

The role of CO₂ capture and utilisation in mitigating climate change

Authors: Niall Mac Dowell^{a,b*}, Paul S. Fennell^c, Nilay Shah^{b,c} and Geoffrey C. Maitland^{b,c}

Affiliation:

a: Centre for Environmental Policy, Imperial College London, South Kensington Campus, London SW7 1NA

b: Centre for Process Systems Engineering, Imperial College London, South Kensington Campus, London SW7 2AZ

c: Department of Chemical Engineering, Imperial College London, South Kensington Campus, London SW7 2AZ

* Corresponding author: niall@imperial.ac.uk

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All authors contributed to the planning of the paper. NMD led the work, benefiting from discussions with all authors. All authors contributed to writing the Commentary, providing comments to the framework and input in terms of numbers and references backing the analysis.

Abstract

The challenges associated with climate change mitigation are vast. In this commentary, we put in perspective the potential contribution of CO₂ utilisation, distinct to CO₂ sequestration, to climate change mitigation. With a view to offsetting the cost associated with CO₂ capture and sequestration (CCS), there has been a growing interest in finding commercially viable end use opportunities for the captured CO₂. Owing to the scale and rate at which CO₂ is produced and at which it can be utilised in a form corresponding to its long-term sequestration, it is highly improbable the chemical conversion of CO₂ will account for more than 1% of the mitigation challenge and even a scaled up CO₂-EOR-CCS industry will likely only account for 4-8%. Therefore, whilst CO₂-EOR may be an important economic incentive for some early CCS projects, CCU may prove to be a financially and politically costly distraction from the real task of mitigating dangerous climate change.

Introduction

The continued growth in anthropogenic CO₂ emissions would appear to be characterised by one word – inexorable. Despite a growing number of climate change mitigation policies, anthropogenic CO₂ emissions in the period 2000 to 2014 grew at an average rate of 2.6%/yr, in contrast with an average rate of 1.72%/yr in the period 1970 – 2000 [1, 2]. Indeed, in the period 2010 to 2014, emissions increased from approximately 31.9 to 35.5 GtCO₂/yr; an average rate of 2.75%/yr [2]. 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 CO₂ emissions.

It has become commonplace to discuss future emission trajectories in terms of scenarios from, for example, the International Energy Agency (IEA) or the Intergovernmental Panel on Climate Change (IPCC). Both the IEA and IPCC project that a world commensurate no more than 2°C of warming above pre-industrial levels is one in which total anthropogenic CO₂ emissions are reduced to something less than 20 GtCO₂/yr 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”. On the other end of the spectrum, allowing anthropogenic emissions to increase to 60 GtCO₂/yr by 2050 is commensurate with warming of approximately 6°C above pre-industrial levels – this is the “six degree scenario” or “6DS” [1, 3].

The conclusion one can draw from the foregoing data is that if anthropogenic emissions of CO₂ continue on any of the recent growth trends, we are poised to very significantly overshoot the

six degree scenario (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 2020's. If emissions peak later, the required rate of reduction similarly increases. For the remainder of this analysis, we hypothesise a world, inspired by recent success in Paris, that reduces emissions to a level commensurate with a 6DS world 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 , *i.e.*, the amount of avoided CO₂ emissions (against a reference case) by a given date, t_f , in order to reduce emissions to a level commensurate with meeting the 2DS, E^{2DS} , which is a function of the year in which emissions peak, t_p , the emission rate in that year, E^{tp} , and lastly the rate at which CO₂ would be emitted in t_f according to a low mitigation scenario (LMS) reference scenario, E^{LMS} .

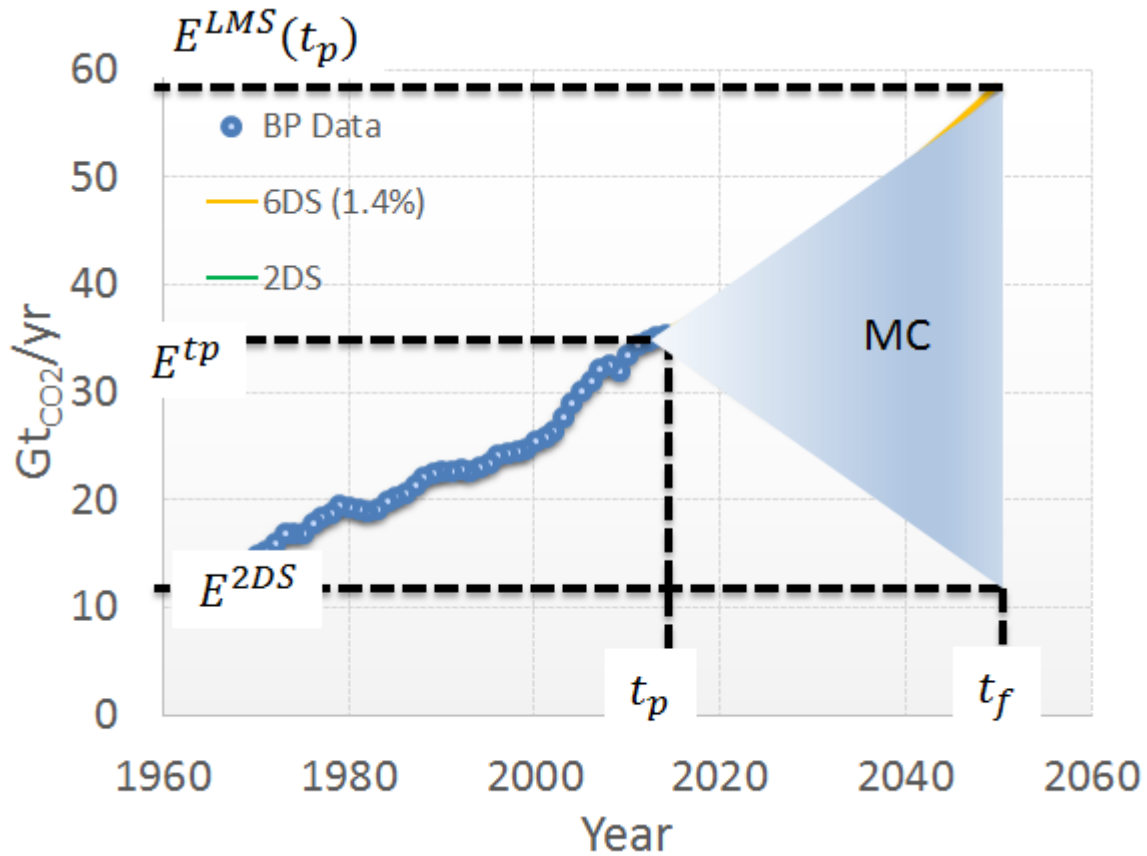


Figure 1: Illustration of the calculation of the mitigation challenge. Here, historical data is sourced from BPs data [2], the BAU scenario chosen here is the IEA's 6DS and the objective is to meet the IEA's 2DS for 2050 [3]. In this example, the MC equates to approximately 800 GtCO₂ in the period to 2050.

Therefore, MC can be expressed as $MC = \frac{(t_f - t_p)(E^{LMS}(t_p) - E^{2DS})}{2}$. In addition to being a function of t_f , E^{LMS} is also a function of t_p , and the average rate of growth of anthropogenic CO_2 associated with the LMS scenario in the period $(t_f - t_p)$. Therefore, $E^{LMS}(t_p) = E^{tp}(1 + r)^{(t_f - t_p)}$. 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 CO_2 in the period to 2050.

Globally, despite an increasing emphasis on renewable energy, annual investment in fossil energy has more than doubled in real terms in the period 2000 to 2013, totalling more than \$950 billion at the end of this period [4]. 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 [5], despite increasing penetration of renewable electricity generation [6]. For this energy mix to be coherent with the long-term ambition of substantially mitigating anthropogenic CO_2 emissions, the widespread deployment of CO_2 capture and storage (CCS) technology [7-9] 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 [7-9]. Two leading options for decarbonising 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 [10]. Oxy-combustion, which relies on the cryogenic separation of air, was developed by Linde in 1902 and was operating at the 30,000 metric tonnes of oxygen per day (MTPD) scale at the Shell Pearl GTL project in Qatar in 2006. This is sufficient oxygen to supply a 2 GW oxy-combustion power plant. Similarly, CO_2 transport and injection has been practiced at scale for enhanced oil recovery (EOR) since the 1950's. As of 2014, there are over 3000 miles of high-pressure pipeline which transport over 60,000,000 tonnes of CO_2 per year for Enhanced Oil Recovery (EOR) in 113 projects in the United States alone, with approximately 120 projects worldwide [11, 12]. Similarly, the distribution and capacity of CO_2 storage locations are also reasonably well characterised with first order estimates of theoretical global CO_2 storage capacity of approximately 11,000 Gt CO_2 [13]. Of this, approximately 1,000 Gt CO_2 capacity is provided by oil and gas reservoirs with

approximately 9,000 – 10,000 Gt_{CO2} capacity provided by deep saline aquifers [14-16]. Further, there is also significant potential capacity in unminable 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 CO₂ concentrations at a level of 450 ppm, i.e., 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_{CO2} via CCS in the period to 2050 [17], with similar trends expected to the end of the century. Therefore we have more than enough CO₂ storage capacity to meet this target and, even without identification of further storage sinks, sufficient to meet even ambitious CO₂ 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 CO₂ arising from H₂ production [18]. CCS is inarguably a well understood, mature technology that is deployable at commercial scale today.

However, despite CCS relying on well-known and 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 CO₂ utilisation (CCU) is often mentioned. As a relatively benign material, it is possible to convert CO₂ 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 CO₂?

Certainly it represents a beguiling opportunity – convert a waste product into high value end products, kick-starting a high-skills regional manufacturing industry. Moreover, global demand for the potential products, such as methanol, appears healthy [19].

Therefore, it is easy to see why the prospect of CO₂ utilisation is an attractive one for a wide variety of academic, industrial and political stakeholders. However, serious questions arise when the narrative around CO₂ utilisation becomes one of “utilisation in parallel to storage” or “utilisation instead of storage”. As will be discussed subsequently in this paper, from the

perspective of mitigating anthropogenic climate change, CO₂ utilisation is highly unlikely to ever be a realistic alternative to long term, secure, geologic 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 CO₂ used in the various options correspond to permanent storage. In all cases, this is contextualised 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 GtCO₂/yr. Typical CO₂ injection and storage conditions are approximately 10 MPa and 40°C, corresponding to a CO₂ density of approximately 600 kg/m³. This corresponds to approximately 1.64×10^8 m³/day, or more than 1,033 million barrels (Mbbl) of CO₂ per day. This is in contrast to current global oil production rates of approximately 87–91Mbbl per day [20, 21]. This means that global CO₂ 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 [22].

Given that CCS is expected to account for the mitigation of approximately 14 - 20% of total anthropogenic CO₂ 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 CO₂ per annum by 2050 [22] with a cumulative CO₂ storage target of approximately 120 - 160 Gt CO₂ in the period to 2050 [17] and between 1,200 - 3,300 Gt CO₂ over the course of the 21st century [13]. This is an exceptionally challenging task, similar in scale to wartime mobilisation, but one from which we should not be daunted. Neither should we be distracted by focusing too much on the long term solution without giving sufficient attention to the short-to-medium term necessity of fossil fuel decarbonisation in a manner that allows them to operate in sympathy with intermittent generation from renewable sources [23].

It is important to note that when CO₂ utilisation has traditionally been discussed, this has been in the context of CO₂-Enhanced Oil Recovery (CO₂-EOR) in the United States. In this paper we include CO₂-EOR within a definition that considers any use of CO₂, physical or chemical,

that prevents immediate release of CO₂ 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, CO₂-EOR faced the challenge of relatively low oil prices and relatively high CO₂ prices. Reservoir management was therefore optimised to maximise profit, not CO₂ sequestration. At the time of writing, CO₂-EOR provides approximately 5% percent of the total U.S. crude oil production [24], and whilst it has the potential to be appreciably expanded [25], it is important to note the relationship between CO₂ price and oil price. At oil prices of approximately \$100/bbl, CO₂ needs to be available at less than \$45/tonne [12] for CCS-EOR to be economically viable. This is the case in the United States, where the business model is very mature and the CO₂-EOR capacity exists onshore, and may not hold for the rest of the world. Thus, current oil prices in the range of \$40 - 60/bbl and CO₂ costs of \$60 - 80/tonne [26, 27], makes CO₂-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 CO₂-EOR offers a large, near-term option to store large quantities of CO₂ at lower net cost, with more than 90% of the world's oil reservoirs seemingly suitable for CO₂-EOR [12], 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* CO₂ injection capacity in the range of 70 -140 Gt [12, 28].

However, this may be a highly optimistic estimate of the total *deployable* CO₂-EOR capacity. As illustrated in Figure 2, the majority of this capacity exists in the Middle East and North Africa and in the USA at 50% and 13% respectively, whereas the estimated CO₂-EOR in South Asia is essentially zero and the Asia Pacific region accounting for only about 3%.

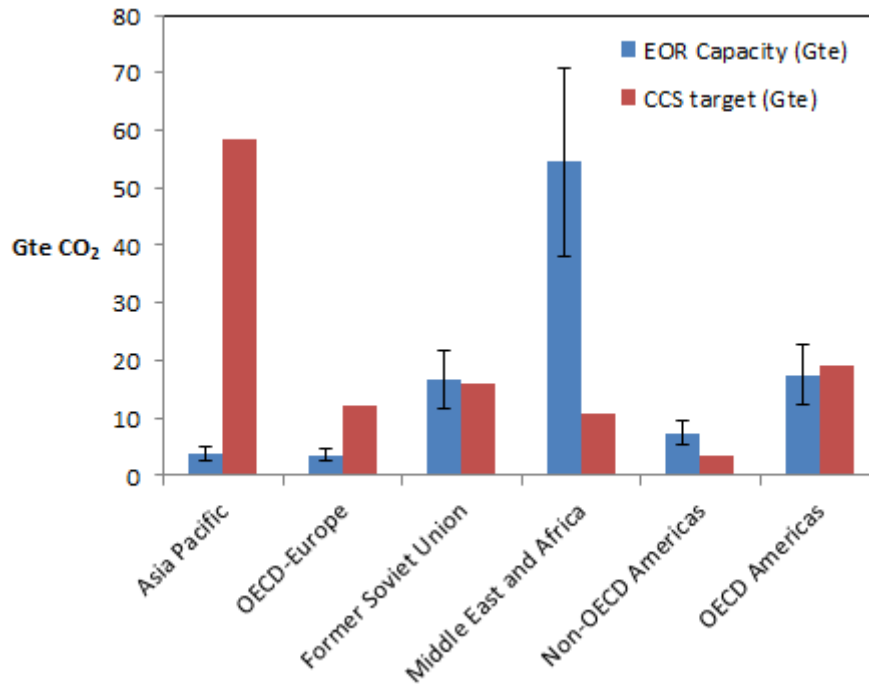


Figure 2: Global CO₂-EOR capacity compared with regional CO₂ sequestration targets. Data from [13, 17, 22]. The error bars included on this data indicate an average calculated variance of 30%. The reported variance is in the range 25 – 35%.

In other words, as illustrated in Figure 2, there appears to be an unfortunate disconnect between regions of substantial CO₂-EOR potential and those regions with the largest anticipated population growth, dependence on fossil fuels and hence requirement to sequester CO₂ over the course of the next century. In fact, the only region where it appears certain that there is sufficient CO₂-EOR capacity to meet the CO₂ storage requirements to 2050 is 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 CO₂-EOR industry in the USA, it is likely that the USA will be a leader in the deployment of CO₂-EOR. If we accept the availability of a CCS-derived stream of CO₂ as a prerequisite for CO₂-EOR, it would make sense to estimate the scale of likely CO₂-EOR activities as matching regional CCS targets. Thus, a more realistic estimate is likely to be on the order of 40 Gt cumulative CO₂ injected for CO₂-EOR. Thereafter, if we consider the average CO₂ footprint of a barrel of oil consumed of 0.43 t_{CO2}/Bbl[29], this results in revising the above estimate down to approximately 35 Gt_{CO2}, or something in the range of 4.5% of the total CO₂ mitigation challenge.

It is, however, important to further note that, given the appropriate incentives and regulatory environment, it is possible to operate a CO₂-EOR operation so as to maximise the storage of CO₂ per bbl_{Oil} recovered [30]. This can have the effect of reducing the amount of oil recovered per tonne of CO₂ injected from approximately 3.33 bbl_{Oil}/t_{CO2} to 1.11 bbl_{Oil}/t_{CO2}. At the lower

end, once the CO₂ emissions associated with the consumption of that oil are accounted for, this can result in the storage of up to $0.52 \frac{t_{CO_2}^{Stored}}{t_{CO_2}^{inj}}$, increasing the contribution of CO₂-EOR to something in the range of 8% of the total CO₂ mitigation challenge. A final point for consideration here is that oil derived from CO₂-EOR could well displace oil that would otherwise be derived from unconventional sources which, is known to have a CO₂ intensity of 108 – 173% of conventional oil [31]. This displacement effect is estimated to be on the order of 80%, owing to market elasticities [30]. Therefore, assuming a constant demand, the deployment of CO₂-EOR could lead to the avoidance of CO₂ 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 CO₂-EOR in mature fields relative to unconventional hydrocarbon production.

Obviously, CO₂-EOR is not the only route to CO₂ utilisation – there are also CO₂ conversion options. There has been active interest in the chemical conversion of CO₂ into platform chemicals, plastics and other materials and fuels since the 1850's [32-35] with the synthesis of salicylic acid, sodium carbonate via the Solvay process, and urea developed in 1869, 1882 and 1922 respectively [36-38]. It is therefore important to recognise that the focus on CO₂ utilisation is not a recent phenomenon. Overall, current annual global CO₂ utilisation is on the order of 200 Mt [35] and it has been suggested that this is likely capped at approximately 650 – 700 Mt [33]. Whilst this estimate was made in 2006 it is in line with current growth rates of the global chemical industry[39]. Further, of these conversion products, approximately 75% is accounted for by compounds which would not correspond to long term sequestration of CO₂; methanol, urea, formic acid and so forth as the CO₂ that is incorporated in these products is released once they are used. Therefore, given a 3%/yr growth rate of CO₂ utilisation and a sequestration rate of 25%, this corresponds to a cumulative total of 15.42 Gt_{CO2} utilised by 2050 and 3.86 Gt_{CO2} sequestered – about 0.49% of the 800 Gt_{CO2} mitigation challenge.

Mineral carbonation is another process which is under consideration [40]. Whilst this process does correspond to the effectively permanent sequestration of CO₂ in a solid form, this is a reaction which happens naturally – albeit at an exceptionally slow rate. Accelerating the rate of these reactions requires the mining (or other collection process), transporting, and finally crushing, grinding and other handling of vast quantities of mineralisable material. This requires very large quantities of decarbonised electricity – which then begs the question: is there not a more profitable purpose to which we could put this decarbonised 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?

Further, whilst it is possible to convert CO₂ to liquid fuels such as methanol for use in ground transport [41], this would result in the near immediate release of the CO₂ to the atmosphere, and, although potentially reducing emissions relative to a baseline, cannot be considered to contribute directly and significantly to the CO₂ mitigation challenge; capturing CO₂ 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/t_{Methanol} [42], the energy required to convert CO₂ into methanol is substantial relative to the energy density of methanol is 19.7 GJ/t_{Methanol}. This corresponds to an energy return on energy invested (EROEI) [43] of approximately 0.45. More than 80% of this energy is associated with the generation of renewable electrolytic H₂, with approximately 10% required for the capture of CO₂ from a fossil-fired power station. If we were to consider the direct capture of CO₂ from the air as the source of CO₂, then one might expect the specific energy footprint of CO₂ derived methanol to increase to the order of 60 GJ/t_{Methanol}, 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 of approximately 19.7 MJ/kg (LHV basis), and could arguably be put to better use elsewhere.

By way of comparison, conventional coal, and oil and gas production processes have an EROEI of approximately 46 and 20 respectively [44, 45], with wind, solar photovoltaic, geothermal and biodiesel having an EROEI of approximately 18 - 20, 10, 9 and 2 - 5 respectively [44, 46].

Given that a fuel or energy is considered to need an EROEI of at least 3 to be considered useful to society [43, 47], the energy required to produce methanol would have to be reduced by a factor of 6 – 10, depending on the source of the CO₂ 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/kg and upon combustion produces 3.09 kgCO₂/kg whereas methanol has an energy density of 19.7 MJ/kg and upon combustion produces 1.38 kgCO₂/kg.

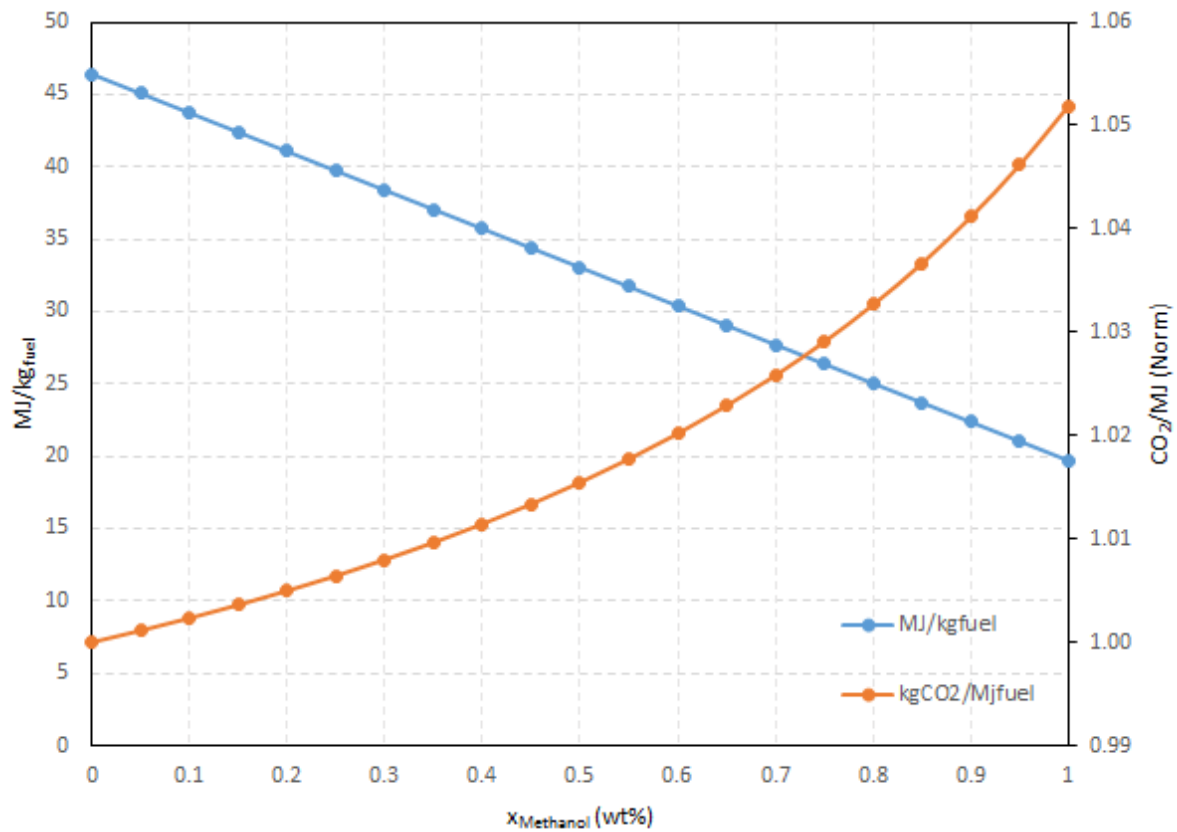


Figure 3: the effect of blending methanol with gasoline is presented here. It can be observed that, as methanol is added to gasoline, the energy density of the fuel decreases, whilst the CO₂ footprint per unit of energy service delivered increases. Therefore, the substitution of methanol for gasoline will potentially increase the CO₂ emissions associated with delivering that energy service.

As can be observed from Figure 3, owing to the reduced energy density of methanol, its use as a fuel will result in the emission of approximately 5 % more CO₂ than would have otherwise been the case.

Moreover, the processes for converting CO₂ to methanol do not have a perfect yield. There will be some fraction of CO₂ purged from the process – typical numbers are 0.08 t_{CO2} purged and 0.67 t_{Methanol} produced per t_{CO2} feedstock [42]. Consider, then, that 1 bbl_{oil} will yield 19 gallons of gasoline, and supply 2,469 MJ/bbl_{oil}, therefore emitting 164.46 kgCO₂/bbl_{oil}. To deliver the same amount of energy requires 125.36 kg_{methanol}/bbl_{oil}^{equiv}. When this methanol is combusted, and accounting for the CO₂ that was emitted in the initial production of the methanol, this corresponds to approximately 188 kgCO₂/bbl_{oil}^{equiv}, or approximately 14% more CO₂ 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 CO₂-EOR and methanol production on the basis of energy service, we first recall that, depending on the version of EOR practiced [30], between 1.1 – 3.3 bbl_{oil}/t_{CO₂} are produced and that each bbl will produce 12 gallons of diesel and 19 gallons of gasoline, which delivers 4,284 MJ/bbl_{oil}. In the default CO₂-EOR case, 3.3 bbl_{oil}/t_{CO₂} are produced and where the EOR operation is optimised for storing CO₂, this is reduced to 1.1 bbl_{oil}/t_{CO₂}.

Table 1: Comparison of the CO₂ footprint associated with CO₂-EOR and CO₂-derived methanol. This calculations account for the energy service delivered by both the diesel and gasoline derived from the oil, and requires the production of sufficient methanol to displace both fuels on an energy service basis. Reading from left to right, the first column indicates the number of barrels of oil recovered per tonne of CO₂ injected, then the energy service delivered by the gasoline derived from that oil and then the CO₂ that is emitted as a result. The fourth column specifies the quantity of methanol required to provide the same service, and finally the quantity of CO₂ that is emitted as a result. It can be observed that converting CO₂ into methanol results in more CO₂ being emitted than for the CO₂-EOR case.

Oil recovered (bbl_{oil}/t_{CO_2})	Energy delivered ($MJ/t_{CO_2}^{inj}$)	Net CO ₂ emitted ($kg_{CO_2}^{emit}/MJ$)	Methanol required (kg)	Net CO ₂ emitted ($kg_{CO_2}^{emit}/MJ$)
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

As illustrated in Table 1, this leads to the net emission of 0.43 and -0.52 52 $t_{CO_2}/t_{CO_2}^{inj}$, respectively and delivering 4,760 - 14,279 MJ/t_{CO₂} or between 0.03 and -0.11 kg_{CO₂}/MJ. Displacing this service with CO₂ derived methanol would require the production of 242 – 725 kg_{Methanol} leading to the emission of approximately 0.08 kg_{CO₂}/MJ. Thus, from the perspective of both EROEI and a carbon balance, the utilisation of CO₂ for EOR would appear to be preferable to the conversion of CO₂ to methanol. In all cases, CO₂-derived methanol would appear to increase the quantity of CO₂ emitted whilst delivering the same service and, under some circumstances, CO₂-EOR can result in the net sequestration of CO₂, 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 utilisation option actually stores the CO₂. It is well accepted that in order to mitigate the effects arising from anthropogenic CO₂ emissions, it is necessary to *permanently* sequester the CO₂ which is excess to the earth's carbon cycle. Chemicals such as urea or methanol store CO₂ only until they are

used; once urea is applied as fertiliser or methanol is used as a fuel, the CO₂ is immediately released to the atmosphere – corresponding to a storage duration of perhaps six months. The conversion of CO₂ into polymers might store the CO₂ 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 CO₂ emissions by 80% of 1990 levels by 2050, it will be necessary to reduce anthropogenic emissions by approximately 42 Gt CO₂/yr 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 Gt CO₂ in the period to 2050 [3, 15, 22], or 16 – 20% of the cumulative mitigation challenge. This corresponds to a rate of CO₂ sequestration of approximately 2.5 Gt CO₂/yr by 2030 increasing to 8 - 10 Gt CO₂/yr by 2050 [3, 15, 22] , with further increases in the rate of sequestration in the period to 2100 [1].

As discussed previously, CO₂-EOR is a potential sink for a substantial amount of CO₂. One of – if not the – major barriers to higher levels of CO₂-EOR on a global basis is an insufficient supply of affordable CO₂. In 2004, there was a supply shortfall of approximately 40 Mt CO₂/yr for CO₂-EOR in the Permian Basin. Subsequently, between 2007 and 2010, an additional supply of approximately 5 Mt CO₂/yr was sourced in response to this demand [28]. This is very possibly the world's first example of a “demand pull” on anthropogenic CO₂ capture. Recent years have seen a steadily increasing share of this CO₂ supply being provided by anthropogenic sources; as of 2010 this was 12 Mt/yr [12]. 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 CO₂-EOR activity of 11%/yr is feasible, given appropriate initial conditions such as secure supplies of CO₂. From a baseline of approximately 0.06 Gt_{CO2}/yr used for CO₂-EOR, this could grow to perhaps 26 – 27 Gt_{CO2}/yr in 2050. This could correspond to a cumulative total of approximately 40 - 60 Gt_{CO2} injected, and 35 – 70 Gt_{CO2} stored. As previously, this represents about 4 - 8% of the ~ 800 Gt_{CO2} mitigation challenge by 2050.

Concerning other options for CO₂ conversion, data from some recent estimates of current and near-term market sizes is presented here in Table 2. One should note that the two largest sinks for CO₂ – urea and methanol – do not correspond to storing CO₂ for any significant period of time. Similarly, the “Technological” category appears to be a catch-all for CO₂ utilisation in food and drink manufacture, fire suppression, as an inerting agent, dry ice and other miscellaneous activities. Again, these options do not correspond to long term sequestration of the CO₂.

Table 2: Present and short-term uses of CO₂ based on production data and forecasts from [35]. The final two columns of this table is the interpretation of the authors of the data presented by [35]

Compound	2013 production (Mt/yr)	CO ₂ used in 2013(Mt/yr)	2016 production forecast (Mt/yr)	2016 Forecast CO ₂ needed (Mt/yr)	Rate of growth of production (%/yr)	Rate of growth of CO ₂ utilisation (%/yr)
Urea	155	114	180	132	5%	5%
Methanol	50	8	60	10	7%	8%
Carbonates	0.2	0.005	2	0.5	300%	3300%
Polycarbonates	4	0.01	5	1	8%	3300%
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	6633%	6633%
Grand total:	426	200	518	299	7.2%	16.5%

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%/yr [39], it is difficult to accept however that this could, in any way, be indicative of a long term trend. Further, there appear to be significant assumptions in these data [35] surrounding the *rate of displacement* of CO₂ derived products in the market. Other, more conservative estimates of CO₂ utilisation for the manufacture of chemicals place an upper limit of 650 – 700 MtCO₂/yr for total global utilisation [33]. This implies a growth rate of 3%/yr in the period 2010 – 2050, which is in line with the current rate of growth of the global chemical industry [39]. This would correspond to a cumulative total of 15.42 GtCO₂ utilised in the period 2010 – 2050.

As discussed previously, only about 25% of these products correspond to sequestering the CO₂ for any significant duration, therefore this total is reduced to 3.86 GtCO₂ – or slightly less than 0.5% of the CO₂ mitigation challenge of 800 GtCO₂ by 2050.

Putting it in perspective

When we take these data and then compare them for the period to 2050, we obtain the results illustrated in Figure 4. Presented in this way, it becomes clear how negligible the contribution of CCU will be to the global CO₂ **mitigation** challenge.

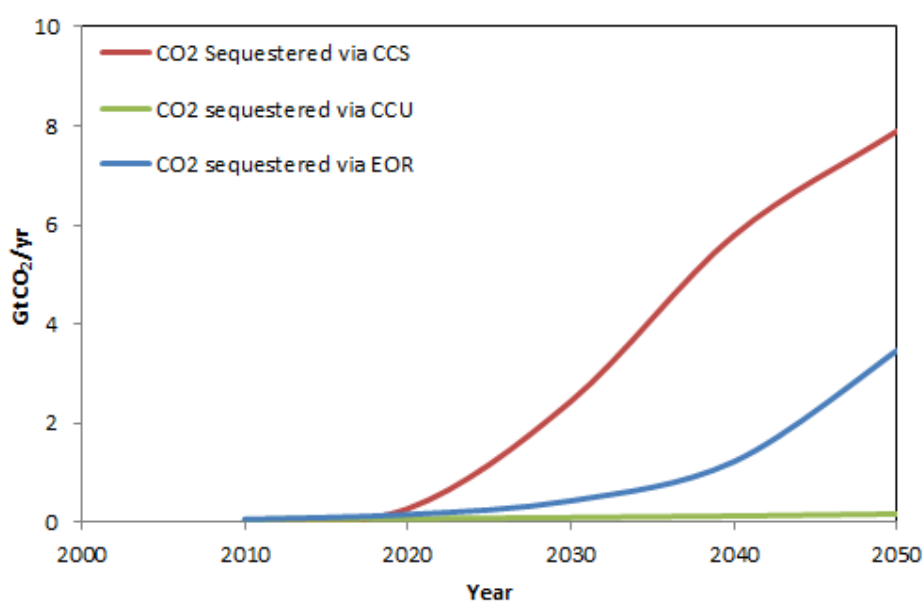


Figure 4: CCS vs CCU - a perspective for the period 2010 to 2050

This emphasises the danger of reinforcing the narrative that CO₂ utilisation is key to making CCS “profitable” in a simplistic commercial sense. If this narrative continues, it introduces the very real risk that our emission mitigation targets will not be met and that CCS through geological storage will not be deployed in any meaningful way. From a commercial and policy perspective, CCU should be encouraged when and only when CO₂ is useful as a cheap feedstock, or when it can robustly and reliably shown that the CO₂-derived product can a) reasonably displace the incumbent product, *i.e.*, deliver the same service at the same price and b) not result in an increase in the emission of CO₂ associated with delivering that service, but not otherwise. The driver should be feedstock substitution and the production of materials at a lower cost and with lower fossil content. The primary driver should not be locking up CO₂ as this can never happen at the required magnitude without geological storage.

Underpinning research into CO₂ conversion should certainly continue in order to expand options and reduce costs. CO₂-EOR, whilst no panacea, can be deployed at a sufficient scale to facilitate the deployment of CO₂ transport infrastructure and potentially stacked CO₂ 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 [48, 49]. Whilst CO₂-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 with a careful and thorough analysis of associated primary and associated opportunity costs.

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