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PERSPECTIVE

The technological and economic prospects for CO_2 utilisation and removal

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Capturing and utilising 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 such pathways. Pathways involving chemicals, fuels, and microalgae might reduce carbon dioxide emissions but have limited potential for carbon dioxide removal; pathways involving construction materials can both utilise 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 Gt carbon dioxide utilisation annually, although barriers remain substantial and resource constraints prevent the simultaneous deployment of all pathways.

CO_2 utilisation is receiving increased interest from the scientific community[1], partly due to climate change considerations and partly because using CO_2 as a feedstock can be a cheaper or cleaner production process than using conventional hydrocarbons[2]. CO_2 utilisation is often promoted as a way to reduce net costs – or increase profits – of reducing emissions or removing carbon dioxide from the atmosphere, and therefore to help scale mitigation or removal efforts[3]. CO_2 utilisation 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 CCS[6], the term 'CO_2 utilisation' 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, *e.g.*, amines to capture and concentrate the CO_2 from air, potentially with solar energy. However, excluded is the production of an identical fuel from the same essential inputs, but where the CO_2 is captured by plant-based photosynthetic processes.

Here, we consider CO_2 utilisation 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 utilisation can generate economic value in the form of, *e.g.*, wood products for buildings, increased plant yields from enhanced soil carbon uptake, and even the production of biofuel and bio-derived chemicals. We employ 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 which could potentially assist in identifying routes to climate change mitigation.

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In this perspective, we consider a non-exhaustive selection of ten CO_2 utilisation pathways. We provide a transparent assessment of the potential scale and cost for each pathway, namely: (i) CO_2-based chemical products, including polymers; (ii) CO_2-based fuels; (iii) microalgae fuels and other microalgae products; (iv) concrete building materials; (v) CO_2 enhanced oil recovery (CO_2-EOR); (vi) bio-energy with carbon capture and storage (BECCS); (vii) enhanced weathering (EW) (viii) forestry techniques including afforestation/reforestation (AF/RF), forest management and wood products; (ix) land management *via* soil carbon sequestration (SCS) techniques; and (x) biochar.

These ten CO_2 utilisation pathways (described in Table 1 and in the Supplementary Materials and depicted by the thin arrows in Figure 1) can also be characterised as 'cycling', 'closed' and 'open' utilisation pathways. For instance, many (but not all) conventional industrial utilisation 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 can reduce emissions *via* industrial CO_2 capture that displaces fossil fuel use. In contrast, 'closed' pathways involve utilisation and near-permanent CO_2 storage, such as in the lithosphere (*via* CO_2-EOR or BECCS), deep oceans (*via* terrestrial EW), or in mineralised carbon in the built and natural environments. Finally, 'open' pathways tend to be biologically-based and characterised by large removal potentials and storage in 'leaky' natural systems such as biomass and soil with risks of large-scale flux back to atmosphere.

Our pathways include some novel or emerging pathways, such as a CO_2-based fuel economy, for which current flows are near-zero, as well as established pathways such as CO_2-EOR and afforestation/reforestation. Pathways were selected based upon discussions at a joint meeting of the US National Academy of Sciences and the UK Royal Society[1]; each is relatively well studied to date and has an acknowledged potential to scale. Many other pathways meet our definition but are not reviewed here (Supplementary Materials).

This perspective is structured as follows. First, the ten utilisation 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 is assessed. Third, a selection of key barriers to scaling are identified. Fourth, we assess the outlook for CO_2 utilisation, and conclude with future research and policy priorities.

CO_2 utilisation pathways and the carbon cycle

Carbon dioxide utilised by a pathway (CO_2u) is not necessarily the same as carbon dioxide removed (CO_2r) or carbon dioxide stored (CO_2s); does not necessarily reduce emissions ($CO_2\rho$); and does not necessarily deliver a net climate benefit, once indirect and other effects are accounted for. The various concepts overlap and relate to each other, but are distinct (Figure S1, Supplementary Materials). Some carbon capture and utilisation (CCU) processes achieve carbon dioxide removal (CDR) from the atmosphere. Some CCU processes involve carbon capture and storage (CCS). CCS itself can contribute either to mitigation (*e.g.* reducing net emissions from a gas-fired power plant) or to atmospheric removals (*e.g.* direct air carbon capture and storage, or DACCS) – CCS does not necessarily imply CDR. Further, 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.

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

Box 1: Concepts: CO_2 utilisation, removal, storage, reduced emissions and net climate benefit

Does CO_2 utilisation (CO_2u) leads to a climate benefit? It might reduce emissions ($CO_2\rho$), or remove CO_2 (CO_2r) from 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 utilisation[84]. Assiduously calculating direct impacts in one place, and one time, is of little use if there is a 'waterbed effect' (also referred to as a 'rebound' or 'leakage') and emissions occur somewhere else, or later.

For instance, a barrel of oil derived *via* CO_2-enhanced oil recovery (CO_2-EOR) utilises CO_2 which can remain in the oil formation rather than being re-emitted into the atmosphere. Assuming the CO_2 does not return to atmosphere, the CO_2 utilised is equal to the CO_2 emissions stored, *i.e.* $CO_2u = CO_2s$, 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 atmosphere. Emissions have been reduced, and $CO_2\rho = CO_2u = CO_2s > 0$, even though $CO_2r = 0$.

To see 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 'utilisation' scenario, in which the CO_2 from the power plant is used for CO_2-EOR instead, *i.e.*, CO_2u = 1 t CO_2. Total emissions in this 'utilisation' scenario comprise the 1.5 t CO_2 from the consumption of the CO_2-EOR oil. $CO_2\ \rho = 2.5 - 1.5 = 1.0$ t $CO_2\ \rho$ which is identical to the CO_2u, but net $CO_2r = 0$ because the CO_2 came from fossil power plant, rather than 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 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 injected into the well than extracted.

Life-cycle analyses (LCAs) on some industrial CO_2 utilisation pathways suggests that the potential for net emission reductions ($CO_2\rho$) is much larger than for net removals (CO_2r), which appears very modest[95]. Up to 3 t CO_2 emissions may be avoided for every 1 t CO_2 utilised in polycarbonate polyols[2], even though no CO_2 is removed from atmosphere. Nearly 4 t CO_2 emissions may be avoided for each tonne of dry wood utilised that displaces concrete-based materials[96].

Other LCAs have found neutral or negative impacts of CO_2 utilisation on $CO_2\rho$ [75,97-99]. For instance, CO_2 utilisation pathways requiring energy inputs that are not decarbonised may result in net lifecycle increases in CO_2[97-100].

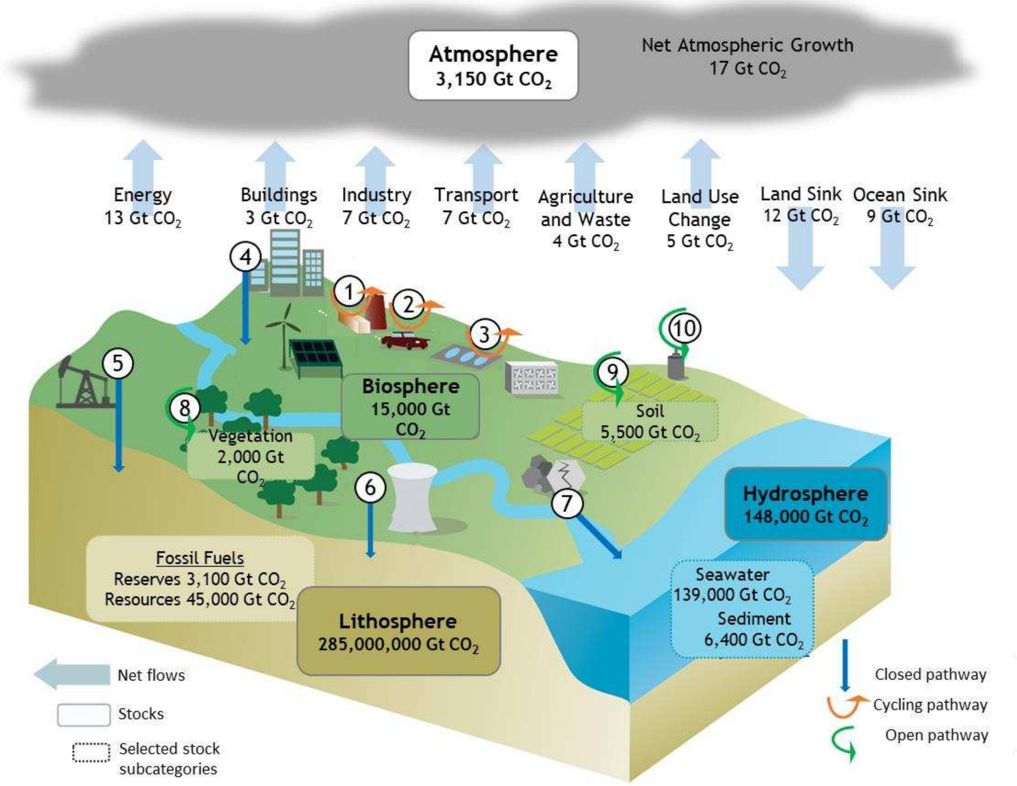

Figure 1 | Stocks and net flows of CO_2 including potential utilisation and removal pathways. Orange, blue and green arrows (numbered 1-10, as described in Table 1) represent *cycling, closed* and *open* pathways for utilisation and removal. Grey block arrows represent annual flows to and from the atmosphere, with estimates averaged over the 2008-2017 period[15,92]. Solid boxes represent stocks in the Earth's spheres, with all estimates based on IPCC estimates[16] except where noted, and converted from C to CO_2. Carbon stocks in the hydrosphere comprise of seawater, sediment, and dissolved organic carbon (not shown, ~2,600 Gt CO_2). The vast majority of carbon stocks in the lithosphere are locked in the Earth's crust[93], with estimated accessible fossil fuel reserves and resources of >45,000 Gt CO_2[25]. Atmospheric stocks are converted from the 2017 estimates of atmospheric CO_2 of 405 ppm[94] using a conversion factor of 2.12. Carbon stocks in the biosphere include those stored in permafrost and wetlands (not shown, ~7,500 Gt CO_2), vegetation, and soils. Soil stocks to 1m depth have been recently estimated at 5,500 Gt CO_2[63]. Illustration by Jillian Ditner and Ella Adlen.

For CO_2 utilisation to contribute usefully to reducing atmospheric CO_2 concentrations, the scale of the pathways must be meaningful in comparison with the net flows of CO_2 in Figure 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}, Figure 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 annum, this would contribute to achieving net zero emissions, as per the '4 per mille' initiative[17], but this is challenging[18]. Five of the ten pathways in Table 1 leverage our ability to perturb these land-based fluxes.

The other five conventional industrial CO_2 utilisation 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] (~2.4 Gt CO_2 yr^{-1}, of which around two-thirds are wood products) that could be met in part through CO_2 utilisation. 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 has been sequestered in human infrastructure as mineralised carbonates in cement from 1930-2013, at current rates of ~1 Gt CO_2 yr^{-1} [20,21].

Table 1 | Ten CO_2 utilisation and removal pathways

Pathway (Fig 2#)	Removal and/or Capture (Figure 2 step A, B and/or C)	Utilisation product [Figure 2 yellow boxes]	Storage[a] (Figure 2 step D, E, or F) and likelihood of release (high/low)	Emission on use (Figure 2 step G) / Release during storage (Figure 2 steps H, I or J)	Figure 2 Cycle examples
(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	Mineralisation 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 [b]	N/A	«KCD»
(6) Bioenergy with carbon capture and storage (BECCS)	Growth of plant biomass	Bioenergy crop biomass	Geological sequestration (millennia) - low[b]	N/A	«BCD»
(7) Enhanced weathering (EW)	Mineralisation of atmospheric CO_2 *via* the application of pulverised 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 (SCS) 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»

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[a] 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 centuries timescale or more[22] This is also relevant only for conventional operations.

[b] Release during geological storage is usually a consequence of engineering implementation error.

The flow of CO_2 through the different utilisation pathways can be represented by a combination of different steps (labels A to L, ure 2 and Table 1). Utilisation pathways often (but not always) involve removal (**«A»** or **«B»**) and storage (**«D», «E»** or **«F»**), but the permanence of CO_2 storage varies dramatically from one utilisation pathway to another, with storage timeframes ranging from days to millennia. Permanence partially depends upon where the carbon ends up (Figure 1): (i) the lithosphere, by geological sequestration into reservoirs such as saline aquifers or depleted oil and gas reservoirs, or by mineralisation into rocks; (ii) the biosphere, in trees, soils and the human built environment; or (iii) 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 more human and natural disturbances[23] like wildfires and pests, as well as changes in climate[24]. However, even 'closed' pathways do not offer completely permanent storage over geological timescales (>100,000 years[25]), giving rise to intergenerational ethical questions[26].

In the short run, products created with concentrated CO_2 by **«L»** (albeit, CO_2 conversion is not a necessary requirement for utilisation) could leverage 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 to achieve net zero emissions, implying that CO_2 will need to be sourced from the atmosphere, potentially *via* direct air capture (DAC) **«A»** or land-use based uptake by photosynthesis or mineralisation **«B»**. For instance, net zero CO_2-based fuels must shift the current flows of carbon, from lithosphere to atmosphere **«KCLG»**, to an atmosphere to atmosphere cycle **«ALG»** (Figure 2).

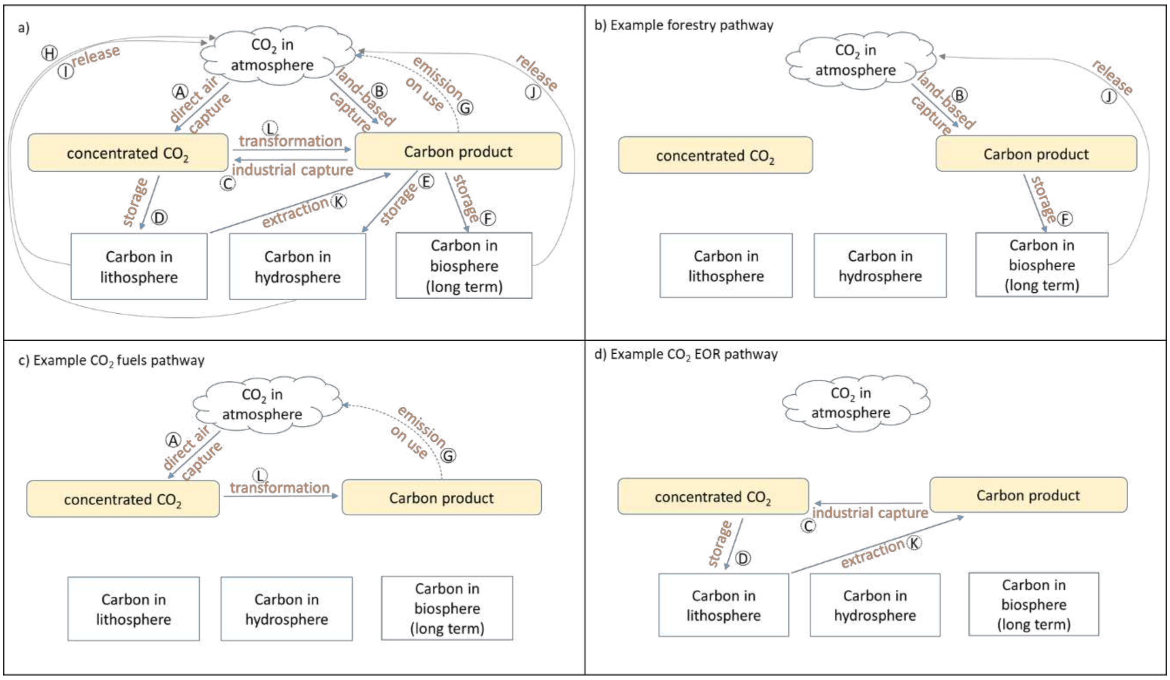

Figure 2| Carbon dioxide utilisation and removal cycle. Utilisation pathways are represented as a combination of steps, A-L. Panel a) represents the full cycle, with panels b), c) and d) showing three potential routes through the cycle. Conventional fossil fuel extraction, combustion and CO_2 emission to the atmosphere traces «KG». Panel b) uses the example of an open pathway such as forestry (pathways 8-10 in Table 1 and Figure 1). Panel c) uses the example of CO_2 fuels (pathway 2 in Table 1 and Figure 1) using DAC to acquire CO_2. Panel d) is an example of CO_2-EOR (pathway 5 in Table 1 and Figure 1). Cycling pathways (with the exception of polymers) end with G; closed pathways end with D, E or F; and open pathways end with J. See Table 1 for further description. All flows are net of process emissions.**E**

Scale and economics of utilisation pathways

We assess the peer-reviewed literature comprising over 11,000 papers on the ten pathways. For the conventional pathways, our scoping review covered over 5,000 papers, a minority (n=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, land-use-based utilisation pathways, we build upon existing CO_2 removal estimates (also derived from a scoping review[28] of over 6,000 papers, of which n=927 provide usable estimates, and an expert judgement process) and identify preliminary published research on the relationship between CO_2 removal and CO_2 utilisation to offer estimates of scale and cost of CO_2 utilisation.

Where possible, breakeven costs in 2015 \$/t CO_2 for each pathway are calculated. The breakeven CO_2 cost represents the incentive per tonne of CO_2 utilised 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 utilisation, although we are not recommending such a subsidy.

Conventional utilisation pathways

Depending on a multitude of technological, policy and economic factors that remain unresolved, utilisation potential in the conventional pathways – chemicals, fuels, microalgae, building materials and CO_2-EOR – might each achieve around 0.5 Gt CO_2 yr^{-1} or more in 2050 respectively. Of that, 0.2 to 3.2 Gt CO_2 yr^{-1} could be simultaneously removed and stored in the lithosphere or the biosphere for centuries or more.

[Chemicals] CO_2 can be transformed efficiently into a range of chemicals, but only a few of these technologies are economically viable and scalable. Some are commercialised[29], such as urea[30] and polycarbonate polyols[31]. Some are technically possible but not widely adopted, such as CO_2-derived methanol in the absence of carbon monoxide[c] [32]. Breakeven costs per tonne of CO_2 calculated from the scoping review for urea (circa -\$100) and polyols (circa -\$2,590) reflect currently profitable markets. The estimated utilisation potential for CO_2 in chemicals is ~0.3 to 0.6 Gt CO_2 yr^{-1} in 2050, with a scoping review interquartile range of breakeven costs of -\$80 to \$320/t CO_2.

The largest scale chemical utilisation pathway is for urea production. Urea yield boosting is a large existing market (current global production 200 Mt yr^{-1} [33]) for CO_2. Urea is produced from ammonia (produced by the energy-intensive Haber-Bosch process $3H_2 + N_2 \rightarrow 2NH_3$) and CO_2 according to $2NH_3 + CO_2 \rightleftharpoons CO(NH_2)_2 + H_2O$, usually with coal or natural gas providing the necessary energy. Within a matter of 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, *e.g.*, using direct air capture, and a renewable energy source. All nitrogen-based fertilisers produce N_2O, a greenhouse gas around 300 times more potent than CO_2 over a 100-year time horizon[34]. Increasing urea inputs may thus have a negative impact on climate[35].

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

[Fuels and microalgae] CO_2-derived fuels are argued to be an attractive option in the decarbonisation process[37,38] as they can be employed within existing transport infrastructure. CO_2-derived fuels might play a role in harder-to-decarbonise sectors, such as aviation[39], given hydrocarbons have energy densities orders of magnitude above that 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

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[c] Methanol is a platform chemical for a multitude of other reaction pathways, including to fuels. The dominant present day manufacturing method for methanol is the hydrogenation of a mixture of CO and around 1-2% CO_2, added to boost methanol yield.

energy and low-cost scalable clean hydrogen production *e.g.* by electrolysis of water or novel alternatives.

Here we consider products such as methanol; methane; dimethyl ether (DME); and Fischer-Tropsch fuels as potential CO_2 energy carriers for transportation. The wide range of estimated potential for the scale of CO_2 utilisation in fuels, from ~1 to 4.2 Gt CO_2 yr^{-1}, reflects uncertainties in potential market penetration. The high end represents a future where synfuels have sizeable market shares, due to cost reductions and policy drivers. The low end, which is itself considerable, represents very modest market penetration in 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, or with direct sequestration.

A CO_2-to-methanol plant operates in Iceland, and various power-to-gas plants operate worldwide. However, these may represent special cases that are difficult to replicate because they are exploiting geographic advantages, such as cheap geothermal energy. Whilst producing more complex hydrocarbons is energetically and therefore economically expensive[11], rapid cost-reductions could potentially occur, particularly with policy support, given that the cost of renewable energy is a large proportion of the total. The US Department of Energy's target for hydrogen production costs, \$2/kg-H_2, is roughly equivalent to \$2 per gasoline-gallon equivalent, and would require carbon free electricity to cost <US\$0.03/kWh[40] (accounting for kinetics and other losses to the enthalpy of electrolysis-based hydrogen production ~40 kWh/kg-H_2). Several wind and solar power auctions around the world have been won in recent years with prices below US\$0.03/kWh[41].

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

For pathways with high capital costs, the benefits of economies of scale and learning could be considerable[42]. This is particularly relevant for algal pathways requiring photobioreactors[43] and fuel synthesis pathways requiring electrolysers[44]. Microalgae are a subject of long-standing research interest given their potential to fix CO_2 efficiently (up to 10%, vs 1 to 4% for other biomass[45]), as well as produce a range of products such as biofuels, high-value carbohydrate and proteins, and plastics[43]. The estimated 2050 potential for microalgae is again wide, given complex production economics, 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/t CO_2.

[Concrete building materials] We estimate that CO_2 utilisation pathways in concrete building materials may remove, utilise and store ~0.1 to 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 breakeven costs of -\$30 to \$70/t CO_2. This estimate mostly comprises the use of CO_2 as a curing agent in cement, and the high end might reflect a scenario (amongst other possibilities) whereby the technology is fully adopted by the precast concrete market and has a 70% penetration into pourable cement markets. We also consider aggregates produced from carbonated industrial wastes such as cement and demolition waste, steel slag, cement kiln dust, and coal pulverised fuel ash,.

Cement requires the use of lime (CaO), which is produced by the emissions-intensive calcination of limestone, so unless calcination is paired with carbon capture and sequestration, it is difficult for building-related pathways to deliver CO_2 emissions reductions on a life-cycle basis. Several commercial initiatives seek 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] in the end product completely, but regulatory barriers curently prevent these approaches from scaling.

[CO_2-EOR] Enhanced oil recovery using CO_2 currently provides ~5% of total US crude oil production[48]. Conventionally, operators aim to maximise both the oil and the CO_2 recovered (rather than CO_2 stored) per tonne of CO_2 injected, with between 1.1 and 3.3 barrels (bbl)) of oil produced per tonne of CO_2 injected under conventional operation and within the constraints of natural reservoir heterogeneity[49]. However, CO_2-EOR can in principle (and depending on operating conditions and project type) be operated such that, on a life cycle basis, more CO_2 is injected than 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], implying that as much as 140 Gt CO_2 could be utilised and stored in this way[5]. We estimate a 2050 utilisation rate of ~0.1 to ~1.8 Gt CO_2 yr^{-1}. If EOR was deployed to maximise CO_2 storage, rather than oil output, then CO_2 reduced could approximately equal CO_2 utilised, depending on the emissions-intensity of the counterfactual and relevant inefficiencies (Box 1).

At oil prices of approximately $100/bbl, EOR is economically viable if CO_2 can be sourced for between $45 and $60/t CO_2[51,52], implying a breakeven cost of CO_2 of -$60 to -$45/t CO_2. These cost estimates are specific to the United States, where the business model is mature, but may not hold for the rest of the world.

Non-conventional utilisation pathways

The five non-conventional utilisation pathways reviewed comprise BECCS, enhanced weathering, forestry techniques, land management practices and biochar. Prior reviews[18,28,53-55] demonstrate that these pathways offer substantial *removal* potential; based on a recent substantive scoping review[28], 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, and 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 of ~$200/t CO_2[28]. Not all of this potential involves *utilisation* of carbon dioxide resulting in economic value, but the approximate scale of CO_2u described below is potentially considerable. The breakeven costs per tonne of CO_2u estimated here are low and 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[56] (particularly in the light of concerns over land use competition with food crops) 100–300 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. Whilst a number of cost estimates exist in the literature, *e.g.* ~$200/t 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 generated. Approximating those revenues using a basket of wholesale electricity prices across countries suited to host BECCS systems[57], we estimate breakeven costs of between ~$60 and ~$160/t CO_2 utilised.

[EW] For terrestrial enhanced weathering (EW) employed on croplands, a yield-enhancing impact is anticipated[28]. This yield enhancement effect is unlikely to originate directly from soil carbon improvements, but to nutrient uptake facilitated by pH effects[58]; however under our broad definition there may still be an as-yet-unquantified CO_2u associated with the increase in net primary productivity (NPP).

[Forestry techniques] In sustainable forestry, atmospheric CO_2 is removed *via* photosynthesis into carbon in standing forests, and 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 utilisation (standing forests provide ecosystem services, not quantified here). CO_2u in wood products will occur additionally to CO_2r directly by forests under certain highly specific circumstances; sustainable harvesting can maintain carbon stocks in forests while providing a source of renewable biomass[59,60].

Our estimate is that of the volumes of CO_2 sequestered *via* afforestation/reforestation in 2050, 0.07 to 0.5 Gt CO_2u yr^{-1} may flow into industrial roundwood products, at approximate breakeven costs of between ~-$40 and ~$10/t CO_2 utilised. An optimistic scenario might also consider the volumes of wood products that are sustainably harvested from existing forests and plantations. Yearly inflows of carbon utilised as wood products is estimated to be ~1.8 Gt CO_2 in 2050. An additional 0.6 Gt CO_2 utilised may arise from the portion of those flows that are industrial roundwood products sustainably harvested for use in the construction industry (Supplementary Materials), leading to a top-end estimate of 1.1 Gt CO_2u yr^{-1} from AF/RF and sustainable forestry techniques.

Wood products have the potential to be long-term stores of carbon, particularly when used in long-lived buildings, wherein lifespans can be conservatively estimated at 80-100 years[60]. We estimate that around half of the carbon in the wood product pool may continue to be stored beyond their usable product life (the non-decomposed fraction (~77%) of the portion of wood presently committed to landfill (~60%)[61]). The remainder will return to atmosphere as a fraction (~0.5 Gt CO_2 yr^{-1}) of the 5 Gt CO_2 yr^{-1} land use change flux portrayed in Figure 1.

[SCS & biochar] CO_2 in land management and biochar pathways is properly considered to be 'utilised' if it enhances economically valuable agricultural output. The CO_2 taken up by land is ultimately either CO_2u (with increased output) or CO_2r (stored in soils), but not both. We estimate that ~0.9 to 1.9 Gt CO_2 yr^{-1} may be utilised by SCS techniques on croplands and grazing lands by 2050, at approximate breakeven costs of between -$90 and -$20/t CO_2 utilised, due to yield increases associated with increases in soil organic carbon stock. We tentatively estimate that ~0.2 to 1 Gt CO_2 yr^{-1} may be utilised *via* yield increases following the application of biochar on managed lands at approximate breakeven costs of between -$70 and -$60/t CO_2 utilised. These estimates are based on currently reported yield increases (of 0.9% to 2% associated with SCS techniques[62,63] and 10% associated with biochar[64]) from sparse literature, using crop production as a proxy for net primary productivity. Yield impacts are likely to be highly variable, *e.g.* according to climatic zone[65]. Crop productivity increases are important not only for economic returns for operators but also for land-use requirements. For instance if tropical biomass yield increases following biochar application reached 25%, the associated reduction of land requirements would equate to 185m ha, and would result in a cumulative net emission benefit from those increased yields of 49 Gt C to 2100[66].

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

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

Pathway	Global gross removal potential in 2050 (Mt CO_2r yr^{-1})	Global gross utilisation potential in 2050 (Mt CO_2u yr^{-1})	Breakeven cost of CO_2 utilisation (2015 \$/tCO_2u)
CONVENTIONAL UTILISATION			
CHEMICALS	~10 to 30	300 to 600	-\$80 to \$320
FUELS	0	1,000 to 4,210	\$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 UTILISATION			
BECCS	500 to 5,000	500 to 5,000	\$60 to \$160
ENHANCED WEATHERING	2,000 to 4,000	N/C	<\$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

The breakeven cost is the cost in 2015 \$/tCO_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 (*e.g.* a subsidy for CO_2 utilisation). 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 (where the magnitude of difference reflects the diversity of technological and economic assumptions available within and across each sub-pathway) or (for land-use based pathways) top-down estimates of revenues that may accrue (where the uncertainty of the accuracy of the estimation is high). Breakeven costs presented with a * are calculated unadjusted for revenues and by-product credits. To get the utilisation potential high and low values for conventional pathways, we averaged the interpolated expert opinions with a co-author estimate. For non-conventional utilisation pathways, estimated utilisation potential ranges are based on estimates of additional realised yield of carbon in vegetation (for soil carbon sequestration and biochar, additional yield approximates to net primary productivity (NPP), and for afforestation/reforestation, it approximates to wood products). These are first rough estimates based on preliminary but sparse published research reporting relationships between C storage and additional C that can be utilised.

Techno-economic barriers to scaling

Numerous challenges exist for scaling CO_2 utilisation. Here we consider cost, technology and energy related issues. Although market penetration can be facilitated by cost competitiveness there is no certainty that the cheapest CO_2 utilisation pathways will scale up. Geographical, financing, political and societal considerations are briefly addressed in the Supplementary Materials, but further investigation of these issues is warranted particularly in light of the UN Sustainable Development Goals (SDGs).

Cost and performance differentials

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

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

Pathway	**Cost of product made with CO_2 utilisation ($/t product)**	**Selling price of product ($/t product)**		**Anticipated cost relative to incumbent in 2050**	**Anticipated direction of cost relative to incumbent in 2050**
	Median, scoping review	**Present day**	**% difference**	**Summary, expert opinion survey & author judgement**	**Summary, expert opinion survey & author judgement**
Polymers	1440	2040	-30%	Likely cheaper	↘
Methanol	510	400	+30%	Insufficient consensus	↘
Methane	1740	360	+380%	Likely more expensive	↘
FT fuels	4160	1200	+250%	Likely more expensive	↘
DME	2740	660	+320%	Insufficient consensus	↘
Microalgae	2680	1000	+170%	Likely more expensive	Insufficient consensus
Aggregates	21	18	+20%	Insufficient consensus	↘
Cement Curing	56	71	-20%	Likely cheaper	↘
CO_2-EOR	N/A	N/A	N/A	Likely more expensive	↗

Median cost estimates for products made with CO_2 utilisation are derived from the backward-looking scoping review. References for the selling prices are set out in more detail in the Supplementary Materials, Table S4. The costs and cost trends anticipated in 2050 are derived from a forward-looking expert opinion survey and coauthor judgement.

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

Our cost estimates for conventional pathways, because they are based on a backward-looking scoping review, 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. Participants from industry were particularly likely to express confidence that costs in pathways that are already economic (for instance in CO_2 cement curing and polyols) would continue to decrease relative to incumbent product costs.

Energy requirements

Some CO_2 utilisation pathways involve chemical transformations with substantial energy inputs (Figure S2). Some require energy to increase CO_2 concentrations from 0.04% towards 100%[67]. Lifecycle 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. While photosynthesis is an inefficient process (average efficiency is around 0.2% globally[68]), biological pathways are not necessarily more expensive. In industrial processes, hydrogen often serves as feedstock. 'Brown' hydrogen is currently primarily and most cheaply generated by reforming methane,[69] with associated CO_2 emissions. These emissions could be captured and stored, producing 'blue' hydrogen. Production of 'green' hydrogen by electrolysis of water also has potential, and the ultimate technology choice for hydrogen generation will depend on the rates of cost reduction,[70] among other factors.

The outlook for CO_2 utilisation

Our high-end and low-end scale and cost estimates in Table 2 are drawn as cost curves in (A) low and (B) high scenarios in Figure 3. These curves are constructed using currently available (and often sparse) data in the peer-reviewed literature, or (where data is not available) 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, do not represent *n*th of a kind costs, and 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[71] and 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 utilises 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 (*e.g.* BECCS) might preclude the application of another at scale (*e.g.* biochar).

Notwithstanding the many caveats, the potential scale of utilisation could be considerable. Much of this potential CO_2 utilisation – notably in 'closed' and 'open' pathways - may be economically viable without dramatic shifts in prices. The specific assumptions of the low scenario, which do not account for potential overlaps in utilisation volumes between pathways, imply an upper bound of over 1.5 Gt CO_2 yr^{-1} at well under \$100/t CO_2u. For policymakers interested in climate change, these figures demonstrate the theoretical potential for correctly designed policies to incentivise the displacement of fossil fuels or the removal of CO_2 from the atmosphere.

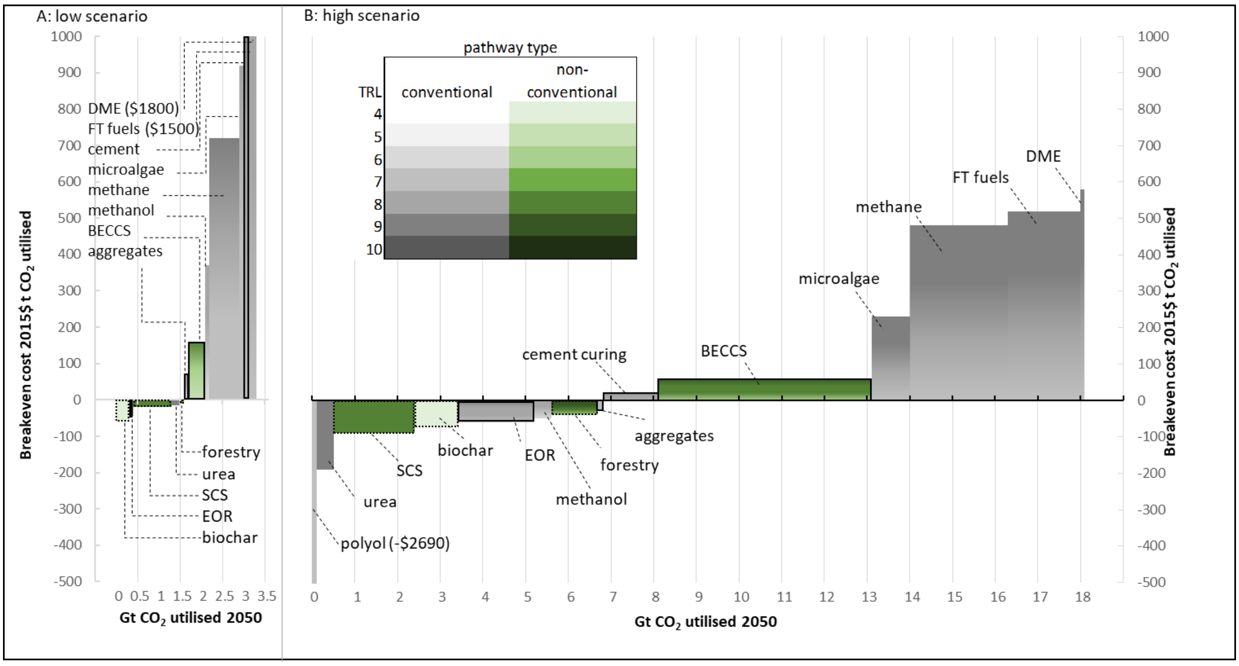

Figure 3 | Estimated CO_2 utilisation potential and breakeven cost of different sub-pathways in a (A) low and (B) high scenario. The breakeven cost is the incentive, measured in 2015\$/t CO_2, required to make the pathway economic. Negative breakeven costs indicate that the pathway is already profitable, without any incentive to utilise CO_2 (such as a tax on CO_2 emissions in the case where utilisation avoids emissions, or a subsidy for CO_2 removed from atmosphere in the case where utilisation removes CO_2). Utilisation estimates are based on 2050 projections. Many technologies are at very early stages of research and cost optimization via research and development could dramatically change these estimates. Colour shadings reflect the level of technology readiness levels (TRL) of the pathways, which again vary dramatically within each pathway. Solid borders indicate that the pathway offers CO_2 storage durations of centuries or more; dotted borders that the pathway offers storage durations of decades; and no borders that the pathway offers storage durations of days or months. See Supplementary Materials for further details.

Figure 3 also highlights some of the economic and technological challenges faced by the pathways. The cycling pathways often (other than urea and polyols) must compete with lower-cost incumbents. The four closed pathways, except for CO_2-EOR, are at low technology readiness levels (TRLs). Open pathways, while both theoretically profitable and implementable, often incur additional operating costs such as implementation, transaction, institutional, and monitoring costs, which can be high[72].

Each of the potentially large scale, low-cost pathways also face challenges as mitigation strategies. CO_2-EOR utilises 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 problems, including major land-use change emissions[73]. Land management, biochar and forestry all suffer risks of permanence and 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 removals, unless paired with DAC in a net zero world. Building materials face a challenging route to market penetration due to regulatory barriers which may take decades to surmount. In general, low TRLs will also challenge pathways' ability 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 utilisation pathways will in many cases depend upon the emissions intensity of prevailing processes[74]. For instance, CO_2-EOR might currently contribute to an overall reduction in atmospheric CO_2, compared to business-as-usual[49]. As decarbonisation proceeds, the climate benefit of CO_2-EOR is reduced. At some point before full decarbonisation, EOR without DAC will result in a net increase in CO_2 emissions[75]. Conversely, in an economy with high supply chain emissions, the climate benefit from BECCS is low[73]. In a decarbonised world, those supply-chain emissions will be close to zero so the climate benefit from BECCS will be amplified.

Each of the utilisation pathways described here should be seen as a part of the cascade of mitigation options available. For instance, using recycled organic matter to reduce fertiliser use and emissions is a priority, followed by more efficient user of fertiliser[76], 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[77] should be used to supplement fertilizers derived from organic materials. Similarly, a robust finding in the integrated assessment modelling literature is that the electricity sector should be decarbonized first, which then facilitates decarbonisation in other more difficult sectors[78]. In terms of climate impact per kWh of electricity use, available renewable electricity is more efficiently directed towards e-mobility and heat pumps rather than hydrogen-based CCU technologies in the chemical industry[74].

Future priorities for CO_2 utilisation

An important caveat for policymakers and practitioners is that scaling up CO_2 utilisation will not necessarily be beneficial for climate stability; policy should not aim to support utilisation *per se*, but instead seek to incentivise genuine emission reductions and removals on a life cycle basis, and thus provide incentives for the deployment of CO_2 utilisation that is climate beneficial. The depth and quality of much of the literature underlying the scoping reviews that support this article is in many senses insufficient in this respect.

Nonetheless given the slow nature of the innovation process, and the urgency of the climate problem, prioritisation 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 (i.e. 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 other barriers to adoption.

Conventional utilisation 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[40,79]. In the longer term, cheaper direct air capture (based on clean energy) would support the scale up of these pathways[80]. The cost of DACCS has recently been assessed as being between $600 and $1000/t CO_2 for the first-of-a-kind plant, with nth-of-a-kind costs potentially on the order of $200/t CO_2[80].

Research on materials and catalysts for CO_2 reduction could enable the efficient and lower-cost transformation of CO_2 into a broader range of products[79]. This includes developing catalysts for efficient production of syn gas *via* dry reforming of methane with CO_2, efficient photo/electro-catalysts to release hydrogen from water, along with photo/electro-catalysts that can reduce CO_2, or new high-temperature, reversibly reducible metal oxides[79] to produce syn gas using concentrated sunlight. New membrane materials that can separate miscible liquids, *e.g.*, methanol and water, have a role to play[81]. Catalytic processes can be optimised to increase CO_2 emission reductions or reduce energy consumption[82]. One important research challenge is to produce materials showing 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 urbanising[83], there is an urgent one-time opportunity to deploy new building materials (including wood, discussed below) that utilise and store CO_2 and displace emissions-intensive Portland cement. In this area, as others, progress would be helped by techno-economic analyses and lifecycle analyses with clearer system boundaries, counterfactuals, and accounting for co-products,[84] and integrated modelling frameworks that can co-assess background system changes[85].

Non-conventional utilisation pathways

Figure 1 and Figure 3 imply that land-based biological processes offer a large opportunity to utilise, 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 impacts on water, food and water systems, and other resources. Such research might fruitfully prioritise multiple-land-use approaches, such as agro-forestry plantations; rice straw as biomass; low-displacement bioenergy strategies like crassulacean acid metabolism (CAM) 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[86].

Biochar is at a low TRL, with associated uncertainties, but 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. The key challenge is to improve variations in yield effects that will likely be a hindrance in the economic decisions on the part of farmers to use biochar applications[87], 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 worth pursuing. Whilst 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[88] aimed at new markets may also have potential. Specification, quality and safety measures for these products are approaching comparability for many concrete structures[89], and current manufacturing scale-up suggests 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 utilisation include creating carbon prices of around US$40-80/t$CO_2$, rising over time, to penalise CO_2 emissions[90] and to incentivise verifiable CO_2 emissions reductions and removals from atmosphere. We do not advocate a direct subsidy for utilisation. Instead, subsidies for CO_2 removals and reductions (or penalties for emissions) are justified and these will support CO_2 utilisation where it is beneficial for the climate. For instance, our analysis suggests 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 to close gaps in knowledge across a portfolio of pathways,[91] are also desirable. Financing and managing the emergence of a globally important new set of CO_2 utilisation industries will likely need clear direction and industrial support from government. An enabling 'net zero' legislative regime – such as that 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 directly comparing 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 utilisation pathways to accelerate emissions reductions and removals.

CO_2 utilisation 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, where the climate will benefit from CO_2 utilisation and where it will not, and how expensive it will be.

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Author contributions

JB conceived of the paper. CH and EA conducted the analysis and drafted the paper, with extensive input from NMD, and critical input on estimates, methodology and drafting from JB, EC, SF, JM, PS and CW.

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