Joseph. 2024. *Recycling carbon dioxide into household chemicals*. Argonne National Laboratory. Link.
[48] Pope, Eve. 2024. *CO2 Utilization: Emerging Synthesis Pathways for Chemicals and E-fuels*. IDTechEx. Link
[49] Chandler, David L. 2024. *MIT engineers make converting CO2 into useful products more practical*. MIT News. Link
[50] Pope, Eve. 2024. *CO2 Utilization Market to Grow To US$240 Billion by 2045*. IDTechEx. Link.
[51] Ibid
[52] Galimova, T. et al. (2022). *Global demand analysis for carbon dioxide as raw material from key industrial sources and direct air capture to produce renewable electricity-based fuels and chemicals*. Journal of Cleaner Production. Volume 373, Link

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Costs & Enabling Policies. For CO_2-derived chemicals to achieve commercial status as an effective replacement for conventional methods of chemical production, the cost and source of electricity used in the process will need to be optimized. This will depend on the type of chemical being produced, and the process used in production. In addition to the cost of carbon capture and CO_2 transport, the energy required to convert CO_2 to chemicals and intermediates is usually more than the energy provided by the finished product[53]. Exceptions include certain conversions to plastics, where the displacement of fossil fuels with CO_2 in the conversion process is both profitable and carbon-reductive[54]. Opportunities to reduce the cost of e-chemicals and make them more competitive with fossil-based alternatives include co-locating chemical plants in proximity to point-sources of CO_2 or DAC plants and routing CO_2 transport logistics close to existing chemical production plants. The implementation of carbon pricing will also provide an incentive for chemical producers, especially in jurisdictions with high amounts of variable renewable energy. Future opportunities include increasing the use of atmospheric CO_2 as the feedstock to achieve carbon neutrality, although this ability to do this broadly is limited by the type of chemical being produced[55].

Supply & Demand. As with most utilisation pathways, the supply of CO_2-derived chemicals is dependent on the availability of captured CO_2 adjacent to chemical plants or easily accessible through CO_2 pipelines or shipping. It is assumed that the global demand for chemicals will match projections irrespective of the feedstock source. The relative lack of technological maturity of e-chemicals as previously shown, means that not as much work has been done to test them in practical applications. If e-chemicals are deemed too expensive or limited in geographic availability, long-term demand could be eroded by the development of other technologies that are not derived from CO_2. Regulatory policies that restrict or eliminate the unabated use of fossil-based fuels could also drive an increase in the demand for CO_2-derived chemicals.

Summary of CCU Pathways and Market Potential

Table 1 provides a summary of products that can benefit from the commercialisation of CCU pathways, along with projections for production and market size up to 2050. The potential market penetration of CCU is referenced along with the volume of CO_2 production required to achieve the median penetration.

Table 1: CCU Market Potential (2040-2050)

Utilisation Pathway	Commercial Product	Projected Production (Mt)	Projected Market Size ($B)	CCU Market Penetration	Annual Utilisation ($MtCO_2$)
Agriculture	Biochar	118	2.5	~50%	1300
Building Materials	Precast Concrete	32000	260	16%-25%	400
Building Materials	Aggregates	16500	386	12%-16%	7000
E-Fuels	Methanol	500	38.5	10%-60%	200
E-Fuels	SAF	400	402	30%-98%	150
Chemicals	Ethylene	340	400	10%	949

Source: Various

Analysis

When it comes to carbon management policy, the focus of most governments is on establishing a regulatory framework that compels resource providers, industrial firms and other end users to defer or permanently store CO_2 emissions. While the mechanism may differ – carbon taxes, investment credits,

[53] Ibid
[54] University of Oxford. 2019. *Capturing carbon dioxide to make useful products could become big business*. University of Oxford News. Link
[55] Galimova, T. et al. (2022). *Global demand analysis for carbon dioxide as raw material from key industrial sources and direct air capture to produce renewable electricity-based fuels and chemicals*. Journal of Cleaner Production. Volume 373. Link

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emissions trading schemes or a combination of all – the end goal is driven by the inability of CCS, BECCS or DAC to generate economic value for investors in isolation. What they do is enable continued industrial growth, while offering a solution for hard-to-abate sectors that are integral components of the global economy. Unlike CCS, carbon utilisation offers a series of pathways for direct and indirect conversion of CO_2 into useful products that can displace fossil fuel-based alternatives and retain – or potentially increase - the economic value of those products. While a degree of regulatory support is required, the extent to which this is the dominant factor in CCU viability is limited to the interface with CO_2 capture (point-source or atmospheric) and transport since the volume of CO_2 captured and stored far exceeds the volume that can be utilised. In other words, CCS viability is highly dependent on regulatory support, while CCU viability is highly dependent on isolation from carbon storage. It should also be noted that CO_2 from industrial capture is penalized – by surrendering emission allowances – under the EU-ETS, a potential regulatory barrier to the use of CO_2 as a feedstock when other potential pollutant feedstocks – methane and CO – are not treated the same way.

The volume of CO_2 produced is another potential constraint on CCU growth, highlighting its limited supporting role in the overall carbon management market. The estimated demand of 10GtCO_2 required annually to support the projections outlined in Table 1 is at the higher end of the most optimistic projections for CCUS in general, even without including CCS or other utilisation pathways. This contrasts with the current design for CCUS networks, where captured CO_2 is transported to a permanent storage location or shipping port by pipeline, with utilisation firms only acting as 'micro' off-takers along the pipeline. Regulations and policies have also been implemented or proposed to incentivize storage, given the relatively larger volumes that can be sequestered that way without the need for additional investment outside of the CCUS network.

This is not to suggest that policy should not be considered in CCU deployment. From a regulatory standpoint, certain countries or jurisdictions may choose to enact incentives for atmospheric CO_2 to improve the climate neutrality of utilisation pathways. This could lead to, for example, more investment in chemicals and polymers – which are less dependent on co-location with industrial producers of CO_2 - compared to building aggregates, the production and use of which is best co-located with the hard-to-abate cement manufacturing sector. However, such a push would also necessitate increased investment in green electricity generation, increasing the cost – and reducing the profitability and scalability – of the pathway due to the high energy penalties involved. What CCU will require is a high degree of coordination, not just within countries or regions, but industry-wide at a global level. This coordination will be important to ensure that there is no destructive competition amongst utilisation pathways especially in the early stages of development, when CO_2 capture volumes are still relatively low. Coordination would also help ensure that the economics of the CCUS value chain are supported even if storage or shipping volumes are impacted by the dynamics of the utilisation market.

From a contemporary perspective, e-fuels targeted at the aviation market are among the most viable utilisation pathways. The technologies are not only the most mature but are also commercially available and are relatively straightforward swaps with existing fuels without significant infrastructure changes. While costs are still up to three times more expensive than conventional fuels, a combination of policies (Canada's Clean Fuel Standard and the European Union's ReFuelEU Aviation are examples) and geopolitically driven price shocks could create enough capacity for the cost-learning associated with increased scale. Similarly, the growth expected in the cement and concrete production by 2050 – with few credible alternatives – increases the viability of building aggregates. The added benefit of leveraging proximity to point-source capture, and any investment or emissions credits associated with concrete production to reduce costs, can further enable this pathway.

CO_2-derived polymers and chemicals, along with CO_2-enriched biochar, have significant potential but most of them are at a lower technological readiness than other utilisation pathways. In addition to the high energy costs associated with their conversion, product alternatives are being developed which could erode market potential. This does not diminish the value of e-chemicals and biochar but likely means that their emergence will be dependent on policies mandating minimum CO_2 content, proximity to carbon capture points (atmospheric or industrial), large-scale variable electricity generation combined with long-duration storage to drive down energy costs and end-use subsidies to make switching easier.

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While actual costs may be competitive, and some CO_2-derived chemicals like formic acid are commercially viable, the overall impact on the CCUS market is expected to be minimal from a volumetric standpoint.

The emergence – and increasing relevance – of CCU pathways can help strengthen the business cases for CCUS hubs and engage emerging economies in the wider CCUS discussion. Beyond the lower value use of CO_2 in food and beverage production, or the contentious use of CO_2 to stimulate depleted oil and gas reservoirs; the ability to utilize CO_2 in the production of useful commercial products holds broad global appeal. At present, most of the research in this area is largely both regional and industry-specific (even firm-specific), but they share common attributes. These include a demonstrated ability to deliver equivalent to their conventional alternatives, but at high costs and with stiff energy penalties to attain carbon neutrality, especially when capture and conversion are powered by renewable energy.

The viable pathways further highlight the need for integrated planning and coordination of CCUS technology development, deployment and operations. Research and development work is likely to occur in parallel and is currently concentrated in OECD countries, but it is also important to note that some of the most significant markets for CO_2 utilisation may be in BRICS and other emerging economies. Finally, all carbon utilisation pathways are not created equal. Coordination efforts should look to optimize pathways that are in proximity to captured CO_2, can be dropped in to conventional processes and are carbon reductive. A realisation that CCU is not going to temper the need for CCS and CDR is also important to ensure that investment and time are focused on the best use cases.

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