

# The role of CO<sub>2</sub> capture and utilization in mitigating climate change

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**To offset the cost associated with CO<sub>2</sub> capture and storage (CCS), there is growing interest in finding commercially viable end-use opportunities for the captured CO<sub>2</sub>. In this Perspective, we discuss the potential contribution of carbon capture and utilization (CCU). Owing to the scale and rate of CO<sub>2</sub> production compared to that of utilization allowing long-term sequestration, it is highly improbable the chemical conversion of CO<sub>2</sub> will account for more than 1% of the mitigation challenge, and even a scaled-up enhanced oil recovery (EOR)-CCS industry will likely only account for 4–8%. Therefore, whilst CO<sub>2</sub>-EOR may be an important economic incentive for some early CCS projects, CCU may prove to be a costly distraction, financially and politically, from the real task of mitigation.**

The continued growth in anthropogenic CO<sub>2</sub> emissions would appear to be characterized by one word—inexorable. Despite a growing number of climate change mitigation policies, anthropogenic CO<sub>2</sub> emissions in the period 2000–2014 grew at an average rate of 2.6% per year, in contrast with an average rate of 1.72% per year in the period 1970–2000<sup>1,2</sup>. Indeed, in the period 2010–2014, emissions increased from approximately 31.9 to 35.5 Gt<sub>CO<sub>2</sub></sub> per year; an average rate of 2.75% per year<sup>2</sup>. With the exception of a one-year reduction from 2008 to 2009, every year of this century has seen a year-on-year increase in anthropogenic CO<sub>2</sub> emissions.

It has become commonplace to discuss future emission trajectories in terms of scenarios from, for example, the International Energy Agency (IEA) or the IPCC. Both the IEA and IPCC project that a world commensurate with no more than 2 °C of warming above pre-industrial levels is one in which total anthropogenic CO<sub>2</sub> emissions are reduced to something less than 20 Gt<sub>CO<sub>2</sub></sub> per year by 2050, with further reductions to near-zero or even net-negative emissions by the end of the century. This is typically referred to as the two-degree scenario or 2DS. At the other end of the spectrum, allowing anthropogenic emissions to increase to 60 Gt<sub>CO<sub>2</sub></sub> per year by 2050 is commensurate with warming of approximately 6 °C above pre-industrial levels—this is the six degree scenario, 6DS<sup>1,3</sup>.

The conclusion one can draw from the foregoing data is that if anthropogenic emissions of CO<sub>2</sub> continue along any of the recent growth trends, we are poised to very significantly overshoot the 6DS. To even meet the 6DS, we would need to reduce the annual rate of growth of emissions to 1.4% and to meet the 2DS, the rate of growth needs to be –1.5% if global emissions peak in the 2020s. If emissions peak later, the required rate of reduction similarly increases. For the remainder of this analysis, we hypothesize a world, inspired by recent success in Paris, that reduces emissions to a level commensurate with the 6DS by 2020 and aims thereafter to transition to a world commensurate with the 2DS, focusing on the period to 2050. This allows us to introduce the quantity mitigation challenge (MC), the amount of avoided CO<sub>2</sub> emissions (against a reference case) by a given date,  $t_p$ , in order to reduce emissions to a level commensurate with meeting the 2DS,  $E_{2DS}$ .  $E_{2DS}$  is a function of the year in which emissions peak,  $t_p$ , the emission rate in that year,  $E_p$ , and lastly the rate at which CO<sub>2</sub> would be emitted in  $t_i$  according to a low

mitigation scenario (LMS) reference scenario,  $E_{LMS}$ . Therefore, MC can be expressed as equation (1):

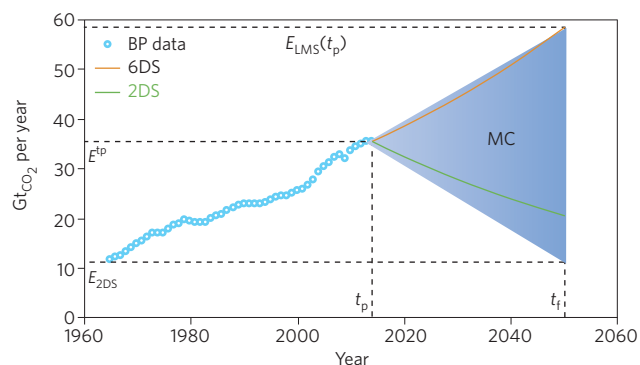
$$MC = \frac{(t_i - t_p)(E_{LMS}(t_p) - E_{2DS})}{2}$$

In addition to being a function of  $t_p$ ,  $E_{LMS}$  is also a function of  $t_i$ , and the average rate of growth of anthropogenic CO<sub>2</sub> associated with the LMS scenario in the period  $(t_i - t_p)$ . Therefore,  $E_{LMS}(t_p) = E_p(1+r)^{(t_i - t_p)}$ . Thus, in order to meet the IEA's 2DS with the 6DS as a baseline, it is necessary to avoid the cumulative emission of approximately 800 Gt<sub>CO<sub>2</sub></sub> in the period to 2050 (Fig. 1).

Globally, despite an increasing emphasis on renewable energy, annual investment in fossil energy has more than doubled in real terms in the period 2000–2013, totalling more than US\$950 billion at the end of this period<sup>4</sup>. It is therefore not unreasonable to suggest that fossil fuels will continue to be important to, if not dominate, the world's energy landscape for some time to come, with some estimates indicating that fossil fuels will still account for over 65% of the total energy mix in 2100<sup>5</sup>, despite increasing penetration of renewable electricity generation<sup>6</sup>. For this energy mix to be coherent with the long-term ambition of substantially mitigating anthropogenic CO<sub>2</sub> emissions, the widespread deployment of CCS technology<sup>7–9</sup> will most likely be a vital part of the least-cost energy system of the future, working in conjunction with renewable energy to deliver energy which is low carbon, available, and affordable.

From one perspective, CCS is a readily deployable technology solution, relying on well-understood components<sup>7–9</sup>. Two leading options for decarbonizing both the power and industrial sectors are the oxy-combustion of fuel or post-combustion scrubbing of the exhaust gas arising from a conventional combustion process. Both of these technologies are highly mature. Alkanolamine gas scrubbing was first patented in the 1930s and has since been widely used for natural gas sweetening<sup>10</sup>. Oxy-combustion, which relies on the cryogenic separation of air, was developed by Linde in 1902 and was operating at 30,000 t<sub>oxygen</sub> per day at the Shell Pearl gas to liquids project in Qatar in 2006. This is sufficient oxygen to supply a 2 GW oxy-combustion power plant. Similarly, CO<sub>2</sub> transport and injection has been practiced at scale for EOR since the 1950s. As of 2014, there are over 3,000 miles of high-pressure pipeline which transport

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**Figure 1 | Illustration of the calculation of the mitigation challenge.**

Here, historical data is sourced from BP data<sup>2</sup>, the low-mitigation scenario chosen here is the IEA's 6DS, and the objective is to meet the IEA's 2DS for 2050<sup>3</sup>. In this example, the MC equates to approximately 800 Gt<sub>CO<sub>2</sub></sub> in the period to 2050.

over 60 million tonnes of CO<sub>2</sub> per year for EOR in 113 projects in the US alone, with approximately 120 projects worldwide<sup>11,12</sup>. Similarly, the distribution and capacity of CO<sub>2</sub> storage locations are also reasonably well-characterized, with first order estimates of the theoretical global CO<sub>2</sub> storage capacity of approximately 11,000 Gt<sub>CO<sub>2</sub></sub> (ref. 13). Of this, approximately 1,000 Gt<sub>CO<sub>2</sub></sub> capacity is provided by oil and gas reservoirs with approximately 9,000–10,000 Gt<sub>CO<sub>2</sub></sub> capacity provided by deep saline aquifers<sup>14–16</sup>. Furthermore, there is also significant potential capacity in unmineable coal seams, with the additional economic benefit that this is may be accompanied by the recovery of coal-bed methane.

In order to stabilize atmospheric CO<sub>2</sub> concentrations at a level of 450 ppm, that is, a concentration consistent with a world with a high likelihood of not exceeding 2 °C of warming, it is expected that it will be necessary to store 120–160 Gt<sub>CO<sub>2</sub></sub> via CCS in the period to 2050<sup>17</sup>, with similar trends expected to the end of the century. Therefore we have more than enough CO<sub>2</sub> storage capacity to meet this target and, even without identification of further storage sinks, sufficient to meet even ambitious CO<sub>2</sub> sequestration needs for well beyond the next century, giving ample time for the likely lengthy transition from fossil fuels. Finally, the world's first commercial CCS-equipped power station has started operation at the Boundary Dam facility in Saskatchewan, Canada, with a second project also in operation in Alberta, where Shell are capturing the CO<sub>2</sub> arising from H<sub>2</sub> production<sup>18</sup>. CCS is inarguably a well-understood, mature technology that is deployable at commercial scale today.

However, despite CCS relying on well-known and well-understood technology components, the transition to its widespread deployment continues to be an uphill battle. The financing of this transition is a particular challenge, one which requires the combination of strong policy and price signals to ensure that low-carbon and energy efficiency investments offer a sufficiently attractive risk-adjusted return.

It is in this context that CCU is often mentioned. As a relatively benign material, it is possible to convert CO<sub>2</sub> into a wide variety of end products, in addition to its potential for enhanced hydrocarbon recovery. In this context, therefore, why should we not actively and favourably consider the reuse of captured CO<sub>2</sub>?

Certainly it represents a beguiling opportunity—convert a waste product into high-value end products and kick-start a highly skilled regional manufacturing industry. Moreover, global demand for the potential products, such as methanol, appears healthy<sup>19</sup>.

Therefore, it is easy to see why the prospect of CO<sub>2</sub> utilization is an attractive one for a wide variety of academic, industrial, and political stakeholders. However, serious questions arise when the narrative around CO<sub>2</sub> utilization becomes one of utilization in parallel with storage or utilization instead of storage. As will be

discussed subsequently in this paper, from the perspective of mitigating anthropogenic climate change, CO<sub>2</sub> utilization is highly unlikely to ever be a realistic alternative to long-term, secure, geological sequestration.

The remainder of this paper is laid out as follows; we first discuss the scale at which various CCU options could be deployed, we then go on to discuss the rate at which they could be deployed before finally discussing how much of the CO<sub>2</sub> used in the various options corresponds to permanent storage. In all cases, this is contextualized with reference to the aforementioned mitigation challenge.

### It's a matter of scale

To put this in some perspective, current total global anthropogenic emissions are about 35.5 Gt<sub>CO<sub>2</sub></sub> per year. Typical CO<sub>2</sub> injection and storage conditions are approximately 10 MPa and 40 °C, corresponding to a CO<sub>2</sub> density of approximately 600 kg m<sup>-3</sup>. This corresponds to approximately 1.64 × 10<sup>8</sup> m<sup>3</sup> per day, or more than 1,033 million barrels (MMbbl) of CO<sub>2</sub> per day. This is in contrast to current global oil production rates of approximately 87–91 MMbbl per day<sup>20,21</sup>. This means that global CO<sub>2</sub> production today is approximately a factor of 10 greater than global oil production today, and, at current rates of growth, may be as much as a factor of 20 greater in 2050<sup>22</sup>.

Given that CCS is expected to account for the mitigation of approximately 14–20% of total anthropogenic CO<sub>2</sub> emissions, in 2050 the CCS industry will need to be larger by a factor of 2–4 in volume terms than the current global oil industry. In other words, we have 35 years to deploy an industry that is substantially larger than one which has been developed over approximately the last century, resulting in the sequestration of 8–10 Gt<sub>CO<sub>2</sub></sub> per annum by 2050<sup>22</sup> with a cumulative CO<sub>2</sub> storage target of approximately 120–160 Gt<sub>CO<sub>2</sub></sub> in the period to 2050<sup>17</sup> and between 1,200–3,300 Gt<sub>CO<sub>2</sub></sub> over the course of the twenty-first century<sup>13</sup>. This is an exceptionally challenging task, similar in scale to wartime mobilization, but it is a task we should not be daunted by. Neither should we be distracted by focussing too much on the long-term solution without giving sufficient attention to the short-to-medium-term necessity of fossil-fuel decarbonization in a manner that allows them to operate in sympathy with intermittent generation from renewable sources<sup>23</sup>.

It is important to note that when CO<sub>2</sub> utilization has traditionally been discussed, this has been in the context of CO<sub>2</sub>-EOR in the United States. In this paper we include CO<sub>2</sub>-EOR within a definition that considers any use of CO<sub>2</sub>, physical or chemical, that prevents immediate release of CO<sub>2</sub> to the atmosphere as part of CCU. EOR is already a very mature technology with a history reaching back several decades, having well-defined techno-economic parameters, and is often considered to be an important part of the CCU landscape. In the early years of its development, CO<sub>2</sub>-EOR faced the challenge of relatively low oil prices and relatively high CO<sub>2</sub> prices. Reservoir management was therefore optimized to maximize profit, not CO<sub>2</sub> sequestration. At the time of writing, CO<sub>2</sub>-EOR provides approximately 5% of the total US crude oil production<sup>24</sup>, and whilst it has the potential to be appreciably expanded<sup>25</sup>, it is important to note the relationship between CO<sub>2</sub> price and oil price. At oil prices of approximately US\$100 per bbl, CO<sub>2</sub> needs to be available at less than US\$45 per tonne (ref. 12) for CO<sub>2</sub>-EOR to be economically viable. This is the case in the US, where the business model is very mature and the CO<sub>2</sub>-EOR capacity exists onshore, but this may not hold for the rest of the world. Thus, current oil prices in the range of US\$40–60 per bbl and CO<sub>2</sub> costs of US\$60–80 per tonne (refs 26,27) make CO<sub>2</sub>-EOR less viable as a means of balancing the costs of large scale CCS operations, and separate economic or policy incentives are likely to be required.

Nevertheless, there is little question that CO<sub>2</sub>-EOR offers a large, near-term option to store large quantities of CO<sub>2</sub> at lower net cost,

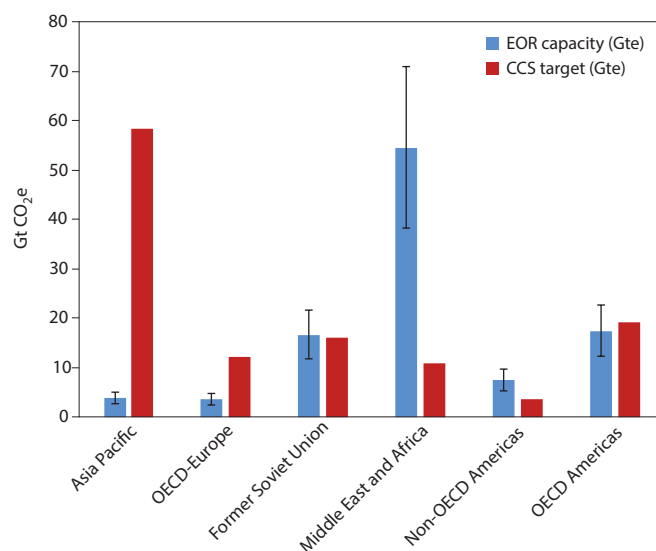
with more than 90% of the world's oil reservoirs seemingly suitable for CO<sub>2</sub>-EOR<sup>12</sup>, if treated early enough, before the reservoir pressure drops below the minimum miscibility pressure. Thus, there exists the theoretical potential to produce 470 billion bbl of additional oil, corresponding to a cumulative theoretical CO<sub>2</sub> injection capacity in the range of 70–140 Gt (refs 12,28).

However, this may be a highly optimistic estimate of the total deployable CO<sub>2</sub>-EOR capacity. As illustrated in Fig. 2, the majority of this capacity exists in the Middle East and North Africa and in the US at 50% and 13% respectively, whereas the estimated CO<sub>2</sub>-EOR in South Asia is essentially zero and the Asia Pacific region accounts for only about 3%.

In other words, there appears to be an unfortunate disconnect between regions of substantial CO<sub>2</sub>-EOR potential and those regions with the largest anticipated population growth, dependence on fossil fuels, and hence requirement to sequester CO<sub>2</sub> over the course of the next century. In fact, the only regions where it appears certain that there is sufficient CO<sub>2</sub>-EOR capacity to meet the CO<sub>2</sub> storage requirements to 2050 are the Middle East and Africa—although the requirements are close in North America and the former Soviet Union. Given the size and rate of growth of the CO<sub>2</sub>-EOR industry in the US, it is likely that the US will be a leader in the deployment of CO<sub>2</sub>-EOR. If we accept the availability of a CCS-derived stream of CO<sub>2</sub> as a prerequisite for CO<sub>2</sub>-EOR, it would make sense to estimate the scale of likely CO<sub>2</sub>-EOR activities as matching regional CCS targets. Thus, a more realistic estimate is likely to be on the order of 40 Gt<sub>CO<sub>2</sub></sub> cumulatively injected for CO<sub>2</sub>-EOR. Thereafter, if we consider the average CO<sub>2</sub> footprint of a barrel of oil consumed, 0.43 t<sub>CO<sub>2</sub></sub> per bbl (ref. 29), this results in revising the above estimate down to approximately 35 Gt<sub>CO<sub>2</sub></sub>, or something in the range of 4.5% of the total CO<sub>2</sub> mitigation challenge.

It is, however, important to further note that, given the appropriate incentives and regulatory environment, it is possible to operate a CO<sub>2</sub>-EOR operation so as to maximize the storage of CO<sub>2</sub> per bbl<sub>oil</sub> recovered<sup>30</sup>. This can have the effect of reducing the amount of oil recovered per t<sub>CO<sub>2</sub></sub> injected from approximately 3.33 bbl<sub>oil</sub> per t<sub>CO<sub>2</sub></sub> to 1.11 bbl<sub>oil</sub> per t<sub>CO<sub>2</sub></sub>. At the lower end, once the CO<sub>2</sub> emissions associated with the consumption of that oil are accounted for, this can result in the storage of up to 0.52 t<sub>CO<sub>2</sub></sub> stored per t<sub>CO<sub>2</sub></sub> injected, increasing the contribution of CO<sub>2</sub>-EOR to something in the range of 8% of the total CO<sub>2</sub> mitigation challenge. A final point for consideration here is that oil derived from CO<sub>2</sub>-EOR could well displace oil that would otherwise be derived from unconventional sources which are known to have a CO<sub>2</sub> intensity of 108–173% of conventional oil<sup>31</sup>. This displacement effect is estimated to be on the order of 80%, owing to market elasticities<sup>30</sup>. Therefore, assuming a constant demand, the deployment of CO<sub>2</sub>-EOR could lead to the avoidance of CO<sub>2</sub> that would otherwise be emitted by the production of unconventional hydrocarbon resources, in addition to the reduced environmental and social risks of oil production via CO<sub>2</sub>-EOR in mature fields relative to unconventional hydrocarbon production.

Obviously, CO<sub>2</sub>-EOR is not the only route to CO<sub>2</sub> utilization—there are also CO<sub>2</sub> conversion options. There has been active interest in the chemical conversion of CO<sub>2</sub> into platform chemicals, plastics, and other materials and fuels since the 1850s<sup>32–35</sup> with the synthesis of salicylic acid, sodium carbonate via the Solvay process, and urea developed in 1869, 1882, and 1922 respectively<sup>36–38</sup>. It is therefore important to recognize that the focus on CO<sub>2</sub> utilization is not a recent phenomenon. Overall, current annual global CO<sub>2</sub> utilization is on the order of 200 Mt (ref. 35) and it has been suggested that this is likely capped at approximately 650–700 Mt in 2050 (ref. 33). Whilst this estimate was made in 2006, it is in line with current growth rates of the global chemical industry<sup>39</sup>. Further, of these conversion products, approximately 75% is accounted for by compounds which would not correspond to long-term sequestration of CO<sub>2</sub> as the incorporated CO<sub>2</sub> is released once the products are used.



**Figure 2 | Global CO<sub>2</sub>-EOR capacity compared with regional CO<sub>2</sub> sequestration targets.** Data from refs 13,17,22. The error bars included on this data indicate an average calculated variance of 30%. The reported variance is in the range 25–35%.

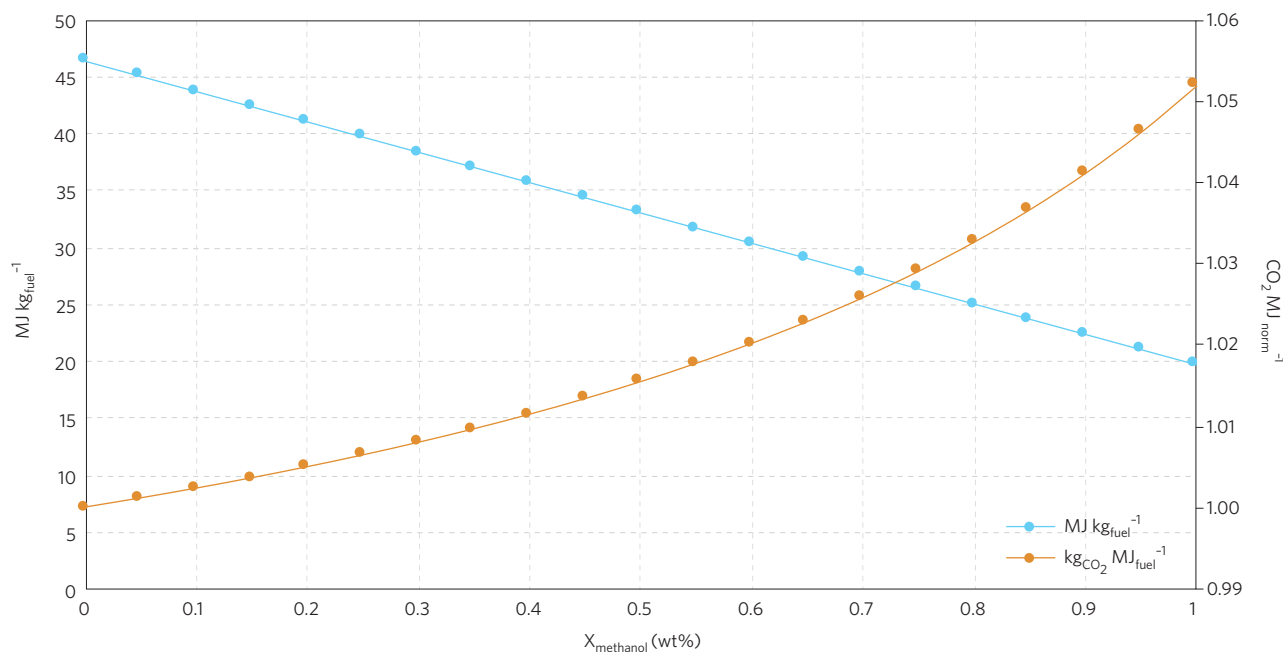
Therefore, given a 3% per year growth rate of CO<sub>2</sub> utilization and a sequestration rate of 25%, this corresponds to a cumulative total of 15.42 Gt<sub>CO<sub>2</sub></sub> utilized by 2050 and 3.86 Gt<sub>CO<sub>2</sub></sub> sequestered—about 0.49% of the 800 Gt<sub>CO<sub>2</sub></sub> mitigation challenge.

Mineral carbonation is another process that is under consideration<sup>40</sup>. Whilst this process does correspond to the effectively permanent sequestration of CO<sub>2</sub> in a solid form, this is a reaction that happens naturally—albeit at an exceptionally slow rate. Accelerating the rate of these reactions requires mining (or other collection processes), transporting, crushing, grinding and handling of vast quantities of material suitable for carbonation. This requires very large quantities of decarbonized electricity—which then begs the question: is there not a more profitable purpose to which we could put this decarbonized electricity—electrification of heating, or charging an electric vehicle, for example, and allow the carbonation of this material to take place naturally, noting that this may take an extremely long time?

Furthermore, whilst it is possible to convert CO<sub>2</sub> into liquid fuels such as methanol for use in ground transport<sup>41</sup>, this would result in the near-immediate release of the CO<sub>2</sub> to the atmosphere, and, although potentially reducing emissions relative to a baseline, cannot be considered to contribute directly and significantly to the CO<sub>2</sub> mitigation challenge; capturing CO<sub>2</sub> directly from a vehicle is unlikely to be feasible in the medium term.

Leaving the toxicity of methanol to one side, at 43–44 GJ per t<sub>methanol</sub> (ref. 42), the energy required to convert CO<sub>2</sub> into methanol is substantial relative to the energy density of methanol (19.7 GJ per t<sub>methanol</sub>). This corresponds to an energy return on energy invested (EROEI)<sup>43</sup> of approximately 0.45. More than 80% of this energy is associated with the generation of renewable electrolytic H<sub>2</sub>, with approximately 10% required for the capture of CO<sub>2</sub> from a fossil-fired power station. If we were to consider the direct capture of CO<sub>2</sub> from the air as the CO<sub>2</sub> source, then one might expect the specific energy footprint of CO<sub>2</sub>-derived methanol to increase to the order of 60 GJ per t<sub>methanol</sub> or an EROEI of approximately 0.33. This represents a substantial quantity of renewable energy, which compares extremely poorly with the methanol's energy density (lower heating value basis), and could arguably be put to better use elsewhere.

By way of comparison, conventional coal and oil–gas production processes have an EROEI of approximately 46 and 20 respectively<sup>44,45</sup>,



**Figure 3 | The effect of blending methanol with gasoline.** It can be observed that, as methanol is added to gasoline, the energy density of the fuel decreases, whilst the  $\text{CO}_2$  footprint per unit of energy service delivered increases. Therefore, the substitution of methanol for gasoline will potentially increase the  $\text{CO}_2$  emissions associated with delivering that energy service.

with wind, solar photovoltaic, geothermal, and biodiesel having an EROEI of approximately 18–20, 10, 9 and 2–5 respectively<sup>44,46</sup>.

Given that a fuel or energy needs an EROEI of at least 3 to be considered useful to society<sup>43,44</sup>, the energy required to produce methanol would have to be reduced by a factor of 6–10, depending on the source of the  $\text{CO}_2$ , in order to become viable: this is a substantial challenge.

The relatively low energy density of methanol also presents substantial challenges to its use as a fuel. Gasoline has an energy density of 46.4 MJ per kg and upon combustion produces 3.09  $\text{kg}_{\text{CO}_2}$  per kg, whereas methanol has an energy density of 19.7 MJ per kg and upon combustion produces 1.38  $\text{kg}_{\text{CO}_2}$  per kg.

As can be observed from Fig. 3, owing to the reduced energy density of methanol, its use as a fuel will result in the emission of approximately 5% more  $\text{CO}_2$  than would have otherwise been the case.

Moreover, the processes for converting  $\text{CO}_2$  to methanol do not have a perfect yield. There will be some fraction of  $\text{CO}_2$  purged from the process—typical numbers are 0.08  $t_{\text{CO}_2}$  purged and 0.67  $t_{\text{methanol}}$  produced per  $t_{\text{CO}_2}$  feedstock<sup>42</sup>. Consider, then, that 1  $\text{bbl}_{\text{oil}}$  will yield 19 gallons of gasoline, and supply 2,469 MJ per  $\text{bbl}_{\text{oil}}$ , therefore emitting 164.46  $\text{kg}_{\text{CO}_2}$  per  $\text{bbl}_{\text{oil}}$ . To deliver the same amount of energy requires 125.36  $\text{kg}_{\text{methanol}}$  per barrel of oil equivalent. When this methanol is combusted, and accounting for the  $\text{CO}_2$  that was emitted in the initial production of the methanol, this corresponds to approximately 188  $\text{kg}_{\text{CO}_2}$  per barrel of oil equivalent or approximately 14% more  $\text{CO}_2$  than would have been produced had conventionally-sourced crude oil been used. This demonstrates the difficulty in using methanol production as a carbon sequestration process.

In order to compare  $\text{CO}_2$ -EOR and methanol production on the basis of energy service, we first recall that, depending on the version of EOR practiced<sup>30</sup>, between 1.1–3.3  $\text{bbl}_{\text{oil}}$  per  $t_{\text{CO}_2}$  are produced and that each  $\text{bbl}$  will produce 12 gallons of diesel and 19 gallons of gasoline, which delivers 4,284 MJ per  $\text{bbl}_{\text{oil}}$ . In the default  $\text{CO}_2$ -EOR case, 3.3  $\text{bbl}_{\text{oil}}$  per  $t_{\text{CO}_2}$  are produced and where the EOR operation is optimized for storing  $\text{CO}_2$ , this is reduced to 1.1  $\text{bbl}_{\text{oil}}$  per  $t_{\text{CO}_2}$ .

This leads to the net emission of 0.43 and  $-52 t_{\text{CO}_2}$  per  $t_{\text{CO}_2}$  injected, respectively and delivering 4,760–14,279 MJ per  $t_{\text{CO}_2}$  injected or between 0.03 and  $-0.11 \text{ kg}_{\text{CO}_2}$  per MJ (Table 1).

Displacing this service with  $\text{CO}_2$ -derived methanol would require the production of 242–725  $\text{kg}_{\text{methanol}}$ , leading to the emission of approximately 0.08  $\text{kg}_{\text{CO}_2}$  per MJ. Thus, from the perspective of both EROEI and a carbon balance, the utilization of  $\text{CO}_2$  for EOR would appear to be preferable to the conversion of  $\text{CO}_2$  to methanol. In all cases,  $\text{CO}_2$ -derived methanol would appear to increase the quantity of  $\text{CO}_2$  emitted whilst delivering the same service and, under some circumstances,  $\text{CO}_2$ -EOR can result in the net sequestration of  $\text{CO}_2$ , whereas it does not appear that this is feasible with methanol.

### It's a matter of time

A further point which must be taken into account is the period for which each utilization option actually stores the  $\text{CO}_2$ . It is well-accepted that in order to mitigate the effects arising from anthropogenic  $\text{CO}_2$  emissions, it is necessary to permanently sequester the  $\text{CO}_2$  that is excess to the earth's carbon cycle. Chemicals such as urea or methanol store  $\text{CO}_2$  only until they are used; once urea is applied as fertilizer or methanol is used as a fuel, the  $\text{CO}_2$  is immediately released to the atmosphere—corresponding to a storage duration of perhaps six months. The conversion of  $\text{CO}_2$  into polymers might store the  $\text{CO}_2$  for several decades, perhaps as much as 50 years. This is in contrast to geological sequestration, which can be considered permanent.

### It's a matter of rate

In order to reduce global  $\text{CO}_2$  emissions to 80% of 1990 levels by 2050, it will be necessary to reduce anthropogenic emissions by approximately 42  $\text{Gt}_{\text{CO}_2}$  per year by 2050 compared to a 1990 baseline in line with the IEA and IPCC scenarios. To achieve this, it is anticipated that, amongst other things, it will be necessary to sequester a cumulative 120–160  $\text{Gt}_{\text{CO}_2}$  in the period to 2050<sup>3,15,22</sup>, or 16–20% of the cumulative mitigation challenge. This corresponds to a rate of  $\text{CO}_2$  sequestration of approximately 2.5  $\text{Gt}_{\text{CO}_2}$  per year by 2030, increasing to 8–10  $\text{Gt}_{\text{CO}_2}$  per year by 2050<sup>3,15,22</sup>, with further increases in the rate of sequestration in the period to 2100<sup>1</sup>.

As discussed previously,  $\text{CO}_2$ -EOR is a potential sink for a substantial amount of  $\text{CO}_2$ . One of the major barriers—if not the

**Table 1 | Comparison of the CO<sub>2</sub> footprint associated with CO<sub>2</sub>-EOR and CO<sub>2</sub>-derived methanol.**

Oil recovered (bbl <sub>oil</sub> per t <sub>CO<sub>2</sub></sub> )	Energy delivered (MJ per t <sub>CO<sub>2</sub></sub> injected)	Net CO <sub>2</sub> emitted (kg <sub>CO<sub>2</sub></sub> emitted per MJ)	Methanol required (kg)	Net CO <sub>2</sub> emitted (kg <sub>CO<sub>2</sub></sub> emitted per MJ)
3.33	14,279	0.03	725	0.08
1.67	7,139	-0.04	362	0.08
1.11	4,760	-0.11	242	0.08

These calculations account for the energy service delivered by both the diesel and gasoline derived from the oil, and require the production of sufficient methanol to displace both fuels on an energy service basis. From left to right, the first column indicates the number of barrels of oil recovered per tonne of CO<sub>2</sub> injected, the second column indicates the energy service delivered by the gasoline derived from that oil and the third column indicates the CO<sub>2</sub> that is emitted as a result. The fourth column specifies the quantity of methanol required to provide the same service, and the fifth column specifies the quantity of CO<sub>2</sub> that is emitted as a result. It can be observed that converting CO<sub>2</sub> into methanol results in more CO<sub>2</sub> being emitted than for the CO<sub>2</sub>-EOR case.

**Table 2 | Present and short-term uses of CO<sub>2</sub> based on production data and forecasts from ref. 35.**

Compound	2013 production (Mt per year)	CO <sub>2</sub> used in 2013 (Mt per year)	2016 production forecast (Mt per year)	2016 forecast CO <sub>2</sub> needed (Mt per year)	Rate of growth of production (% per year)	Rate of growth of CO <sub>2</sub> utilization (% per year)
Urea	155	114	180	132	5	5
Methanol	50	8	60	10	7	8
Carbonates	0.2	0.005	2	0.5	300	3,300
Polycarbonates	4	0.01	5	1	8	3,300
Carbamates	5.3	0	6	1	4	-
Polyurethanes	8	0	10	0.5	8	-
Acrylates	2.5	0	3	1.5	7	-
Formic acid	0.6	0	1	0.9	22	-
Inorganic carbonates	200	50	250	70	8	13
Technological		28		80	0	62
Algae for biodiesel	0.005	0.01	1	2	6,633	6,633
<b>Total</b>	<b>426</b>	<b>200</b>	<b>518</b>	<b>299</b>	<b>7.2</b>	<b>16.5</b>

The final two columns of this table contain figures calculated by the authors using data presented in ref. 35.

major barrier—to higher levels of CO<sub>2</sub>-EOR on a global basis is an insufficient supply of affordable CO<sub>2</sub>. In 2004, there was a supply shortfall of approximately 40 Mt<sub>CO<sub>2</sub></sub> per year for CO<sub>2</sub>-EOR in the Permian Basin. Subsequently, between 2007 and 2010, an additional supply of approximately 5 Mt<sub>CO<sub>2</sub></sub> per year was sourced in response to this demand<sup>28</sup>. This is very possibly the world's first example of a demand pull on anthropogenic CO<sub>2</sub> capture. Recent years have seen a steadily increasing share of this CO<sub>2</sub> supply being provided by anthropogenic sources; as of 2010 this was 12 Mt per year<sup>12</sup>. This represents a very significant rate of increase in the size of this industry, and we would cautiously suggest that a global rate of increase in CO<sub>2</sub>-EOR activity of 11% per year is feasible, given appropriate initial conditions such as secure supplies of CO<sub>2</sub>. From a baseline of approximately 0.06 Gt<sub>CO<sub>2</sub></sub> per year used for CO<sub>2</sub>-EOR, this could grow to perhaps 26–27 Gt<sub>CO<sub>2</sub></sub> per year in 2050. This could correspond to a cumulative total of approximately 40–60 Gt<sub>CO<sub>2</sub></sub> injected, and 35–70 Gt<sub>CO<sub>2</sub></sub> stored. As previously, this represents about 4–8% of the ~800 Gt<sub>CO<sub>2</sub></sub> mitigation challenge by 2050.

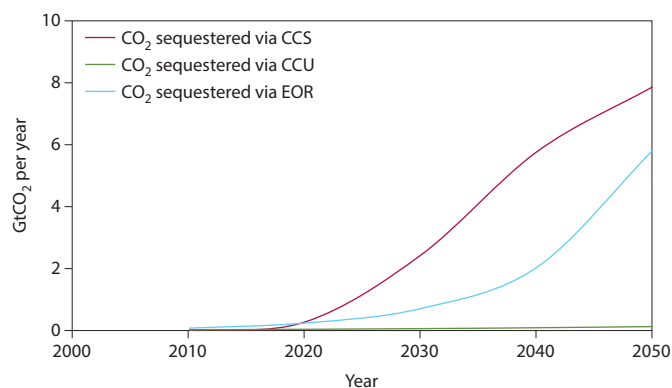
Concerning other options for CO<sub>2</sub> conversion, data from some recent estimates of current and near-term market sizes is presented in Table 2. It should be noted that the two largest sinks for CO<sub>2</sub>—urea and methanol—do not correspond to storing CO<sub>2</sub> for any significant period of time. Similarly, the technological category appears to be a catch-all for CO<sub>2</sub> utilization in food and drink manufacture, fire suppression, as an inerting agent and dry ice, and other miscellaneous activities. Again, these options do not correspond to long-term sequestration of CO<sub>2</sub>.

It is worth considering for a moment the rates of growth implicit in the figures presented in Table 2. Given that the current rate of growth of the global chemical industry is approximately 3% per year<sup>39</sup>, it is difficult to accept that this could, in any way, be indicative of a long-term trend. Furthermore, there appear to be significant assumptions in these data<sup>35</sup> surrounding the rate of displacement of CO<sub>2</sub>-derived products in the market. Other, more conservative estimates of CO<sub>2</sub> utilization for the manufacture of chemicals place an upper limit of 650–700 Mt<sub>CO<sub>2</sub></sub> per year on total global utilization<sup>33</sup>. This implies a growth rate of 3% year in the period 2010–2050, which is in line with the current rate of growth of the global chemical industry<sup>39</sup>. This would correspond to a cumulative total of 15.42 Gt<sub>CO<sub>2</sub></sub> utilized in the period 2010–2050. As discussed previously, only about 25% of these products correspond to sequestering the CO<sub>2</sub> for any significant duration: therefore this total is reduced to 3.86 Gt<sub>CO<sub>2</sub></sub>—or slightly less than 0.5% of the CO<sub>2</sub> mitigation challenge of 800 Gt<sub>CO<sub>2</sub></sub> by 2050.

### Putting it in perspective

When we take these data and then compare them for the period to 2050, it becomes clear how negligible the contribution of CCU will be to the global CO<sub>2</sub> mitigation challenge (Fig. 4).

This emphasizes the danger of reinforcing the narrative that CO<sub>2</sub> utilization is key to making CCS profitable in a simplistic commercial sense. If this narrative continues, it introduces the very real risk that emission mitigation targets will not be met and that CCS through geological storage will not be deployed in



**Figure 4 | CCS versus CCU—a perspective for the period 2010 to 2050.**

CO<sub>2</sub>-EOR has the potential to materially contribute to the sequestration of CO<sub>2</sub> whereas the contribution of CCU is negligible.

any meaningful way. From a commercial and policy perspective, CCU should be encouraged when and only when CO<sub>2</sub> is useful as a cheap feedstock, or when it can robustly and reliably be shown that the CO<sub>2</sub>-derived product can reasonably displace the incumbent product, that is, deliver the same service at the same price, and also not result in an increase in the emission of CO<sub>2</sub> associated with delivering that service. The driver should be feedstock substitution and the production of materials at a lower cost and with lower fossil carbon content. The primary driver should not be locking up CO<sub>2</sub>, as this can never happen at the required magnitude without geological storage.

Underpinning research into CO<sub>2</sub> conversion should continue in order to expand options and reduce costs. CO<sub>2</sub>-EOR, whilst no panacea, can be deployed at a sufficient scale to facilitate the deployment of CO<sub>2</sub> transport infrastructure and potentially stacked CO<sub>2</sub> storage options. There is clearly a role for this technology to play in some early CCS demonstrations, as exemplified by the Sask Power Boundary Dam and the Air Products steam methane reformer projects in Canada and the United States, respectively. The key to climate change mitigation is scale, and it is generally accepted that the CCS cost reduction will be primarily achieved via deployment at scale<sup>47,48</sup>. Whilst CO<sub>2</sub>-EOR projects can be deployed at a sufficient scale to facilitate learning, leading to material cost-reduction, the same is not true for the majority of CCU technologies. Thus, from the perspective of mitigating climate change, CCU can, at most, be seen as supplementing CCS to a small extent. Any proposals for its large-scale deployment should be accompanied by a careful and thorough analysis of associated primary and associated opportunity costs.

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## References

- IPCC *Climate Change 2014: Mitigation of Climate Change* (eds Edenhofer, O. et al.) (Cambridge Univ. Press, 2014).
- BP Statistical Review of World Energy June 2015* (BP, 2015).
- Energy Technology Perspectives 2014—Harnessing Electricity's Potential* (IEA, 2014).
- World Energy Investment Outlook 2014 Factsheet* (IEA, 2014).
- Jaccard, M. *Sustainable Fossil Fuels: The Unusual Suspect in the Quest for Clean and Enduring Energy* (Cambridge Univ. Press, 2006).
- Brown, J. A. G., Eickhoff, C. & Hanstock, D. J. *Capacity and Balancing Options for the Design of Power Plant in the UK* (Institution of Chemical Engineers, 2014); <http://go.nature.com/2lTDsAF>
- Mac Dowell, N. et al. An overview of CO<sub>2</sub> capture technologies. *Energy Environ. Sci.* **3**, 1645–1669 (2010).
- Boot-Handford, M. E. et al. Carbon capture and storage update. *Energy Environ. Sci.* **7**, 130–189 (2014).
- IPCC *IPCC Special Report on Carbon Dioxide Capture and Storage* (eds Metz, B. et al.) (Cambridge Univ. Press, 2005).
- Rochelle, G. T. Amine scrubbing for CO<sub>2</sub> capture. *Science* **325**, 1652–1654 (2009).
- Wallace, M. & Kuuskraa, V. *Near-Term Projections of CO<sub>2</sub> Utilization for Enhanced Oil Recovery* (NETL, 2014).
- Godec, M. L. *Global Technology Roadmap for CCS in Industry: Sectoral Assessment CO<sub>2</sub> Enhanced Oil Recovery* (United Nations Industrial Development Organisation, 2011).
- Dooley, J. J. et al. *Carbon Dioxide Capture and Geologic Storage* (Global Energy Technology Strategy Program, 2006).
- Blunt, M. *Carbon Dioxide Storage*. Briefing Paper No. 4 (Grantham Institute for Climate Change, 2010).
- CO<sub>2</sub> Capture and Storage: A Key Carbon Abatement Option* (IEA, 2008).
- Gale, J. Geological storage of CO<sub>2</sub>: what's known, where are the gaps, and what more needs to be done? *Greenhouse Gas Control Technol.* **1**, 201–206 (2003).
- Technology Roadmap: Carbon Capture and Storage* (IEA, 2013).
- The Global Status of CCS: 2015* (Global CCS Institute, 2015).
- Driven by China, Global Methanol Demand to Rise Nearly 80 Percent by 2023; North America Marks Return as “Production Powerhouse”. *IHS* (29 August 2014).
- The World Factbook* (CIA, accessed 18 August 2014); <http://go.nature.com/2mbQZ7T>
- Key World Energy Statistics* (IEA, 2012).
- Energy Technology Perspectives 2012—How to Secure a Clean Energy Future* (IEA, 2012).
- Heuberger, C. et al. Quantifying the value of CCS for the future electricity system. *Energy Environ. Sci.* **9**, 2497–2510 (2016).
- Dai, Z. et al. CO<sub>2</sub> accounting and risk analysis for CO<sub>2</sub> sequestration at enhanced oil recovery sites. *Environ. Sci. Technol.* **50**, 7546–7554 (2016).
- Dai, Z. et al. An integrated framework for optimizing CO<sub>2</sub> sequestration and enhanced oil recovery. *Environ. Sci. Technol. Lett.* **1**, 49–54 (2014).
- Charles, D. Stimulus gives DOE billions for carbon-capture projects. *Science* **323**, 1158 (2009).
- Vora, S. D. *DOE/NETL Advanced Carbon Dioxide Capture R&D Program: Technology Update* (National Energy Technology Laboratory, 2013).
- Optimisation of CO<sub>2</sub> Storage in CO<sub>2</sub> Enhanced Oil Recovery Projects* (Advanced Resources International, 2010).
- GHG Equivalencies Calculator—Calculations and References* (EPA, 2016).
- Lipponen, J. *Storing CO<sub>2</sub> Through Enhanced Oil Recovery: Combining EOR with CO<sub>2</sub> Storage (EOR+) For Profit* (IEA, 2015).
- Mui, S. et al. *GHG Emission Factors for High Carbon Intensity Crude Oils* (Natural Resources Defense Council, 2010).
- Inoue, S., Koinuma, H. & Tsuruta, T. Copolymerization of carbon dioxide and epoxide. *J. Polymer Sci. B Polymer Lett.* **7**, 287–292 (1969).
- Song, C. Global challenges and strategies for control, conversion and utilization of CO<sub>2</sub> for sustainable development involving energy, catalysis, adsorption and chemical processing. *Catal. Today* **115**, 2–32 (2006).
- Song, C. In *CO<sub>2</sub> Conversion and Utilization* (eds Song, C. et al.) 2–30 (ACS, 2002).
- Aresta, M., Dibenedetto, A. & Angeini, A. The changing paradigm in CO<sub>2</sub> utilization. *J. CO<sub>2</sub> Utilization* **3–4**, 65–73 (2013).
- Kolbe, H. & Lautemann, E. Über die Constitution und Basicität der Salicylsäure. *Ann. Chem.* **113**, 125–127 (1869).
- Solvay, E. Absorption of ammonia in soda ash production. US patent 263,981 A (1882).
- Bosch, C. & Meiser, W. Process of manufacturing urea. US patent 1,429,483 A (1922).
- Department, B. World chemical outlook 2017. *Chem. Eng. News* **91**, 11–19 (2013).
- Kirchofer, A., Brandt, A., Krevor, S., Prigiobbe, V. & Wilcox, J. Impact of alkalinity sources on the life-cycle efficiency of mineral carbonation technologies. *Energy Environ. Sci.* **5**, 8631–8641 (2012).
- Olah, G. A., Goeppert, A. & Surya Prakash, G. K. *Beyond Oil and Gas: The Methanol Economy*. (Wiley, 2009).
- Van-Dal, E. S. & Bouallou, C. Design and simulation of a methanol production plant from CO<sub>2</sub> hydrogenation. *J. Cleaner Prod.* **57**, 38–45 (2013).
- Hall, C., Balogh, S. & Murphy, D. What is the minimum EROI that a sustainable society must have? *Energies* **2**, 25–47 (2009).
- Hall, C. A. S., Lambert, J. G. & Balogh, S. B. EROI of different fuels and the implications for society. *Energy Policy* **64**, 141–152 (2014).
- Dale, M., Krumdieck, S. & Bodger, P. Global energy modeling: a biophysical approach (GEMBA) part 1: an overview of biophysical economics. *Ecol. Econ.* **73**, 152–157 (2012).

46. Kubiszewski, I., Cleveland, C. & Endres, P. Meta-analysis of net energy return for wind power systems. *Renew. Energy* **36**, 218–225 (2010).
47. Rubin, E. S. *et al.* Use of experience curves to estimate the future cost of power plants with CO<sub>2</sub> capture. *Int. J. Greenhouse Gas Control* **1**, 188–197 (2007).
48. van den Broek, M. *et al.* Effects of technological learning on future cost and performance of power plants with CO<sub>2</sub> capture. *Prog. Energy Combustion Sci.* **35**, 457–480 (2009).

### Author contributions

All authors contributed to the planning of the paper. N.M.D. led the work, benefiting from discussions with all authors. All authors contributed to writing the paper,

providing comments to the framework, and input in terms of numbers and references backing the analysis.

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### Competing financial interests

The authors declare no competing financial interests.