Perspective

The technological and economic prospects for CO_2 utilization and removal

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The capture and use of carbon dioxide to create valuable products might lower the net costs of reducing emissions or removing carbon dioxide from the atmosphere. Here we review ten pathways for the utilization of carbon dioxide. Pathways that involve chemicals, fuels and microalgae might reduce emissions of carbon dioxide but have limited potential for its removal, whereas pathways that involve construction materials can both utilize and remove carbon dioxide. Land-based pathways can increase agricultural output and remove carbon dioxide. Our assessment suggests that each pathway could scale to over 0.5 gigatonnes of carbon dioxide utilization annually. However, barriers to implementation remain substantial and resource constraints prevent the simultaneous deployment of all pathways.

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CO_2 utilization is receiving increasing interest from the scientific community[1]. This is partly due to climate change considerations and partly because using CO_2 as a feedstock can result in a cheaper or cleaner production process compared with using conventional hydrocarbons[2]. CO_2 utilization is often promoted as a way to reduce the net costs—or increase the profits—of reducing emissions or removing carbon dioxide from the atmosphere, and therefore as a way to aid the scaling of mitigation or removal efforts[3]. CO_2 utilization is also seen variously as a stepping stone towards[4] or a distraction away from[5] the successful implementation of carbon capture and storage (CCS) at scale.

In most of the literature—including the IPCC 2005 Special Report on Carbon Dioxide Capture and Storage[6]—the term 'CO_2 utilization' refers to the use of CO_2, at concentrations above atmospheric levels, directly or as a feedstock in industrial or chemical processes, to produce valuable carbon-containing products[6–11]. Included in this conventional definition is the industrial production of fuels using, for example, amines to capture and concentrate the CO_2 from air, potentially with solar energy. However, the definition excludes cases in which an identical fuel is produced from the same essential inputs, but the CO_2 utilized is captured by plant-based photosynthetic processes.

Here, we consider CO_2 utilization to be a process in which one or more economically valuable products are produced using CO_2, whether the CO_2 is supplied from fossil-derived waste gases, captured from the atmosphere by an industrial process, or—in a departure from most (but not all[12,13]) of the literature—captured biologically by land-based processes. Biological or land-based forms of CO_2 utilization can generate economic value in the form of, for example, wood products for buildings, increased plant yields from enhanced soil carbon uptake, and even the production of biofuel and bio-derived chemicals. We use this broader definition deliberately; by thinking functionally, rather than narrowly about specific processes, we hope to promote dialogue across scientific fields, compare costs and benefits across pathways, and consider common techno-economic characteristics across pathways that could potentially assist in the identification of routes towards the mitigation of climate change.

In this Perspective, we consider a non-exhaustive selection of ten CO_2 utilization pathways and provide a transparent assessment of the potential scale and cost for each one. The ten pathways are as follows: (1) CO_2-based chemical products, including polymers; (2) CO_2-based fuels; (3) microalgae fuels and other microalgae products; (4) concrete building materials; (5) CO_2 enhanced oil recovery (CO_2-EOR); (6) bioenergy with carbon capture and storage (BECCS); (7) enhanced weathering; (8) forestry techniques, including afforestation/reforestation, forest management and wood products; (9) land management via soil carbon sequestration techniques; and (10) biochar.

These ten CO_2 utilization pathways can also be characterized as 'cycling', 'closed' and 'open' utilization pathways (Fig. 1, Table 1, Supplementary Materials). For instance, many (but not all) conventional industrial utilization pathways—such as CO_2-based fuels and chemicals—tend to be 'cycling': they move carbon through industrial systems over timescales of days, weeks or months. Such pathways do not provide net CO_2 removal from the atmosphere, but they can reduce emissions via industrial CO_2 capture that displaces fossil fuel use. By contrast, 'closed' pathways involve utilization and near-permanent CO_2 storage, such as in the lithosphere (via CO_2-EOR or BECCS), in the deep ocean (via terrestrial enhanced weathering) or in mineralized carbon in the built and natural environments. Finally, 'open' pathways tend to be based in biological systems,

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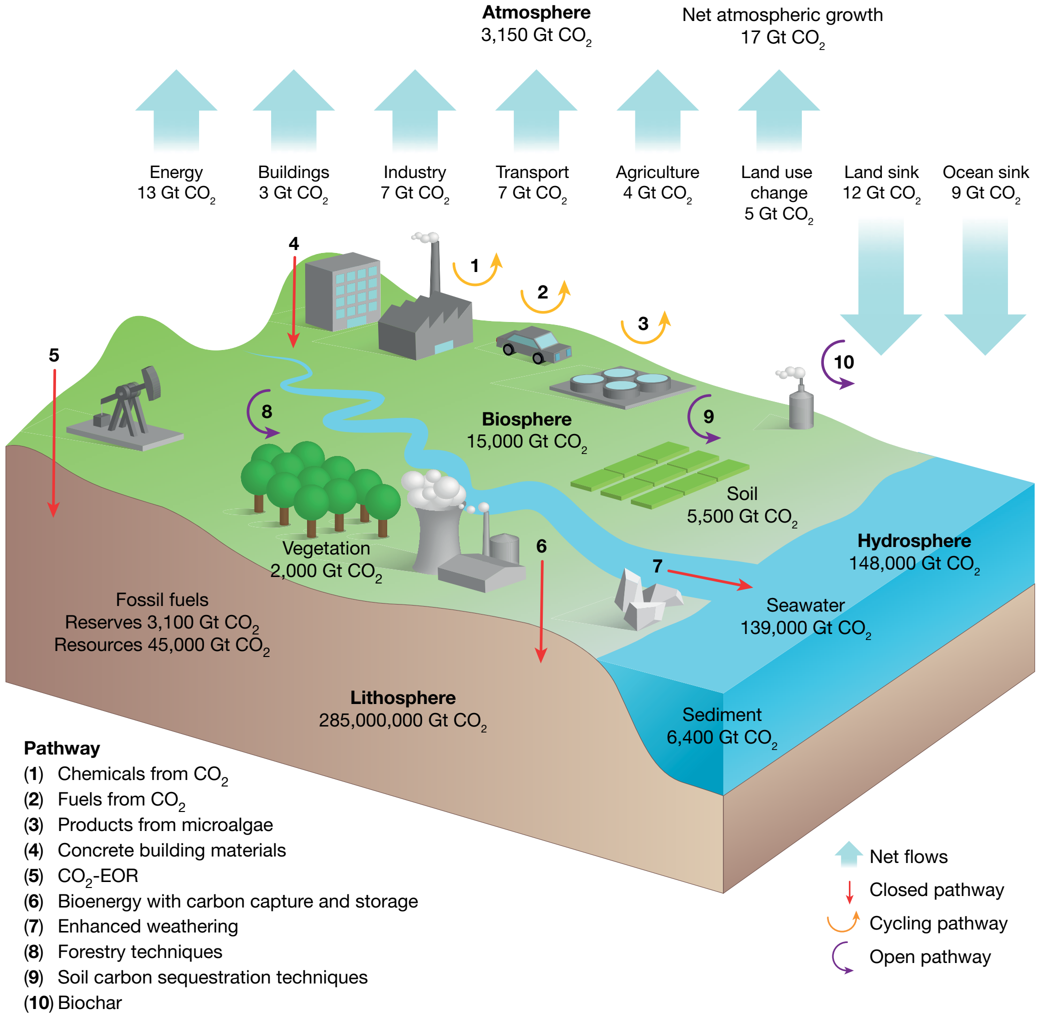

Fig. 1 | Stocks and net flows of CO_2 including potential utilization and removal pathways. Orange, red and purple arrows (numbered 1–10, as described in Table 1) represent cycling, closed and open pathways for CO_2 utilization and removal. Teal block arrows represent annual flows to and from the atmosphere, with estimates averaged over the 2008–2017 period[15,91]. Estimates of stocks in the Earth's spheres (lithosphere, biosphere, hydrosphere and atmosphere, labelled in bold) and selected stock subcategories are given. All estimates are based on IPCC estimates[16] except where noted, and are converted from C to CO_2. Carbon stocks in the hydrosphere comprise seawater, sediment, and dissolved organic carbon (not shown, around 2,600 Gt CO_2). The vast majority of carbon stocks in the lithosphere are locked in the Earth's crust[92], with estimated accessible fossil fuel reserves and resources of more than 45,000 Gt CO_2[25]. Atmospheric stocks are converted from the 2017 estimates of atmospheric CO_2 of 405 ppm[93] using a conversion factor of 2.12. Carbon stocks in the biosphere include those stored in permafrost and wetlands (not shown, around 7,500 Gt CO_2), vegetation, and soils. Soil stocks to 1-m depth have been recently estimated at 5,500 Gt CO_2[62].

and are characterized by large removal potentials and storage in 'leaky' natural systems—such as biomass and soil—with the risk of large-scale flux back to the atmosphere.

Of the pathways we discuss, some are novel or emerging—such as CO_2-fuels, for which current flows are near-zero—whereas others are well established, such as CO_2-EOR and afforestation/reforestation. Pathways were selected on the basis of discussions at a joint meeting of the US National Academy of Sciences and the UK Royal Society[1]; each pathway is relatively well studied to date and has an acknowledged potential to scale. There are many other pathways that meet our definition but are not reviewed here (Supplementary Materials).

This Perspective is structured as follows: first, the ten utilization pathways are presented in the context of the scale of CO_2 stocks and flows on Earth. Second, the potential scale and economics of each pathway are assessed. Third, a selection of key barriers to scaling is identified. Fourth, we assess the outlook for CO_2 utilization, and conclude with priorities for future research and policy.

CO_2 utilization and the carbon cycle

The amount of carbon dioxide that is utilized by a pathway is not necessarily the same as the amount of carbon dioxide removed or carbon dioxide stored. CO_2 utilization does not necessarily reduce emissions and does not necessarily deliver a net climate benefit, once indirect and other effects have been accounted for. The various concepts overlap and relate to each other, but are distinct (Supplementary Fig. 1, Supplementary Materials). Some carbon capture and utilization (CCU) processes achieve carbon dioxide removal (CDR) from the atmosphere, and some involve CCS. CCS itself can contribute either to the mitigation of CO_2 (for example, by reducing net emissions from a gas-fired power plant) or to atmospheric removals (for example, by direct air carbon capture and storage, or DACCS); CCS does not necessarily imply CDR. Furthermore, CCS and CDR can fail to deliver a climate benefit. For instance, perverse indirect effects—such as land-use change resulting from BECCS[14]—could increase net atmospheric CO_2 concentrations.

Table 1 | Ten CO_2 utilization and removal pathways

Pathway[a]	Removal and/or capture[b]	Utilization product	Storage[c,d] and likelihood of release (high/low)	Emission on use[f] or release during storage[g]	Example cycles[h]
(1) Chemicals from CO_2	Catalytic chemical conversion of CO_2 from flue gas or other sources into chemical products	CO_2-derived platform chemicals such as methanol, urea and plastics	Various chemicals (days/decades) – high	Hydrolysis or decomposition	KCLG; KCLF; ALFJ; ALG
(2) Fuels from CO_2	Catalytic hydrogenation processes to convert CO_2 from flue gas or other sources into fuels	CO_2-derived fuels such as methanol, methane and Fischer–Tropsch-derived fuels	Various fuels (weeks/months) – high	Combustion	KCLG; ALG
(3) Products from microalgae	Uptake of CO_2 from the atmosphere or other sources by microalgae biomass	Biofuels, biomass, or bioproducts such as aquaculture feed	Various products (weeks/months) – high	Combustion (fuel) or consumption (bioproduct)	KCLG; BG
(4) Concrete building materials	Mineralization of CO_2 from flue gas or other sources into industrial waste materials, and CO_2 curing of concrete	Carbonated aggregates or concrete products	Carbonates (centuries) – low	Extreme acid conditions	KCLF; ALF
(5) CO_2-EOR	Injection of CO_2 from flue gas or other sources into oil reservoirs	Oil	Geological sequestration (millennia) – low[e]	n.a.	KCD
(6) Bioenergy with carbon capture and storage (BECCS)	Growth of plant biomass	Bioenergy crop biomass	Geological sequestration (millennia) – low[e]	n.a.	BCD
(7) Enhanced weathering	Mineralization of atmospheric CO_2 via the application of pulverized silicate rock to cropland, grassland and forests	Agricultural crop biomass	Aqueous carbonate (centuries) – low	Extreme acidic conditions	BE
(8) Forestry techniques	Growth of woody biomass via afforestation, reforestation or sustainable forest management	Standing biomass, wood products	Standing forests and long-lived wood products (decades to centuries) – high	Disturbance, combustion or decomposition	BFJ
(9) Soil carbon sequestration techniques	Increase in soil organic carbon content via various land management practices	Agricultural crop biomass	Soil organic carbon (years to decades) – high	Disturbance or decomposition	BFJ
(10) Biochar	Growth of plant biomass for pyrolysis and application of char to soils	Agricultural or bioenergy crop biomass	Black carbon (years to decades) – high	Decomposition	BFJ

n.a., not applicable.
[a]The ten pathways are depicted in Fig. 1 and are represented as a combination of steps in Fig. 2.
[b]Removal and/or capture corresponds to steps A, B and/or C in Fig. 2.
[c]Storage corresponds to steps D, E or F in Fig. 2.
[d]Storage durations represent best-case scenarios. For instance, in CO_2-EOR, if the well is operated with complete recycle, the CO_2 is trapped and can be stored on a timescale of centuries or more[22]. This is also relevant only for conventional operations.
[e]Release during geological storage is usually a consequence of engineering implementation error.
[f]Emission on use corresponds to step G in Fig. 2.
[g]Release during storage corresponds to steps H, I or J in Fig. 2.
[h]The letters stated are the steps from Fig. 2 that comprise the example cycle.

CO_2 utilization does not necessarily contribute to addressing climate change, and careful analysis is essential to determine its overall impact. Identifying the counterfactual—what would have happened without CO_2 utilization—is important but is often particularly challenging, and the impact of a given CO_2 utilization pathway on the mitigation of climate change varies as a function of space and time (Box 1).

For CO_2 utilization to contribute usefully to the reduction of atmospheric CO_2 concentrations, the scale of the pathways must be meaningful in comparison with the net flows of CO_2 shown in Fig. 1. The flux of carbon from fossil fuels and industry to the atmosphere (34 Gt CO_2 yr^{-1})[15] is dwarfed by the gross flux to land via photosynthesis in plants (440 Gt CO_2 yr^{-1})[16]. However, only 2%–3% of this photosynthetic carbon remains on land (12 Gt CO_2 yr^{-1}), and only for decades; the remainder is re-emitted by plant and soil respiration. If soil carbon uptake could be increased by 0.4% per year, this would contribute to achieving net zero emissions—as per the '4 per mille' initiative[17]—but this is challenging[18]. Of the ten pathways we discuss, five leverage our ability to perturb these land-based fluxes.

The other five conventional industrial CO_2 utilization pathways could also perturb the net flows of CO_2. The production of plastics and other products creates a demand for so-called 'socioeconomic carbon'[19] (around 2.4 Gt CO_2 yr^{-1}, of which around two-thirds is wood products) that could be met in part through CO_2 utilization. The total stock of carbon accumulated in products (such as wood products, bitumen, plastic and cereals) has been estimated at 42 Gt CO_2 in 2008, of which 25 Gt CO_2 is in wood products[19]. Up to 16 Gt CO_2 was sequestered in human infrastructure as mineralized carbonates in cement between 1930 and 2013, with current rates[20,21] estimated to be around 1 Gt CO_2 yr^{-1}.

The flow of CO_2 through the different utilization pathways can be represented by a combination of different steps (labels A to L; Fig. 2, Table 1). Utilization pathways often (but not always) involve removal (A or B) and storage (D, E or F); however, the permanence of CO_2 storage varies greatly from one utilization pathway to another, with storage timeframes ranging from days to millennia. In part, permanence depends upon where the carbon ends up (Fig. 1): the lithosphere, by geological sequestration into reservoirs such as saline aquifers or

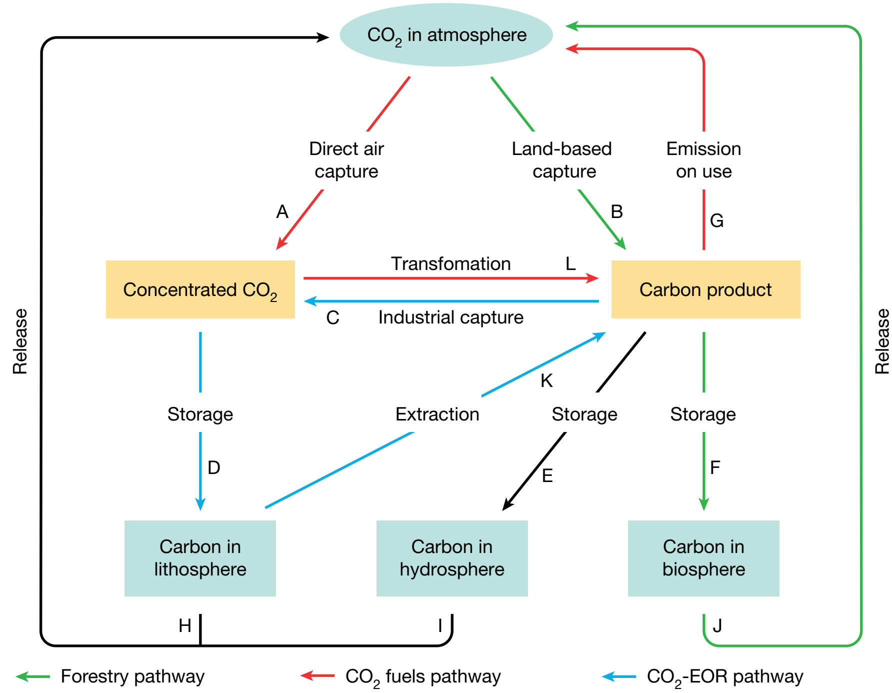

Fig. 2 | Carbon dioxide utilization and removal cycle. Utilization pathways are represented as a combination of steps, A–L. Green arrows trace an example open pathway, forestry (BFJ). Red arrows trace an example cycling pathway, CO_2 fuels with direct air capture (ALG). Blue arrows trace an example closed pathway, CO_2-EOR (KCD). Cycling pathways (with the exception of polymers) end with step G; closed pathways end with steps D, E or F; and open pathways end with step J. See Table 1 for further description. All flows are net of process emissions.

depleted oil and gas reservoirs, or by mineralization into rocks; the biosphere, in trees, soils and the human-built environment; or the hydrosphere, with storage in the deep oceans. Geological storage, when executed correctly, is considered to be more permanent[22] than storage in the biosphere, which is shorter and subject to human and natural disturbances[23] such as wildfires and pests, as well as changes in climate[24]. However, even 'closed' pathways do not offer completely permanent storage over geological timescales (more than 100,000 years[25]), which gives rise to intergenerational ethical questions[26].

In the short term, the creation of products from concentrated CO_2, as in step L (albeit, CO_2 conversion is not a necessary requirement for utilization), could leverage the industrial capture of flue gases following the extraction and combustion of fossil fuels (KC)[27]. In the longer term, the CO_2 loop will need to be closed in order to achieve net zero emissions, implying that CO_2 will need to be sourced from the atmosphere, potentially via direct air capture (A) or through land-based uptake by photosynthesis or mineralization (B). For instance, net zero CO_2-based fuels must shift the current flows of carbon, from a lithosphere-to-atmosphere (KCLG) to an atmosphere-to-atmosphere cycle (ALG) (Fig. 2).

Scale and economics of CO_2 utilization

We assess the peer-reviewed literature on the ten pathways, which comprises over 11,000 papers. For the conventional pathways, our scoping review covered over 5,000 papers, a minority (186) of which provide cost estimates. Estimates of potential scale were informed by a structured estimation process and an expert opinion survey. For the non-conventional utilization pathways, we build upon existing CO_2 removal estimates (also derived from a scoping review[28] of over 6,000 papers—of which 927 provide usable estimates—and an expert judgement process) and identify preliminary published research on the relationship between CO_2 removal and CO_2 utilization to offer estimates of the scale and cost of CO_2 utilization.

Where possible, we calculate breakeven costs in 2015 US dollars per tonne of CO_2 for each pathway (hereafter, all costs stated are in US dollars). The breakeven CO_2 cost represents the incentive per tonne of CO_2 utilized that would be necessary to make the pathway economic (see Supplementary Materials, S1.2). This can be thought of as the breakeven (theoretical) subsidy per tonne of CO_2 utilization, although we are not recommending such a subsidy.

Conventional utilization pathways

Dependent on a multitude of technological, policy and economic factors that remain unresolved, each of the conventional pathways—chemicals, fuels, microalgae, building materials and CO_2-EOR—might utilize around 0.5 Gt CO_2 yr^{-1} or more in 2050. We also estimate that between 0.2 and 3.2 Gt CO_2 yr^{-1} could be removed and stored in the lithosphere or in the biosphere for centuries or more.

Chemicals. CO_2 can be transformed efficiently into a range of chemicals, but only a few of the technologies are economically viable and scalable. Some are commercialized[29], such as the production of urea[30] and polycarbonate polyols[31]. Some are technically possible but are not widely adopted, such as the production of CO_2-derived methanol in the absence of carbon monoxide[32] (methanol is a platform chemical for a multitude of other reaction pathways, including to fuels, and is mainly manufactured via the hydrogenation of a mixture of CO and 1%–2% CO_2). Breakeven costs per tonne of CO_2, calculated from the scoping review, for urea (around −\$100) and for polyols (around −\$2,600) reflect that these markets are currently profitable. The estimated utilization potential for CO_2 in chemicals is around 0.3 to 0.6 Gt CO_2 yr^{-1} in 2050, and the interquartile range of breakeven costs obtained from the scoping review is −\$80 to \$320 per tonne of CO_2.

Currently, the largest-scale chemical utilization pathway is that of urea production. 140 Mt CO_2 yr^{-1} is utilized to produce 200 Mt yr^{-1} of urea [33]. Urea is produced from ammonia (which is generated by the energy-intensive Haber–Bosch process; $3H_2 + N_2 \rightarrow 2NH_3$) and CO_2 according to $2NH_3 + CO_2 \rightleftharpoons CO(NH_2)_2 + H_2O$; coal or natural gas typically provides the necessary energy. Within days of being applied as fertilizer, the carbon in urea is released to the atmosphere. For urea to be net zero carbon, it would require its carbon to be sourced from the atmosphere—for example, using direct air capture—and the energy source would need to be renewable. All nitrogen-based fertilizers produce N_2O, a greenhouse gas that is around 300 times more potent than CO_2 over a 100-year time horizon[34]. Increasing urea production may therefore have a negative impact on climate[35].

For the production of polymers, the utilization potential of CO_2 is estimated to be 10 to 50 Mt yr^{-1} in 2050. In the current market structure, around 60% of plastics have applications in sectors other than packaging—including as durable materials for construction, household goods, electronics, and in vehicles. Such products have lifespans of decades or even centuries[36].

Fuels and microalgae. Fuels derived from CO_2 are argued to be an attractive option in the decarbonization process[37,38] because they can be deployed within existing transport infrastructure. Such fuels could also find a role in sectors that are harder to decarbonize, such as aviation[39], since hydrocarbons have energy densities that are orders of magnitude above those of present-day batteries[32]. The long-term use of carbon-based energy carriers in a net zero emissions economy relies upon their production with renewable energy, and upon low-cost, scalable, clean hydrogen production—for example via the electrolysis of water or by novel alternative methods.

Here we consider products such as methanol, methane, dimethyl ether, and Fischer–Tropsch fuels as potential CO_2 energy carriers for transportation. The estimated potential for the scale of CO_2 utilization in fuels varies widely, from 1 to 4.2 Gt CO_2 yr^{-1}, reflecting uncertainties in potential market penetration. The high end represents a future in which synfuels have sizeable market shares, due to cost reductions and policy drivers. The low end—which is itself considerable—represents very modest penetration into the methane and fuels markets, but it could also be an overestimate if CO_2-derived products do not become cost-competitive with alternative clean energy vectors such as hydrogen or ammonia, or with direct sequestration.

A CO_2-to-methanol plant operates in Iceland, and various power-to-gas plants operate worldwide. However, these plants represent special cases that may be difficult to replicate because they are exploiting geographic advantages, such as the availability of cheap geothermal energy. Although the production of more complex hydrocarbons is energetically and therefore economically expensive[11], rapid cost-reductions could potentially occur if renewable energy—which represents a large proportion of total cost—continues to become cheaper, and if policy stimulates other cost reductions. The US Department of Energy's target for the cost of hydrogen production—\$2 per kg of H_2—is roughly equivalent to \$2 per gasoline-gallon equivalent, and would require carbon-free electricity to cost less than \$0.03 kWh^{-1} (accounting for kinetics and other losses to the enthalpy of electrolysis-based hydrogen production, around 40 kWh per kg H_2)[40]. In recent years, several wind and solar power auctions around the world have been won with prices below[41] \$0.03 kWh^{-1}.

The interquartile range for breakeven costs for CO_2 fuels from our scoping review was \$0 to \$670 per tonne of CO_2. Negative breakeven costs appear in studies that model particularly beneficial scenarios, such as low discount rates, free feedstocks, or free or low-cost renewable electricity.

For pathways that have high capital costs, the benefits of economies of scale and learning could be considerable[42]. This is particularly relevant for the algal pathways thatrequire photobioreactors[43] and for the fuel synthesis pathways that require electrolysers[44]. Microalgae are a subject of long-standing research interest because of their high CO_2-fixation efficiencies (up to 10%, compared with 1%–4% for other biomass[45]), as well as their potential to produce a range of products such as biofuels, high-value carbohydrates and proteins, and plastics[43]. The microalgae pathway has complex production economics and the estimated CO_2 utilization potential for microalgae in 2050 ranges from 0.2 to 0.9 Gt CO_2 yr^{-1}, with a breakeven cost interquartile range from the scoping review of \$230 to \$920 per tonne of CO_2.

Concrete building materials. CO_2 utilization pathways in concrete building materials are estimated to remove, utilize and store between 0.1 and 1.4 Gt CO_2 yr^{-1} over the long term—with the CO_2 sequestered well beyond the lifespan of the infrastructure itself—at interquartile

Box 1

CO_2 utilization, removal, storage, reduced emissions and net climate benefit

Does CO_2 utilization (CO_2u) lead to a climate benefit? It might reduce emissions ($CO_2\rho$), or remove CO_2 (CO_2r) from the atmosphere, and/or store it (CO_2s). But various direct and indirect effects over the relevant life cycle must be considered and compared to a plausible baseline or 'counterfactual'—what would have happened without CO_2 utilization[83]. Assiduously calculating direct impacts in one place, and at one time, is of little use if there is a 'waterbed effect' (also referred to as a 'rebound' or 'leakage') in which emissions occur somewhere else, or later.

For instance, obtaining a barrel of oil via CO_2-EOR utilizes CO_2, which can remain in the oil formation rather than being re-emitted into the atmosphere. Assuming that the CO_2 does not return to atmosphere, the CO_2 utilized is equal to the CO_2 emissions stored, that is, $CO_2u = CO_2s$, but whether $CO_2r \geq 0$ depends upon the source of the CO_2; if it is from a fossil power station, there is no net removal of CO_2 from the atmosphere. Emissions have been reduced, and $CO_2\rho = CO_2u = CO_2s > 0$, even though $CO_2r = 0$.

To visualize this, consider a 'reference' scenario in which 1 t CO_2 is emitted from a fossil power plant, and 1.5 t CO_2 are emitted from oil use, such that total emissions are 2.5 t CO_2. Compare this to a 'utilization' scenario, in which the CO_2 from the power plant is used for CO_2-EOR instead—that is, CO_2u = 1 t CO_2. Total emissions in this 'utilization' scenario comprise the 1.5 t CO_2 from the consumption of the CO_2-EOR oil. Emissions reduced is equal to 2.5 – 1.5 = 1.0 t $CO_2\rho$, which is identical to the CO_2u, but net $CO_2r = 0$ because the CO_2 came from a fossil power plant, rather than from the atmosphere.

In reality, the emissions from the baseline barrel of oil that was displaced by the CO_2-EOR oil might be higher or lower, depending on its origin and its production process. If the CO_2-EOR oil displaces the use of renewable electricity in an electric vehicle, CO_2-EOR generates a net increase in emissions. If CO_2-EOR is to offer net removals, the CO_2 must be captured from the atmosphere, and more carbon must be injected into the well than is extracted.

Life-cycle analyses on some industrial CO_2 utilization pathways suggest that the potential for net emission reductions is much larger than for net removals, which appears very modest[94]. Up to 3 tonnes of CO_2 emissions may be avoided for every 1 tonne of CO_2 used in polycarbonate polyols[2], even though no CO_2 is removed from atmosphere. Nearly 4 tonnes of CO_2 emissions may be avoided for each tonne of dry wood used that displaces concrete-based materials[95].

Other life-cycle analyses have found neutral or negative impacts of CO_2 utilization on reducing emissions[74,96–98]. For instance, CO_2 utilization pathways that involve the input of energy from non-decarbonized sources may result in net life-cycle increases in CO_2[96–99].

Table 2 | Range estimates of the potential for CO_2 utilization and present-day breakeven cost

Pathway	Removal potential in 2050 (Mt CO_2 removed per year)	Utilization potential in 2050 (Mt CO_2 utilized per year)	Breakeven cost of CO_2 utilization (2015 US$ per tonne CO_2 utilized)
Conventional utilization			
Chemicals	Around 10 to 30	300 to 600	–$80 to $320
Fuels	0	1,000 to 4,200	$0 to $670
Microalgae	0	200 to 900	$230 to $920
Concrete building materials	100 to 1,400	100 to 1,400	–$30 to $70
Enhanced oil recovery	100 to 1,800	100 to 1,800	–$60 to –$45
Non-conventional utilization			
BECCS	500 to 5,000	500 to 5,000	$60 to $160
Enhanced weathering	2,000 to 4,000	n.d.	Less than $200*
Forestry techniques	500 to 3,600	70 to 1,100	–$40 to $10
Land management	2,300 to 5,300	900 to 1,900	–$90 to –$20
Biochar	300 to 2,000	170 to 1,000	–$70 to –$60

n.d., not determined.

The breakeven cost is the cost in 2015 US$ per tonne of CO_2 adjusted for revenues, by-products, and any CO_2 credits or fees. A breakeven cost of zero represents the point at which the pathway is economically viable without governmental CO_2 pricing (for example, a subsidy for CO_2 utilization). Breakeven costs presented as a range represent either (for conventional pathways with the exception of EOR) 25th and 75th percentile estimates as calculated via the scoping review of the academic literature (in which the magnitude of the difference reflects the diversity of technological and economic assumptions available within and across each sub-pathway) or (for land-based pathways) top-down estimates of revenues that may accrue (when the uncertainty of the accuracy of the estimation is high). Breakeven costs presented with an asterisk are calculated unadjusted for revenues and by-product credits. To obtain the global gross utilization potential high and low values for conventional pathways, we averaged the interpolated expert opinions with an author group estimate. For non-conventional utilization pathways, estimated utilization potential ranges are based on estimates of additional realized yield of carbon in vegetation (for soil carbon sequestration and biochar, additional yield approximates to net primary productivity, and for afforestation/reforestation, it approximates to wood products). These are first rough estimates based on preliminary but sparse published research reporting relationships between carbon storage and additional carbon that can be utilized.

breakeven costs of −$30 to $70 per tonne of CO_2. The high end might reflect a scenario (amongst other possibilities) in which CO_2 is used as a cement curing agent in the entirety of the precast concrete market and in 70% of the pourable cement markets. The estimate also includes aggregates that are produced from carbonated industrial wastes, such as cement and demolition waste, steel slag, cement kiln dust, and coal pulverized fuel ash.

Cement requires the use of lime (CaO), which is produced by the calcination of limestone in an emissions-intensive process. As such, unless calcination is paired with carbon capture and sequestration, it is difficult for building-related pathways to deliver reductions in CO_2 emissions on a life-cycle basis. Several commercial initiatives aim to replace the lime-based ordinary Portland cement—which currently dominates the global market—with alternative binders such as steel-slag based systems[46] or geopolymers made from aluminosilicates[47].

CO_2-EOR. Enhanced oil recovery using CO_2 currently accounts for around 5% of the total US crude oil production[48]. Conventionally, operators aim to maximize both the amount of oil recovered and the amount of CO_2 recovered (rather than CO_2 stored) per tonne of CO_2 injected; between 1.1 and 3.3 barrels (bbl) of oil can be produced per tonne of CO_2 injected under conventional operation and within the constraints of natural reservoir heterogeneity[49]. However, in principle—and depending on operating conditions and project type—CO_2-EOR can be operated such that, on a life-cycle basis, more CO_2 is injected than is produced upon consumption of the final oil product[50].

More than 90% of the world's oil reservoirs are potentially suitable for CO_2-EOR[51], which implies that as much as 140 Gt CO_2 could be used and stored in this way[5]. We estimate a 2050 utilization rate of around 0.1 to 1.8 Gt CO_2 yr^{-1}. If EOR was deployed to maximize CO_2 storage—rather than oil output—then genuine CO_2 emission reductions are possible, depending on the emissions intensity of the counterfactual and on the relevant inefficiencies (Box 1).

At oil prices of approximately $100 bbl^{-1}, EOR is economically viable if CO_2 can be sourced for between $45 and $60 per tonne of CO_2[49,51], implying a breakeven cost of CO_2 of −$60 to −$45 per tonne of CO_2. These cost estimates (realistically or unrealistically) assume $100 bbl^{-1} oil prices and are specific to the United States, where the business model is mature.

Non-conventional utilization pathways

The five non-conventional utilization pathways that we review here are BECCS, enhanced weathering, forestry techniques, land management practices, and biochar. Previous reviews[18,28,52–54] have shown that these pathways offer substantial CO_2 removal potential: a recent substantive scoping review[28] gives values of 0.5 to 3.6 Gt CO_2 yr^{-1} for afforestation/reforestation, 2.3 to 5.3 Gt CO_2 yr^{-1} for land management, 0.3 to 2 Gt CO_2 yr^{-1} for biochar, and 0.5 to 5 Gt CO_2 yr^{-1} for BECCS. Enhanced weathering offers a removal potential of 2 to 4 Gt CO_2 yr^{-1} at costs[28] of around $200 per tonne of CO_2. Not all of this potential involves utilization of carbon dioxide resulting in economic value, but the approximate scale of CO_2 utilized that is described below could be considerable. The breakeven costs per tonne of CO_2 utilized that we estimate here are low and are frequently negative.

BECCS. BECCS involves the biological capture of atmospheric carbon by photosynthetic processes, producing biomass used for the generation of electricity or fuel, before CO_2 is captured and removed. Although there is substantial uncertainty regarding the total quantity of available biomass[55]—particularly in light of concerns over competition for land use with food crops—100 to 300 EJ yr^{-1} of primary energy equivalent of biomass could be deployed by 2050.

BECCS provides two distinct services: bioenergy, and atmospheric CO_2 removal. Although several cost estimates exist in the literature—for example, around $200 per tonne of CO_2[28]—these typically assign all costs to the CO_2 removal service, and thus implicitly assume that no revenue is received for the bioenergy services that are generated. By approximating those revenues using a basket of wholesale electricity prices across countries that are suited to host BECCS systems[56], we estimate breakeven costs of between $60 and $160 per tonne of CO_2 utilized.

Table 3 | Costs of utilization compared with product costs, scoping review

Pathway	Cost of product made with CO_2 utilization (US$ per tonne of product) Median, scoping review	Selling price of product (US$ per tonne of product) Present day	Difference (%)	Anticipated cost relative to incumbent in 2050 (summary, expert opinion survey and author group judgement)	Anticipated direction of cost relative to incumbent in 2050 (summary, expert opinion survey and author group judgement)
Polymers	1,440	2,040	−30%	Likely to be cheaper	Downward
Methanol	510	400	+30%	Insufficient consensus	Downward
Methane	1,740	360	+380%	Likely to be more expensive	Downward
Fischer–Tropsch fuels	4,160	1,200	+250%	Likely to be more expensive	Downward
Dimethyl ether	2,740	660	+320%	Insufficient consensus	Downward
Microalgae	2,680	1,000	+170%	Likely to be more expensive	Insufficient consensus
Aggregates	21	18	+20%	Insufficient consensus	Downward
Cement curing	56	71	−20%	Likely to be cheaper	Downward
CO_2-EOR	n.a.	n.a.	n.a.	Likely to be more expensive	Upward

Median cost estimates for products made with CO_2 utilization are derived from the backward-looking scoping review. References for the selling prices are set out in more detail in Supplementary Table 4. The costs and cost trends anticipated in 2050 are derived from a forward-looking expert opinion survey and from author group judgement.

Enhanced weathering. The use of terrestrial enhanced weathering on croplands could increase crop yields[28]. This yield enhancement is unlikely to originate directly from increases in soil carbon, but from nutrient uptake that is facilitated by pH effects[57]. However, under our broad definition, there may still be an as-yet-unquantified CO_2 utilization potential associated with the increase in net primary productivity.

Forestry techniques. In afforestation/reforestation, atmospheric CO_2 is removed via photosynthesis and the carbon is stored in standing forests. If used for sustainable forestry, a portion of that carbon enters production processes and, after minor energetic losses, becomes wood products. Both wood products and standing forests provide economic value, and can be seen as CO_2 utilization (standing forests provide ecosystem services, which are not quantified here). The utilization of CO_2 in wood products will occur in addition to the direct removal of CO_2 by forests under certain highly specific circumstances; sustainable harvesting can maintain carbon stocks in forests while providing a source of renewable biomass[58,59].

We estimate that, of the volumes of CO_2 sequestered via afforestation/reforestation in 2050, between 0.07 and 0.5 Gt of the CO_2 utilized per year may flow into industrial roundwood products, at approximate breakeven costs of between −$40 and $10 per tonne of CO_2 utilized. An optimistic scenario might also consider the volumes of wood products that are sustainably harvested from existing forests and plantations. Yearly inflows of carbon used as wood products are estimated to be around 1.8 Gt CO_2 in 2050. Of these, 0.6 Gt CO_2 may arise from the portion of those flows that are industrial roundwood products sustainably harvested for use in the construction industry (Supplementary Materials); this leads to a top-end estimate of 1.1 Gt CO_2 utilized per year from afforestation/reforestation and sustainable forestry techniques.

Wood products have potential as long-term stores of carbon—particularly when used in long-lived buildings, the lifespans of which can be conservatively estimated at 80–100 years[59]. We estimate that around half of the carbon in the wood-product pool might continue to be stored beyond the usable life of the products (the non-decomposed fraction of the portion of total wood products that are presently committed to landfill (around 60%) is approximately 77%[60]). The remainder of the carbon in the wood-product pool will return to the atmosphere as a fraction (about 0.5 Gt CO_2 yr^{-1}) of the 5 Gt CO_2 yr^{-1} land-use change flux that is depicted in Fig. 1.

Soil carbon sequestration and biochar. CO_2 in land management and biochar pathways can be considered to be utilized if it enhances economically valuable agricultural output. The CO_2 taken up by land ultimately becomes either CO_2 utilized (with increased output) or CO_2 removed (stored in soils), but not both. We estimate that around 0.9 to 1.9 Gt CO_2 yr^{-1} may be used by soil carbon sequestration techniques on croplands and grazing lands by 2050; approximate breakeven costs are estimated at between −$90 and −$20 per tonne of CO_2 utilized, owing to yield increases that are associated with increases in soil organic carbon stock. We tentatively estimate that approximately 0.2 to 1 Gt CO_2 yr^{-1} may be utilized via yield increases after the application of biochar on managed lands, at approximate breakeven costs of between −$70 and −$60 per tonne of CO_2 utilized. These estimates are based on currently reported yield increases (of 0.9% to 2% associated with soil carbon sequestration techniques[61,62] and 10% associated with biochar[63]) from sparse literature, using crop production as a proxy for net primary productivity. Impacts on yield are likely to be highly variable—for example, according to climatic zone[64]. Crop productivity increases are important not only for economic returns for operators but also for land-use requirements. For instance, if the application of biochar led to an increase in tropical biomass yields of 25%, the associated reduction in land requirements would equate to 185 million hectares, and would result in a cumulative net emission benefit from those increased yields of 180 Gt CO_2 to 2100[65].

Table 2 presents breakeven cost ranges and estimated volumes of CO_2 utilized or removed per year in 2050.

Techno-economic barriers to scaling

There are numerous challenges in scaling CO_2 utilization. Here we consider issues related to cost, technology and energy. Although market penetration can be facilitated by cost-competitiveness, there is no certainty that the cheapest CO_2 utilization pathways will scale up. Geographical, financing, political and societal considerations are briefly addressed in the Supplementary Materials; however, further investigation of these issues is warranted, particularly with regards to the UN Sustainable Development Goals.

Cost and performance differentials

The breakeven cost per tonne of CO_2 is one way to assess the economics of utilization. The impact of CO_2 utilization on the price and value-add proposition of the end product is also important, particularly for CO_2 utilization processes in which the final price differential is immaterial but small differences in key properties may be important. Prices for a fuel product made using CO_2 currently exceed market prices considerably (Table 3).

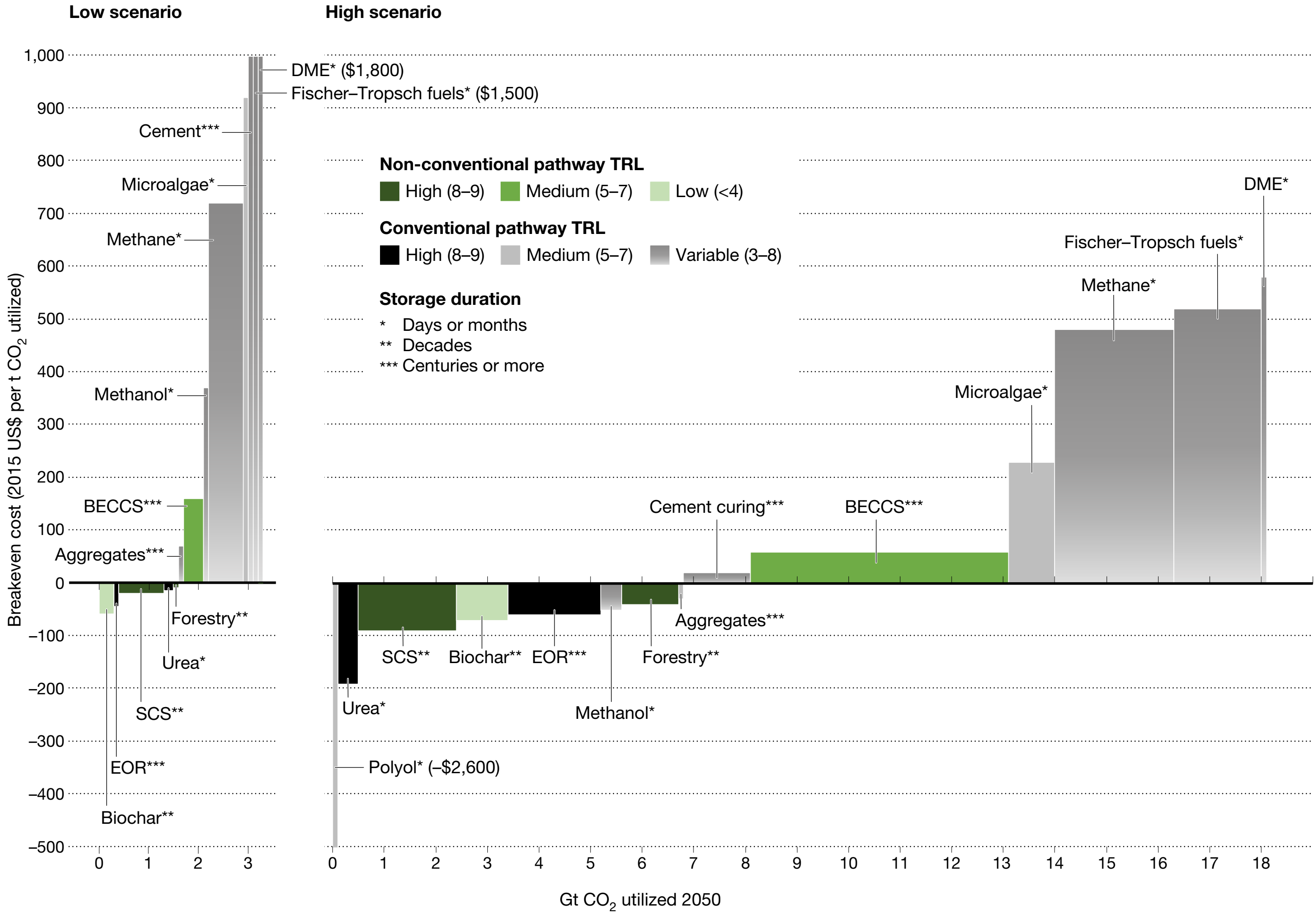

Fig. 3 | Estimated CO_2 utilization potential and breakeven cost of different sub-pathways in low and high scenarios. The breakeven cost is the incentive, measured in 2015 US$ per tonne of CO_2, that is required to make the pathway economic. Negative breakeven costs indicate that the pathway is already profitable, without any incentive to utilize CO_2 (such as a tax on CO_2 emissions in cases in which utilization avoids emissions, or a subsidy for CO_2 removed from the atmosphere in the case in which utilization removes CO_2). Utilization estimates are based on 2050 projections. Many technologies are in the very early stages of development, and cost optimization via research and development could substantially change these estimates. Colour shadings reflect the TRLs of the pathways, which again vary markedly within each pathway. Asterisks denote the storage duration offered by each pathway: days or months (*) decades (**) or centuries or more (***). See Supplementary Materials for further details.

Many of the other pathways—in particular those involving products in construction and plastics—have economics that are driven not only by price but also by the performance characteristics of the end product. There may be trade-offs between product quality and mitigation value, or synergies between the two.

Because they are based on a backward-looking scoping review, our cost estimates for conventional pathways do not capture current unpublished innovations and advances in the industrial arena. Our expert opinion survey, which included sources from both academia and industry, reflected great uncertainty about future costs. Industry participants expressed confidence that costs in pathways that are already economic (such as CO_2 cement curing and polyols) would continue to decrease, relative to incumbent product costs.

Energy requirements

Some CO_2 utilization pathways involve chemical transformations that require the input of substantial amounts of energy (Supplementary Fig. 2). Some require energy to increase CO_2 concentrations from 0.04% towards 100%[66]. Life-cycle emissions and costs depend upon the source of the energy used. Land-based natural processes use solar energy, harnessed by photosynthesis, to transform CO_2 and water into carbohydrates. Although photosynthesis is an inefficient process (the average efficiency is around 0.2% globally[67]) biological pathways are not necessarily more expensive. In industrial processes, hydrogen often serves as feedstock. At present, 'brown' hydrogen is primarily—and most cheaply—generated by reforming methane[68], which has associated CO_2 emissions. In the production of 'blue' hydrogen, these emissions are captured and stored. Production of 'green' hydrogen—by the electrolysis of water— has real potential, and the ultimate choice of technology for the generation of hydrogen will depend on the rates of cost reduction[69], among other factors.

The outlook for CO_2 utilization

Our high-end and low-end scale and cost estimates in Table 2 are drawn as cost curves in low and high scenarios in Fig. 3. These curves are constructed using currently available (and often sparse) data in the peer-reviewed literature, or—where data are not available—using approximations, and should be considered as a speculative first pass at envisioning future scenarios. The curves should not be interpreted as comprehensive assessments of costs, they do not represent *n*th-of-a-kind costs, and they are incompatible with other sequestration or abatement cost curves. The limitations of cost curves—particularly with regards to exogenous costs such as establishment costs—have been previously described[70], and they remain relevant here. An important caveat is that individual potentials cannot be arbitrarily summed: some access the same demand, for instance for transport, which may or may not be filled by a process that utilizes CO_2. For instance, the putative success of CO_2-fuels may reduce the demand for oil, thus also reducing the potential of CO_2-EOR. Furthermore, land availability means that choosing one land-based pathway (for example, BECCS) might preclude the application of another at scale (for example, biochar).

Notwithstanding the many caveats, the potential scale of utilization could be considerable. Much of this potential CO_2 utilization—notably in 'closed' and 'open' pathways—may be economically viable without substantial shifts in prices. The specific assumptions of the low scenario, which do not account for potential overlaps in utilization volumes between pathways, imply an upper bound of over 1.5 Gt CO_2 yr^{-1} at well under \$100 per tonne of CO_2 utilized. For policymakers that are interested in climate change, these figures demonstrate the theoretical potential for correctly designed policies to incentivize the displacement of fossil fuels or the removal of CO_2 from the atmosphere.

Figure 3 also highlights some of the economic and technological challenges that are faced by these pathways. The cycling pathways (other than the production of urea and polyols) must compete with lower-cost incumbents. The four closed pathways, except for CO_2-EOR, are mainly at low technology readiness levels (TRLs). Open pathways, although both theoretically profitable and implementable, often incur additional operating costs—such as implementation, transaction, institutional, and monitoring costs—which can be high[71].

Each of the potentially large-scale, low-cost pathways also face challenges as mitigation strategies. CO_2-EOR utilizes and, with correct policy, stores CO_2 at scale, but may not yield any net climate benefit and may even be detrimental. BECCS has a range of well-articulated risks, including considerable increases in emissions as a result of land-use change[72]. Land management, biochar and forestry offer only shorter-term storage, face saturation, and risk large-scale flows of CO_2 back to the atmosphere[23]. The chemicals pathways may reduce net emissions by displacing fossil fuel use, but will not contribute to net removal unless they are paired with direct air capture in a net zero world. Building materials face a challenging route to market penetration owing to regulatory barriers, which may take decades to surmount. In general, low TRLs will also challenge the ability of pathways to scale rapidly enough and within the desired timeframe for mitigation[5]. The uncertainty in future outcomes is relatively large, and very few industries globally involve over 1 Gt yr^{-1} of material flows.

The net climate impact of the CO_2 utilization pathways will, in many cases, depend upon the emissions intensity from the prevailing processes[73]. For instance, CO_2-EOR might currently contribute to an overall reduction in atmospheric CO_2, compared to business-as-usual[49]. As decarbonization proceeds, however, the climate benefit of CO_2-EOR is reduced. At some point before full decarbonization, EOR without direct air capture will result in a net increase in CO_2 emissions[74]. Conversely, in an economy with high supply-chain emissions, the climate benefit from BECCS is low[72]. In a decarbonized world, those supply-chain emissions will be close to zero and so the climate benefit from BECCS will be amplified.

Each of the utilization pathways described here should be seen as a part of the cascade of mitigation options that are available. For instance, using recycled organic matter to reduce fertilizer use and its associated emissions is a priority, followed by the more efficient use of fertilizer[75], followed by increasing urea yields to reduce total emissions (via more efficient use of NH_3)[30]. Eventually, fertilizers derived from fossil-fuel-free ammonia[76] should be used to supplement fertilizers derived from organic materials. Similarly, a robust finding in the literature on integrated-assessment modelling is that the electricity sector should be decarbonized first, which then facilitates decarbonization in other, more difficult sectors[77]. In terms of the climate impact per kWh of electricity use, available renewable electricity is more efficiently directed towards e-mobility and heat pumps rather than towards hydrogen-based CCU technologies in the chemical industry[73].

Future priorities for CO_2 utilization

Given the slow nature of the innovation process and the urgency of the climate problem, priority should be given to the most promising and least-developed options so that early and effective adoption of a portfolio of techniques can be achieved. For the pathways with apparently negative cost (that is, those that should be profitable in the absence of a theoretical CO_2 subsidy), the challenge—particularly for the open pathways—is to identify and overcome the other barriers to adoption.

An important caveat for policymakers and practitioners is that scaling up CO_2 utilization will not necessarily be beneficial for climate stability; policy should not aim to support utilization per se, but should instead seek to incentivize genuine emission reductions and removals on a life-cycle basis, and thus provide incentives for the deployment of CO_2 utilization that is climate-beneficial.

Conventional utilization pathways

The emissions-reduction potentials of the three cycling pathways would be facilitated by declines in the costs of CO_2 capture. New sorbents could reduce the cost of energy-intensive separation of CO_2 from flue gases and industrial streams[40,78]. In the longer term, cheaper direct air capture (based on clean energy) would support the scale-up of these pathways[79]. The cost of DACCS has recently been assessed to be between \$600 and \$1,000 per tonne of CO_2 for the first-of-a-kind plant, with *n*th-of-a-kind costs potentially of the order of \$200 per tonne of CO_2[79].

Research into materials and catalysts for CO_2 reduction could enable the efficient transformation of CO_2 into a broader range of products at a lower cost[78]. This includes the development of catalysts for the efficient production of syngas via dry reforming of methane with CO_2; efficient photo/electrocatalysts to release hydrogen from water; photo/electrocatalysts that can reduce CO_2; or new high-temperature, reversibly reducible metal oxides[78] to produce syngas using concentrated sunlight. New membrane materials that can separate miscible liquids—for example, methanol and water—will also be important[80]. Catalytic processes can be optimized to increase CO_2 emission reductions or to reduce energy consumption[81]. One important research challenge is to produce materials with the highest material property profiles, in particular temperature stability and wider operating or processing temperature windows. Rigorous, realistic techno-economic analyses of these scientific advances could determine their contribution to valuable cost reductions.

Given the rapid rate at which human societies are urbanizing[82], there is an urgent one-time opportunity to deploy new building materials—including wood, as discussed below—that utilize and store CO_2 and displace emissions-intensive Portland cement. In this area, as in others, progress would be aided by techno-economic analyses and life-cycle analyses with clearer system boundaries, counterfactuals, and accounting for co-products[83], and integrated modelling frameworks that can co-assess changes in background systems[84].

Non-conventional utilization pathways

Figures 1 and 3 suggest that land-based biological processes offer a large opportunity to utilize, remove and store more CO_2. Progress here is partly dependent upon field-based trials to improve understanding of the system-wide impacts of different pathways on plant yields and the impacts on water, food and water systems, and other resources. Such research might prioritize multiple-land-use approaches, such as agroforestry plantations; rice straw as biomass; low-displacement bioenergy strategies such crassulacean acid metabolism plants on marginal land; or nipa palm in mangroves. A better understanding of soil carbon dynamics and improved phenotypic and genotypic plant selection will also help[85].

Biochar is currently at a low TRL and has associated uncertainties. However, if these can be overcome, its position low on the cost curve in both low and high scenarios suggests that this pathway may have considerable potential. A major challenge is to improve variations in yield effects, which are likely to hinder the economic decision made by farmers to apply biochar[86], and to find ways to secure potential revenue streams.

Increased forestation, where land availability and biodiversity constraints allow, and the greater use of wood products in buildings are strategies that appear to be worth pursuing. Although our estimates consider the scale-up of existing industrial roundwood use via afforestation and reforestation, new wood-based products such as cross-laminated timber and acetylated wood[87]—which are aimed at new markets— also have potential. Specification, quality and safety measures for these products are approaching comparability to many concrete structures[88], and current manufacturing scale-up suggests that this may be a market with strong growth prospects.

Cross-cutting efforts

Broad policy and regulatory changes that may support the appropriate scale-up of CO_2 utilization include creating carbon prices of around \$40 to \$80 per tonne of CO_2—increasing over time—to penalize CO_2 emissions[89] and to incentivize verifiable CO_2 emissions reductions and removals from the atmosphere. We do not advocate a direct subsidy for utilization. Instead, incentives for CO_2 removals and reductions (or penalties for emissions) are justified, and these will support CO_2 utilization in cases in which it is beneficial for the climate. For instance, our analysis suggests that closed pathways with scalability—such as BECCS and building materials—would be sensitive to a subsidy for CO_2 removals. Changes to standards, mandates, procurement policies and research and development support, in order to close gaps in knowledge across a portfolio of pathways[90], are also desirable. Financing and managing the emergence of a globally important new set of CO_2 utilization industries will probably require clear direction and industrial support from government. An enabling 'net zero' legislative regime—such as that in place in Sweden and the UK and proposed in New Zealand—can provide clarity about the necessary scale of industries that reduce and remove CO_2, including the pathways examined here.

Collaboration between scholars, public officials and business leaders to ensure accurate comparisons between different alternatives—including the direct comparison of CCU, CDR and CCS pathways—could facilitate the blending of advantageous features of the ten pathways described here, the exploration of pathways not addressed here, and the identification of novel CO_2 utilization pathways to accelerate emissions reductions and removals.

CO_2 utilization is not an end in itself, and these pathways solely or even collectively will not provide a key solution to climate change. Nevertheless, there is a substantial societal value in continued efforts to determine what will and will not work, in what contexts the climate will or will not benefit from CO_2 utilization, and how expensive it will be.

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