Storing Carbon for Geologically Long Timescales to Engineer Climate

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ABSTRACT

To re-establish global climate balance, it is necessary to remove large amounts of fossil carbon emitted by humans, which is currently located in the atmosphere and the upper ocean. Although great attention is given to technologies of capture, the ability to store immense tonnages of carbon stock for geologically long time periods, isolated from atmosphere and ocean interaction, is equally important. In this chapter, the multiple storage locations for carbon stocking on and below land, also within and below the ocean, are evaluated. The evaluation shows that carbon dioxide reduction (CDR) is useful for mitigation, but cannot balance the rate of new emissions from fossil fuel exploitation. Many CDR methods have large uncertainty in their quantity, life-cycle, global impact and engineered feasibility. Competition for biomass and land usage is inevitable. Pathways and reservoirs of carbon in the ocean are complex and interlocked. Engineered storage of carbon will also be expensive, resource intensive and cannot substitute for a greatly reduced usage of fossil carbon. Human industrial and economic activity must "move beyond hydrocarbons" to be sustainable beyond 2050.

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1 Why is Carbon Storage Necessary?

Industrial and advanced societies gain a large part of their energy usage from combustion or dissociation of fossil carbon: coal, oil, and methane. Each one of these has augmented the previous energy vector, but not replaced it. Thus, more wood is combusted today than ever before, as well as more coal and more oil. Although there is certainly a trend towards more hydrogen rich fuels, now expressed as the rise of methane usage, the overall release of fossil carbon from the geosphere into the atmosphere and ocean has proved relentless. The historical rise in carbon emissions continues to accelerate, notably since the industrial revolution, founded in the UK, made condensers so that coal-fuelled steam engines became more efficient and commercially valuable. The rest is, literally, history.

The immediate consequences of utilisation of fossil carbon were, and still are, vastly improved wealth, leading to improved human health, fertility, and long life. These are all highly desirable, and the activity of consuming fossil energy directly, or by proxy, permeates our entire culture. However, it is now clear that the carbon emissions from these activities have overwhelmed the natural processes for circulation of carbon through the Earth's atmosphere, biosphere, and ocean, such that humans now dominate the inelastic parameters of the global carbon cycle. That enables naming of our present geological epoch the ''Anthropocene'',[1] where humans dominate over many Earth processes. Although Arrhenius realised theoretically that carbon dioxide is able to retain solar heat reflected from Earth in the atmosphere,[2] the consequences have only gradually become apparent with the empirical measurements of Keeling,[3] leading to seminal predictions of climate warming by Hansen in 1981.[4] Thirty years of focused and intense scientific investigation has led to a much improved understanding of carbon cycling on Earth, and the contribution that CO_2 makes to the greenhouse gas in the Earth's atmosphere.

There is intense debate concerning the rates of CO_2 increase or the rates of carbon production and the rates of temperature change. However, in a geological context, all these timescales are instantaneous. During the past 250 years, humans have released more than one quarter of the carbon emitted by the Earth during some of its more intense volcanic episodes during the past 600 million years. It is now clear from climate modelling that the rate is not so important, but the total quantity of carbon released is a fundamental controlling factor of global change.[5] The conclusions of climate modelling are supported by the geological record. Although the resolution in calendar years, or hundreds of thousands of years, is poor in comparison with the most recent 100 000 years, it is clear that the Earth has emitted large quantities of carbon dioxide at perhaps five different times during the past 600 million years. At each of those times there has been a rapid period of global change, often associated with temperature warming, which has resulted in geologically instantaneous extinctions of many species. Consequently, the emission of fossil fuels can be viewed as a carbon stock problem, not a rate problem. The present emissions can be viewed as an experiment in undertaking the rapid release of CO_2 during geological time, and thereby experimenting with a sixth extinction.

A logical deduction from these observations is that humans have a vested interest in managing the carbon stock on the Earth's surface. That includes reducing the total quantity of carbon stocked rapidly into the atmosphere and ocean during the past 250 years. If carbon can be captured using diverse natural or engineered processes, where then can this carbon be stored? It is clear from consideration of the Earth as a system, that this carbon has to be stored not just for one year or 100 years, but for thousands or tens of thousands of years whilst the Earth's natural self regulation returns to a level with which we are familiar during the past 15 000 years, after the last de-glaciation. If humans are not able to find methods to reduce the carbon stock, and store carbon for these extended time periods, then the Earth will continue to undergo a global change, similar to many in the geological past, where present climate belts move pole-wards, and the familiar pattern of ocean currents, seasonality, rainfall, temperature, and weather becomes unpredictable. In climate modelling, the threshold at which these adverse effects become unpredictable has conventionally been taken at 2 °C. That is not necessarily a hard boundary, but a clear indication of a threshold, after which reversibility becomes much more conjectural. Taking the analysis of Meinshausen,[5] that 1 000 000 000 000 tonnes of carbon is the regulated total amount, Allen has calculated that this threshold will be reached in 2044.[6] Humans have a large stake in correctly managing the carbon stock before that date is reached.

In the remainder of this article, we assess the different styles by which carbon may be stored, and analyse the known information, the natural processes, and the engineering interventions which could be undertaken to enhance the global rate and tonnage of carbon stocking.

2 The Approach and Controlling Factors

Multiple methods to reduce carbon dioxide, and to store carbon dioxide or carbon, have been proposed during the past 30 years, and it is likely that additional methods will be proposed in the future. Here we categorise the methods which seem, in our analysis, to have the largest global potential. We subject each of these methods to a similar suite of analysis. Firstly we describe the essential features of the method, in terms of its process, geography, and chemistry; we assess its potential impact in terms of global tonnage of CO_2 per year; then we attempt to estimate the cost, engineering feasibility, security of carbon retention through centuries or millennia, the effort needed to maintain that carbon stock through our millennial time-scale; and finally we speculate on the potential adverse effects which may result from the method's adoption.

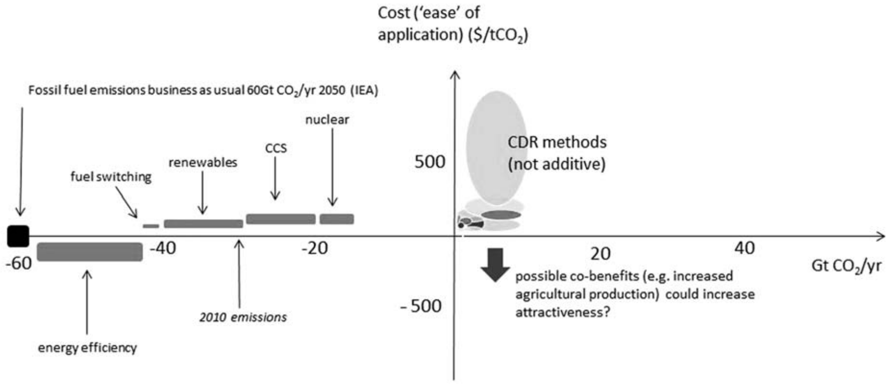

Figure 1 Diagram showing the size of the challenge for engineered carbon production and storage.

To gain some insight into the significance, or impact, of the method, these different opportunities are portrayed in Figure 1 both graphically and numerically, in relation to the present day production of fossil carbon recorded by organisations such as BP,[7] or the International Energy Agency.[8]

Figure 1 illustrates the degree of the challenge facing engineered carbon production and storage. The X axis shows different quantities of CO_2 emission to the left, with diverse possibilities of CO_2 storage to the right. The left black square is the total amount of fossil carbon dioxide emitted each year by 2050 if a 'business as usual' trajectory is followed, according to the International Energy Agency. The series of ellipses to the right of the y-axis show different possibilities of climate engineering to store CO_2. Horizontal dimension estimates the range of CO_2 storage per year, the vertical dimension estimates the range of cost per tonne of CO_2 which that action may incur. It is clear that no single action of carbon storage is anywhere close to being sufficient to balance the fossil CO_2 emitted annually. Additional measures are needed.

The blue horizontal bars estimate the tonnage of CO_2 reduction which could be achieved by different measures which do not involve climate engineering. Bars below the horizontal ($Y = 0$) are actions which save money, and are in principle self funding. Bars above the horizontal are actions which cost money, expressed as $ per tonne of carbon dioxide on the Y axis. Even if all five conventional actions are followed, there is still a net CO_2 emission of around 15 Gt CO_2 yr^{-1}. From this, it remains unclear whether even if all carbon storage engineering actions are taken, they would be capable of balancing the residual CO_2 emissions, especially in the long term. The fundamental conclusion from this diagram is that consumption of fossil carbon, and the rate of emission, has to be curtailed in ways which are not yet calculated. Climate engineering by storage of fossil carbon emitted cannot balance the projected rates of new emission, and therefore cannot, on its own, manage the stabilizing of atmospheric CO_2.

3 Methods of Reduced Emission Rates

There are methods which, in principle, are well understood to enable reduction of fossil carbon emissions. Many of these reside in the domain of energy studies. For example switching of fuel vector from coal, to oil, and then to methane can produce similar amounts of energy with systematically decreased carbon emission. This relies on the oxidation of hydrogen to form H_2O as the main exothermic route. It is well understood that many nations globally depend on combustion of large amounts of coal to produce electricity, and also heat. Examples include China, USA, Germany, and the UK. Coal is both cheap and available. Environmental policies to reduce its use have been ineffective since the 1980s, in spite of the large costs of its extraction, in terms of human life and in direct environmental degradation. More successful, has been the economic case for fuel switching. Since 1990 in the USA, unanticipated discoveries of large resources of shale gas have produced a glut of low-cost fossil hydrocarbon into the USA domestic market. This has out competed coal on its low price, and has led to a decrease in carbon emissions whilst maintaining a similar pattern of energy usage. However, it is clear from basic calculations of energy modelling that switching from coal or oil to gas only buys two extra decades of time before the total global carbon budget is exceeded. More aggressive and even lower carbon methods are required.

A favourite method for many political and industrial leaders is that offered by carbon capture and storage (CCS). This allows continued combustion of coal, oil, or gas at electricity generation plant, or industrial process sites. Emitted CO_2 is avoided by chemical transformation of fuel pre-combustion, or the CO_2 is chemically adsorbed from flue gas after combustion. The pure CO_2 is liquefied, transported by pipeline, and injected 1 to 4 km below ground where it can remain for millennia. This can reduce carbon emissions at industrial sites by 90%. However, the initial projects have proven to be too expensive for national governments to implement, and insufficiently courageous environmental legislation has been produced to enforce market companies to implement CCS. If this group of technologies does eventually become deployed, then that too can buy an extra 20 to 40 years of time until the global carbon budget is exceeded.

It is also well understood that energy usage by industrial societies and individuals is inefficient. If the price of energy were perhaps 10 times its present level then it would be commercially worthwhile to develop district heating schemes, insulate houses, share bus transport rather than use individual cars, or use centralised electricity power plants which have a thermal efficiency greater than 35%. Again, the principles are well known, but the delivery has been perennially slow through many decades. Assertively explained lifestyle changes, predicated around energy efficiency, could reduce consumption rates by 30 to 70%.[7,9] That could buy perhaps another 60 years of time before the carbon budget is exceeded.

In the event that none of these above methods are implemented sufficiently, at scale and globally, then to stabilize climate, humans will be required to undertake deliberate climate engineering to undertake solar radiation management (SRM), or to undertake deliberate carbon extraction and storage from the biosphere atmosphere and ocean. These technologies are analysed in the following sections.

4 Principles of Carbon Dioxide Removal (Negative Emissions Technologies)

Reduced rates of CO_2 emission cannot, on their own, keep the industrialised world within its global carbon budget. Either it will be necessary to undertake several, or all, of the above emissions reductions, or additional technology interventions will be required. Carbon dioxide removal (CDR), or negative emissions technologies,[10] undertake a deliberate removal of CO_2 from the atmosphere and ocean, sending it to storage and isolation for thousands of years. In the compilation below we analyse the arithmetic claims for CDR technologies. The real effects of CDR will be more complex. For example if CO_2 is reduced in the atmosphere, then that will enable additional CO_2 release from the upper ocean.[11] As a second example, increasing forest cover in the tropics may draw down atmospheric CO_2, but this will consequently reduce the rate of vegetation growth. Precise predictions will require much more detailed modelling and life-cycle analysis of interacting natural processes.

5 Life-cycle Assessments

The size of the problem involves very large tonnages of CO_2. Consequently, the development of many of these terrestrial CDR technologies (particularly biomass), which are large enough in scale to have a global climate impact, will incur significant development in control of the land surface as an inevitable consequence. To achieve better quality information, it will therefore be necessary to undertake total life-cycle assessment for each technology alone, and then combinations of proposed technological changes. In a natural context these should include interactions with temperature, atmospheric CO_2 concentration, albedo change, and hydrological demands. The utilisation of biochar is a good example, where complex feedbacks and interactions can be expected.[12] In an engineering or human context, the life-cycle assessment needs to consider the engineering construction; supply chain of equipment and materials; sources of energy to undertake the processes; changes in land use; induced changes of land and water use; fugitive emissions and process emissions and induced emissions *e.g.* in soil carbon;[13–16] transportation and its energy sources; utilisation of minor products; as well as cleanup remediation and waste disposal of sites.[15,16] Impacts on society, or on construction, have a time dimension and may result in a “period of payback” to replace emissions during the setup period. Ultimately, agreed frameworks for the scientific analysis of life-cycle and climate in CDR actions will need to be agreed. Moving towards operations, financial and actuarial accountancy, as well as carbon budgeting, will need to be transparent in the life-cycle analysis.[14]

6 Biomass Availability and Sustainability

Biomass is one of the most contested accessible resources. A fundamental tension exists between utilising biomass for CDR *versus* utilisation of biomass for habitat preservation, or utilisation of biomass for food production. Estimation of the supply of sustainable biomass involves many technical, societal, and climatic variables. Availability to within one order of magnitude depends on assumptions of land, fertiliser, water, food demand, climate, biomass type, and technology utilisation developments.[14,17,18] To support ambitious CDR through biomass requires the potential to convert land from agriculture or natural ecosystems rich in carbon, to produce controlled cropping of biomass. This may also involve large inputs of fertiliser or irrigation. The intentional increase of biomass for CDR will often change albedo, for example an increase of boreal forest will reduce winter albedo if snow sheds from dark leaf trees. Integrated modelling will recognise these limits to helpful impacts on climate. The most fundamental human choice of land-use and biomass in the near future will be preservation of habitat *versus* efficient food production *versus* continued and increasing meat consumption.[19] Inspection of the figures cited by proponents suggests large estimates for land biomass potential, and assumes that planned conversion is undertaken and all biomass is used for CDR. Caution is needed because, although some biomass effects can be synergistic, *e.g.* waste derived from crops or forestry, in general biomass uses are exclusive, not additive for CDR. There is also no requirement that a single global approach is undertaken. Biomass utilisation in particular, is likely to exploit optimal regional choices and appropriate technologies.

7 Carbon Dioxide Storage Availability

Options for long-term storage of carbon, $>$10 000 years, all have geological parameters. These timescales are required to reduce carbon pressures on global change on a long-term or ‘‘permanent’’ timescale. Many of the short-term storage options require continual maintenance and recharging with carbon and are open to variations in societal input, wealth, or extreme climate change. Typical examples could be reforested or afforested regions available for felling, vulnerable to drought, or disappearance due to forest fire. In techno-economic assessments, these generic risks to short-term storage seldom appear to be recognised, in contrast to the durable reliability of long-term geological storage options.

Utilisation of CO_2 is frequently proposed by industrial or business protagonists. However this is fraught with difficulty, when considering the relevant timescale. Utilisation of CO_2 to enhance growth of food (tomatoes and greenhouses), or to augment drinks (carbonated water) indeed has a commercial value, but the storage is fleeting in time, lasting only days or months. Using CO_2 as a feedstock can have a financial value for manufacture of high-value fine chemicals (such as pharmaceuticals), or bulk chemicals (such as carbonate, urea, methane, methanol, formic acid, or liquid fuels).[20] However, if the product is combusted, then that carbon is inevitably released into the atmosphere. Long timescale retention is difficult to justify. It is also clear that the global demand for most of these products is tiny, in comparison to the tonnages of CO_2 produced during power generation.[21,22] Utilisation can, therefore, contribute to the cash flow of early projects, in terms of the present markets, but utilisation is not a long-term storage method or money earner.

Storage of immense CO_2 tonnages can be contemplated below the ground in five types of geological settings. Firstly, by injection into, and reaction with, continental scale basalts – for example the Deccan lavas of India, the Columbia River, USA, and in Iceland.[23,24] Pilot injection tests have been undertaken,[24] but it remains unclear how the majority of rock will be put into contact with injected CO_2. Secondly, utilisation of CO_2 to improve oil recovery has been proven in the USA and several other countries. Commercial methods of CO_2 circulation promote dissolution into remaining oil, or into deep groundwater, making this one of the most secure storage methods, and a method which could find utility as a transient method of generating government taxes, or could be hypothecated to finance capture and transport infrastructure. Set against that, however, is the ugly fact that commercial interests utilise CO_2 to produce additional oil. The carbon balance cannot be reconciled, unless injection to promote CO_2 storage is deliberatively planned, or unless CO_2 injection continues for about the same number of years as oil was produced, beyond the final oil production date. Thirdly, the re-use of depleted methane reservoirs has been proven to securely contain buoyant fluid to recharge limits up to the original natural fluid pressure within the reservoir at the time of discovery. Fourthly, there is the technical possibility of CO_2 injection into sediments of the deep seabed. An optimal zone exists in which liquid CO_2 is denser than the overlying waters, yet less dense than underlying brines.[25,26] This offers potentially immense volumes for CO_2 storage into a failsafe density trapped mechanism. However, the logistics of transport from CO_2 sites to the deep offshore, and injection followed by monitoring, are financially challenging. The fifth approach is the direct injection of liquid CO_2 into regionally widespread saline aquifer formations. These are routinely assessed to be abundant within the oilfield areas currently under investigation, and comprise more than 80% of accessible storage volumes of commercial interest. Evaluation of this type of storage, to the required level of commercial certainty, may require hundreds of millions of pounds to drill test boreholes and produce fluids, for each regional saline formation hosting one gigatonne CO_2 or more. There is good potential to reduce that exploration cost by using legacy boreholes, or existing holes, tracked sideways to inject test CO_2 at more than one horizon within the layer cake stratigraphy.

The conventional assessment of CO_2 storage, seeking sites in saline aquifer formations, still has large uncertainties.[27,28] Improving the site-specific estimates of storage available can be achieved by a combination of improved subsurface geological information, such as seismic reflection surveys or direct drilling. Good examples of progressively improving evaluations of storage are provided by the North American Atlas,[29] the Norwegian Petroleum Directorate surveys,[30] or the UK databases.[31,32]

There are also many options for engineered enhancement of CO_2 storage in single saline formations, such as large-scale production of deep saline water, to be disposed at the surface. This creates ''voidage space' in the deep subsurface which can easily raise CO_2 storage utilisation efficiency from 2% (the amount dissolved in saline water) by a factor of four.[33] Nevertheless it is clear that sedimentary basins, which could have characteristics for geological storage of CO_2, are not uniformly distributed around the Earth.[28] The practical problems arise in detailed matching of CO_2 sources with the nearest storage sink, *i.e.* connecting capture to saline aquifer. Established methods involve construction of overland pipelines, which can be tens or even hundreds of kilometres in length.[27,28,34] CO_2 shipping is also possible using tankers converted from liquefied petroleum gas. All these add expense and complexity, as well as difficulties of public permission. In principle, it is therefore a sensible strategy to relocate surface CO_2 capture facilities above storage sites. This results in many fewer potential sites, for example when using air capture, where the appropriate meteorology and climate lie above the appropriate geological storage.

In simple arithmetic terms the known commercial reserves of fossil hydrocarbon today can be approximately balanced by the estimated global quantity of storage resource. However, if, as has been the historical precedent, the much larger resources of fossil hydrocarbon are gradually converted into commercial reserves, then the amount of known storage on land requires major engineering to improve subsurface storage volumes. Even then, our estimates are that fossil hydrocarbon resources greatly exceed the summation of conventional geological CO_2 storage.

The performance of deep geological storage during long timescales is often the subject of debate. There is an element of dual standards in such discussions when, for example, a reforestation proposition is regarded as more secure carbon storage them deep injection of CO_2. We suggest that forests can be significantly liable to 100% loss of carbon by fire or drought and that is regarded as acceptable. Whereas by contrast geologically stored CO_2 is unlikely to leak, but monitoring technologies struggle to detect leakage rates of 1% per 1000 years, and this is sometimes regarded as unacceptable. We propose that the possibility of modest rates of geological leakage still retain many benefits of carbon reduction which assist climate mitigation in the medium term.[35,36] There is clearly a balance to be struck between tonnages of CO_2 stored for maximum security but with much less available storage capacity, *versus* strategies where storage capacity is maximised whilst accepting a statistical probability of slower rates of long-term leakage.

Figure 2 illustrates the advantages and limitations of the various carbon dioxide storage methods (magnifying details of CDR from Figure 1). The X axis estimates the range of possibility, the Y axis estimates the feasibility expressed as cost per tonne of CO_2. Darker colour shades indicate greater maturity of the technology, for example afforestation is well understood relative to capture. Estimates are gained from the various sources cited in Table 1. As explained previously, many figures are uncertain both in terms of cost and potential tonnage per year. Nevertheless, this diagram provides a visual estimate of the most important actions, which could have greatest potential impact in capturing and storing carbon stock. It is clear that the technologies with the greatest claims are biochar, biomass with carbon storage, and air capture. Note that there may be resource conflicts between biochar and biomass with CCS, as published estimates for maximum deployment assume that each is the sole dominant technology. The conclusion from this is that much greater certainty of costs is needed for all three technologies, and much better estimation of biomass resource availability is needed in the context of food production, and maintaining sustainable

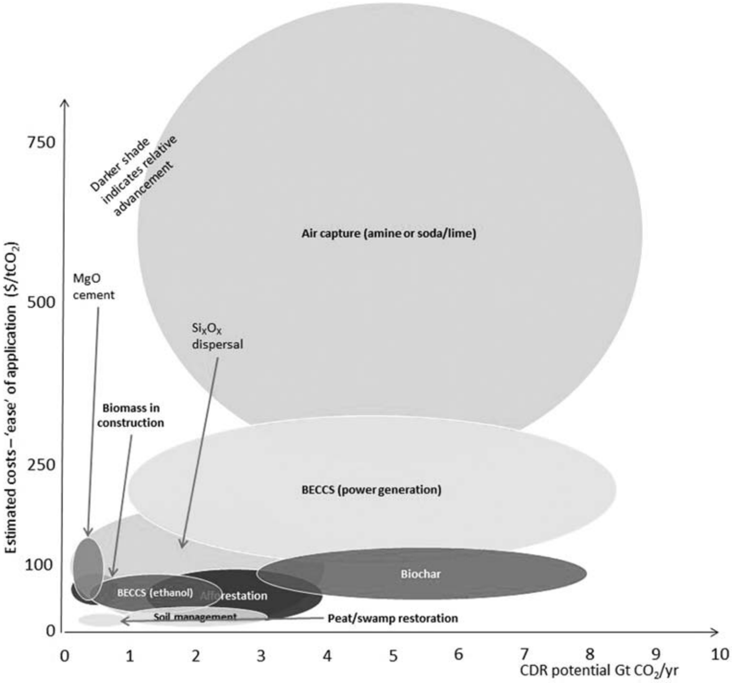

Figure 2 Diagram showing the feasibility, the CO_2 removal potential and maturity of technology for various CO_2 storage methods.

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terrestrial ecosystems immune from multi-decade timescale forest harvesting, or forest gardening.

8 Summary of Carbon Storage Methods

8.1 Increased Terrestrial Biomass: Afforestation

Essential features: planting more trees is easy to understand in principle, but rather more complex to calculate in terms of its benefits. There is a distinction between afforestation and reforestation. Afforestation is where trees are replaced in regions where they have been absent for greater than 50 years, and can also conceptually include increasing the carrying capacity of a landscape for unharvested terrestrial biomass. The concept of reforestation, on the other hand, is where forest loss occurring within the past 50 years is replaced.[37] It is also important to make a distinction between tropical and temperate forest systems, since tropical biomass grows rapidly, with a short replacement timescale, and with minimal albedo effects. By contrast temperate forest systems grow 5 to 10 times more slowly,[43] and can actually decrease albedo by darkening the landscape especially during northern winter when reflective snow can be replaced by an absorbing surface of dark coniferous needles.[42]

Potential impact: estimating the carbon storage impact of forestation has great uncertainty. Optimistic maximum estimates speculate on the regrowth of all deforested regions,[11] replacing a total of 180 +/− 80 gigatonnes of carbon, including soil recarbonisation. However, competition for land use in agriculture means that a realistic figure is much lower.[19] A global potential maximum for sustainable afforestation could be about 1.5–3.0 Gt CO_2 yr^{-1}.[38] Deforestation produced by human activity is estimated to emit 2–4.5 Gt CO_2 yr^{-1}.[39] Complications arise when the payback time is considered.[40,41] Felling of forests could produce a rapid emission of biogenic CO_2 if the wood is combusted, as well as a reduction of soil carbon during harvesting and replanting.[41] Carbon is only actively stored during the maximum growth of new forest, typically from year 10 to year 40 after planting. Subsequent to that timescale, forests can achieve a steady state position with much slower sequestering of atmospheric carbon. Consequently, to utilise reforestation requires continual active management of the forest carbon stock on a global scale. That intensification of use conflicts with most strategies for conservation and habitat management.

Costs: financing the forest carbon stock varies greatly in cost, depending on competition with local demand in agriculture for fertile cropland, from \$20 to >\$100 t^{-1} CO_2. There is also uncertainty in the measurement of stocked carbon – terrestrial methods are slow and labour-intensive, whereas satellite radar methods are much more rapid but are only just emerging as a method. Forests also need to be maintained in very different ways in different settings, and the payment for this is unclear, other than by commercial extractive forestry. Although programmes are being developed such as Reducing Emissions from Deforestation and Forest Degradation (REDD) which aims to offer incentives for developing countries to reduce emissions from forested lands and invest in low-carbon paths to sustainable development.

Security, effort, adverse effects: forestry is well understood in its fundamentals. There is a clear risk from local competition in land use – a problem which needs to be guaranteed through many decades. There can also be catastrophic risk of tree death from drought or from forest fire. In addition, maintaining maximum rates of carbon stocking requires rotational felling after only a few decades, removing the possibility of a long-term stable ecosystem. Adverse effects of forestry include water consumption, albedo change, and the potential to alter regional cloud patterns and rainfall.[19,38] Stocking with rapidly growing non-native species can introduce fungal or pest infection. Cultural changes can also be induced, such as the use of fuel wood, hunting and foraging for food, and the care for valued wildlife.

8.2 *Increased Soil Biomass: Biochar*

Essential features: 'biochar' is a term applied to charcoal produced through low-temperature pyrolysis, intended for utilisation in a soil ecosystem. The placing of char intends to increase the lifetime of biomass carbon within actively managed soil profiles. This can be applied to agriculture or forestry, at local farm or small industrial plant scale, and can use excess biomass derived from many types of feedstock. A range of pyrolysis conditions and time durations at 300°C to 900 °C, span the range from high retention of volatile organics in the char through to complete gasification in a process where oxygen for combustion is incomplete. Co-products include impure bio oil, and flammable syngas which can be used to power the pyrolysis equipment.[12,44,45]

Potential impact: using current land behaviour estimates, and applying biochar globally within all applications and identified niches places carbon stock management with biochar at around 3.5 Gt CO_2 yr^{-1}, with a cumulative total of 500 Gt CO_2 sequestered during 100 years.[12] An optimistic calculation, where biochar is applied to all agricultural grassland areas, derives a maximum global accumulation of 1500 Gt CO_2 (400 Gt C) during 100 years.[12]

Cost: financing biochar depends on multiple factors: predominantly feedstock, transportation, and labour costs. In Western countries, if biomass costs are $<\$100\ t^{-1}$, the least cost applications are \$40 t^{-1} CO_2, ranging up to \$150 t^{-1} CO_2.[45,46] Biochar yield can be estimated as upwards of 25% of the mass from dry feedstock, producing a sequestration of 0.46 t CO_2 per dry tonne of biomass feedstock.[47] In common with many "negative emission technologies", biochar cannot currently compete against the rival proposition of simply burning all the biomass, and thus returning CO_2 rapidly to the atmosphere. This type of problem requires government action to create payments which reward long-term carbon storage. Pyrolysis equipment for multiple small-scale applications is available now, although there is substantial scope for improved control and specification of pyrolysis.[45]

Security and effort: there are several well-publicised examples of Amazonian ‘‘terra preta’’ biochar, which have lifespans of several hundred years in the soil. Matching biochar type to soil type is a topic of active research, and establishing residence times of carbon stock between decades and several centuries seem very probable. Active management is required during initial application, with minimal maintenance thereafter. Routine large area verifying of biochar stock in soil is, as yet, undeveloped, although proxy methods of remote sensing for carbon in soil are under investigation, and manual sampling and analysis is established but slow.

Adverse effects: biochar costs are locally specific, affected by factors such as biomass feedstock prices; costs of collection and handling; transportation energy used; and effective pyrolysis control. Once emplaced into soil, large biochar fragments could be harvested for use as fuel, thereby rendering any benefits void. There are no known negative health impacts from carbonised dust, or mobilisation of volatiles in the soil. Exposure of biochar at the soil surface will reduce albedo, potentially by 13–22% at steady state in the year after application.[48,49] If biochar is applied annually, then large albedo reduction could continue before reaching steady-state.

8.3 Biomass Energy with Carbon Capture and Storage (BECCS)

Essential features: biomass can be combusted to produce heat and power utilising non-fossil carbon. Biomass is currently co-fired in small quantities with fossil coal or lignite, providing about 3% energy input (biomass ranges between 30–80% of the energy density of steam coal.[50] About 1.55% of global electricity was from biomass in 2010.[50] If capture and storage is undertaken on the combined flue gas, then that results in net extraction of carbon from the ambient atmosphere into deep geological burial.[10] Offset against that needs to be a full life-cycle analysis of energy and fertilizer used in planting, maintenance, harvesting and transport, which reduce many of the claimed benefits. Co-firing also introduces problems, such as greater variation of impurities, less concentrated CO_2 in flue gas, variable burn in oxyfiring[51] and disposal of fibres and tar during gasification.

Similar extraction by biomass indirectly from the atmosphere can result if the pure CO_2 waste stream is captured from ethanol production by fermentation, and disposed into a deep geological reservoir. The leading example of this process is the plant of ADM at Decatur, Illinois, USA.[52] A simple calculation of project cost *versus* tonnage stored, shows that this produces a cost of around \$60–70 t^{-1} CO_2. About 85 billion litres of ethanol are produced annually worldwide, which co-produces 68 Mt CO_2.

Finally, bio-methane can be produced by anaerobic digestion, and is added into the gas grid or co-fired in gas power plant as carbon-neutral fuel – where CCS may, eventually, be undertaken.

Potential impact and security: there are three main problems which reduce deployment of bio-ethanol and biomass power. These are biomass availability and sustainability, availability of CO_2 storage, and conversion of legacy infrastructure.[53] The potential of BECCS is estimated at 2.5–10 Gt CO_2 yr^{-1}. The larger estimates include considerable conversion of agricultural land to production of feedstock.[54] The security of long-term storage is identical to that for CCS, *i.e.* permanent CO_2 removal in climate terms.

Costs of operation: estimates vary greatly, because of different assumptions of the value of electricity, or transport fuel, combined with potential cost reductions through improved CCS. Storing CO_2 as a by-product of ethanol is expected to represent the lowest cost, like at the Decatur plant,[52,54] less than the cost of capturing CO_2 from co-fired biomass. Estimates for BECCS at \$100 t^{-1} CO_2 are considered too optimistic,[55] because they are less than the projected costs of CCS with fossil fuel.[56]

Effort needed: BECCS is a continual and intensive resource process, to gain reliable and regular feedstock supply. As with CCS, the capture process and CO_2 compression before transport devour a large proportion of the stated energy input. Regional transport networks from capture to storage would ideally augment or inherit conventional CCS pipelines.

Adverse effects: as with any biomass technology, to have a large impact, this will confront the competition for land-use between energy, food and water. Even though conventional CCS has societal acceptance in most parts of Europe, the industrial aspects of BECCS, and association with coal fueled power plant may reduce its acceptability.

Figure 3 compares commercially available fossil fuel reserves (gigatonnes (Gt) CO_2) with the potential options for CO_2 storage (Gt CO_2) which are ranked by timescales of isolation from the atmosphere. To enable recovery of the planetary climate system, timescales of at least 10 000 years are required, shown by climate models and by the geological record of recovery from past high CO_2 excursions. Differential shading of columns indicates the high and low estimates. Only if estimates of fossil fuel commercial reserves are low is there any possibility to balance with the highest estimates of the CO_2 storage available. That is unlikely. Furthermore, commercially cited reserves of fossil hydrocarbon are expected to be about 10 to 100 times less than the commercially ill-defined natural resource of fossil carbon available.

8.4 Biomass Burial, Carbon Dioxide Use and Algal Carbon Dioxide Capture

Essential features: a simple method of carbon stock storage, is to bury biomass. Normal human operations introduce waste biomass organic material, such as crop waste, manure, or compost, into agricultural land. This could potentially reach 2 Gt CO_2 yr^{-1},[57] however, carbon residence time is extremely short, only years. In agriculture, changed management practices may enable additional carbon to be stored in soil, for example by no till ploughing which reduces carbon loss through oxidation.[57]

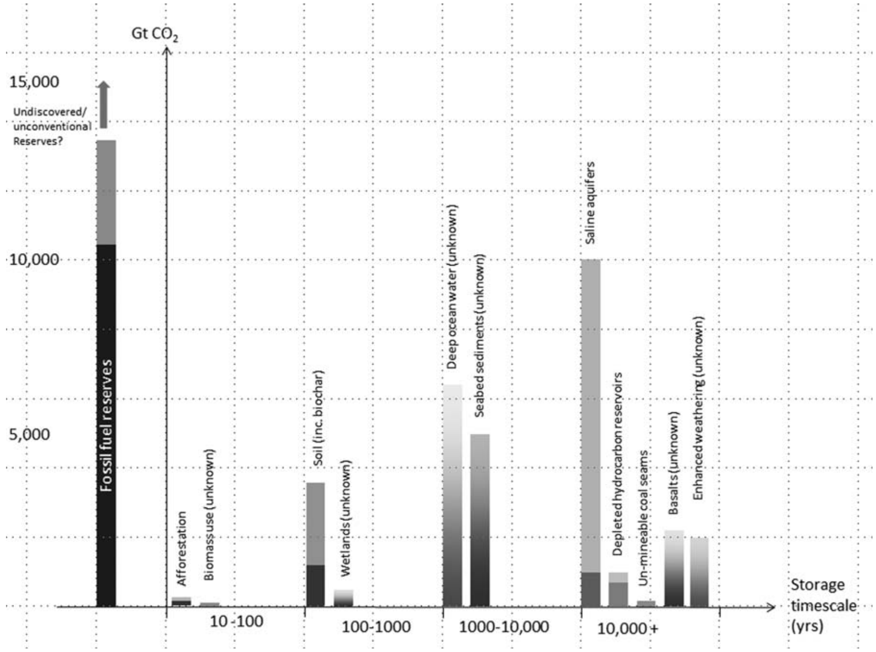

Figure 3 Diagram showing a comparison of commercially available fossil fuel reserves (gigatonnes (Gt) CO_2) and the potential options for CO_2 storage (Gt CO_2) which are ranked by timescales of isolation from the atmosphere.

As a scale-up of this principle it is proposed that biomass could be buried in the deep ocean,[58] where residence time may be hundreds to thousands of years. Especially slow decay may occur where some parts of the Antarctic Ocean may be isolated, for thousands of years, from wood decay organisms.[59]

Another step to industrialising the use of biomass to capture CO_2 and fix carbon is the active development of algae in bioreactors and the adaptation of enzymes as organic catalysts for air capture. The energetic feasibility, costs, and size scale of impact remain poorly known.[60–62]

The use of biomass is well established in construction, predominantly with timber use in houses, but also with potential for installation utilising straw. This will decrease the use of cement, offsetting emissions during its manufacture, but the overall potential is fairly small.[63]

8.5 Direct Air Capture

Essential features: the engineering of direct air capture carbon dioxide reduction is applied to the extraction of CO_2 from ambient atmosphere, with concentration and permanent storage of the captured CO_2. A large field of aspirational technology inventors exists, with the leading 10 promoted through media such as the Virgin Earth challenge,[64] competing for a

$25 million prize. Because of the immensely large commercial potential, precise details of the technologies are hard to obtain.

Processes: widely publicised approaches are: (i) adsorption onto solids, or (ii) absorption into high alkalinity solutions. All methods face three fundamental challenges: (i) overcoming the large thermodynamic barrier (theoretically 500 MJ $tonne^{-1}$ CO_2). This makes the proposed reactions almost impossible to conceive in isolation. The energy barrier is high because of the low CO_2 concentration in air (0.04%);[65] (ii) supplying and sustaining sufficient airflow and immense air volumes through the system using minimal energy to contact with the active surfaces; and (iii) supplying energy to regenerate the active reagents, to compress the CO_2 before pipeline transport and to inject to deep storage. Examples of three of the leading contenders are methods proposed by Global Thermostat, Klaus Lackner and David Keith. Global Thermostat seeks to use amine coated cellular solids to absorb CO_2 directly from air. Amine is regenerated using low-grade process heat associated with power plants or refineries.[66] Thus, successful operation of this technology is intimately dependent on the fossil fuel combustion it seeks to offset. Alternatively, the method proposed by Klaus Lackner[67] involves nonproprietary amine based resins that can capture CO_2 from ambient air movement, and CO_2 is released by hydration under reduced pressure.[68,69] In spite of detailed laboratory measurements, the energetics of these proposals remain intensely contested.[65,72,73] The third method, proposed by David Keith,[70] adapts a well-established circular chemistry method from paper manufacture. Carbon dioxide is absorbed under forced air fan flow by contacting potassium hydroxide which is converted to potassium carbonate. The potassium is regenerated to hydroxide, by reaction with sodium hydroxide, and the resulting sodium carbonate is regenerated by a calcination reaction heating to 900 °C by burning additional methane to release the dissolved CO_2. All emissions, including CO_2 gas heating, are captured within the system.[71]

Costs and feasibility: all these methods are currently in their experimental or small pilot stage. Carbon engineering is progressing most rapidly. The estimation of cost varies greatly, and is intensely contested. Developers claim anything between $90 per tonne CO_2, and $200 per tonne for pilot plant, with expectation of cost reductions at a larger scale.[73] External estimates are always much higher, based on costs of equipment or on fundamentals of thermodynamics; these range from $600 per tonne minimum,[72] to upwards of $1000 per tonne CO_2.[73]

Deployment, adverse effects: the scale of deployment remains unknown. If air capture can work reliably and economically, it is possible that one to 2 gigatonnes CO_2 per year could be extracted. It is equally possible that such development will drive these technologies towards flue gas as a rich source of CO_2 which may restrict air capture into niche markets, including (ironically) the potentially profitable proposition to make CO_2 on site for enhanced oil recovery. Envisaging scale up to impact on atmospheric CO_2 concentrations requires a large leap of faith.[72] Calculation suggests that offsetting CO_2 emissions of the UK by air capture will require tens of thousands of installations around the UK, each sized similarly to the cooling tower of a conventional coal fuelled power plant. The visual impacts will make onshore wind power seem benign.

Air capture approaches could also be applied to other greenhouse gases, for example it is claimed that methane might be commercially extracted from ambient air.[74]

8.6 Silicate Weathering

Essential features: in the natural climate system, weathering of silicates by reaction with atmospheric CO_2 is an important drawdown to maintain climate equilibrium. In the perturbed human system at the present day the natural rate of weathering is about 1% of the rate of CO_2 emission. Enhancement of weathering can be achieved by increasing the surface area of reactive minerals in contact with the atmosphere or ocean. This could be achieved by grinding minerals to smaller particle size and then distributing on land or at sea – or by adding reactive minerals to naturally abrasive settings such as beaches. Two main styles are usually considered, the dispersal of silicate olivine across land,[75,76] or replacement of carbonates in cement by using Mg oxides or silicates or fly ash.[77]

Engineering feasibility: the relevant reactive minerals are abundant in some parts of Earth's surface, for example olivine can be quarried from large parts of Oman. Basic chemical reactions suggests that one tonne of olivine is required to sequester 1 tonne of CO_2. Consequently enhanced weathering methods all require extraction and crushing of rock volumes which are similar in tonnage to those involved in the extraction of fossil fuels. To replace all carbon emitted from cement production, would remove about 5% of human emissions, about 2.5 gigatonnes CO_2 per year, but only 20% of this is considered to be accessible through commercially feasible processes.[78]

Costs: extraction of bulk materials is a low-cost operation, typically \$3–\$7 per tonne. Landscape remediation, transportation costs, and distribution costs also need to be considered and could double that estimate. Nonetheless this appears to be a low-cost option. Although some reactions look attractive on paper, for example replacing carbonate in cement with magnesium silicates removes 0.6 t CO_2 per tonne cement,[77] the immense tonnages of magnesium silicate may only be readily accessible in some parts of China for example – producing much larger costs of transportation.

Adverse effects: although the fundamental reaction of olivine weathering may absorb CO_2, the reaction products run off ultimately to the ocean to create alkaline compounds which, under large scale rapid deployment, would lead to unknown changes of ocean chemistry. The creation of an immense quarrying industry at the land surface, to balance subsurface extraction of coal oil and gas, would utilise land area perhaps four times the extent of coal strip mining.

8.7 Chemical Feedstock

Essential features: there is a burgeoning industry in developing green chemistry which can utilise CO_2 as a reagent.[79] The products include various categories of compounds: fuels, polymers, carbonates, carboxylates, as well as direct bulk applications such as solvents in enhanced recovery, or solvents or growth enhancers in the food industry. The generic problem, of course, is that CO_2 is a molecule of low chemical potential energy, with a Gibbs free energy value that is very negative ($\Delta G = -400$ kJ mol^{-1}), and is difficult to react. Current approaches include: using catalytic methods which utilise hydrogen; harvesting wasted or sustainable energy to drive the reactions; or coupling CO_2 consuming reactions with very exothermic parallel reactions.

Costs feasibility: costs are poorly constrained, and depend closely on the particular reaction undertaken and its method of operation. As with many chemical processes it is perfectly possible to obtain a suite of minor reaction products, the problem being to control side reactions and most of all to increase yield in an energy effective process.

Security of retention and effort: many of the compounds produced have only a short lifespan of human usage until they are recycled into the atmosphere. For example, urea as a bulk chemical can be used in fertiliser, but is then released to atmosphere within months or years – much too short to be of significant impact as a carbon storage method. Consequently the manufacture of chemicals would need to be a continuous effort in drawing down CO_2. A real problem though, is that of scale. Compared to the quantity of CO_2 released from human combustion of fossil fuels, the CO_2 tonnage utilised for chemical products is only a few percent. As a very optimistic example, in 2012 the entire EU27 demand for CO_2 as a feedstock of 235 M tonnes is exceeded by CO_2 output from industrial processes alone (300 M tonnes CO_2).[79] This does not consider the emissions from power and heat generation, so that CO_2 utilisation may at most use 10–20% of emissions. Although chemicals containing CO_2 can provide a high-value income stream to a capture project, the market is easily saturated in commercial terms – especially locally. One example is salicylic acid.[80] Just 60 tonnes day^{-1} of CO_2 from a gas power plant slipstream, can manufacture the global demand. Thus, CO_2 as a chemical feedstock has potential uses in engaging with industries and communities, but it needs a market to be created for its products and/or to find an energetically suitable way of re-making fuels which recycle carbon from emitted CO_2.

8.8 Carbon Dioxide for Enhanced Oil Recovery (CO2-EOR)

Essential features: in North America and China, the processes of carbon capture and storage are usually discussed as "carbon capture utilisation and storage". This utilisation proposes that a large part of CO_2 captured from power plant and industry should be transported for injection into partially depleted hydrocarbon fields. Carbon dioxide enhanced oil recovery

(CO2-EOR) has been undertaken in the USA since the SACROC Texas project commenced in 1972. At cool temperatures and low pressures, the CO_2 fluid can act to re-pressurise the hydrocarbon field and physically drive out additional hydrocarbon production. The CO_2 fluid is even more effective at higher temperatures and elevated pressures, however, as it becomes fully miscible with the hydrocarbons and acts to decrease surface tension. This can enable production of an additional 5 to 20% of the original oil in place. If commercial restraints did not feature, and extended timescales are available, then it is possible in principle that CO_2 injection could move towards production of 100% of the original oil in place. This process is often advocated as a beneficial, sustainable, and economically valuable utilisation of CO_2, which results in net storage in depleted hydrocarbon fields. Between 44 and 84 billion barrels of additional oil are calculated to be producible in the onshore USA alone using CO2-EOR.[79] However, there seems to be a clear arithmetic bear-trap in the life-cycle analysis, being that large quantities of additional hydrocarbon are produced which could counterbalance the CO_2 stored. Convention in the USA has it that any produced hydrocarbon ‘‘does not count’’ as an emission for climate budgeting purposes of a project. Whereas in Europe, the convention is that any production of hydrocarbon counts as an emission for climate purposes, even if not counted for trading scheme purposes until combusted. In established CO2-EOR in the USA, about 160–300 kg of CO_2 are used to produce 1 barrel of oil, which emits 430 kg CO2 on combustion.[80] Clearly more carbon is produced than is stored. However, the picture is complicated by the economic fact that CO_2 to undertake EOR in the USA costs money, paid by the oilfield operators. Therefore a commercially profitable operation requires minimisation of CO_2 purchase and use. The market system, as it currently exists, does not place a levy on carbon emitted or repay value to carbon recovered and stored. By contrast using CO_2 for the purposes of sequestration may promote additional CO_2 storage, but only if the CO_2 has a disposal value attached. It is possible to re-design CO_2 injection for EOR, such that an overall storage of carbon is the result.[81] A combination of credit for CO_2 disposal plus enforcing environmental legislation will be required to ensure that CO2-EOR is environmentally beneficial, rather than adding even more emissions to an acute problem.

8.9 Deep Sea Sediments

Essential features: although there is much discussion of enhancing CO_2 accumulation in shallow ocean water, and dispersal into deep ocean water, there has been little investigation of utilising vast areas of sediments along the continental margins and the deep ocean. One theoretical possibility is to inject CO_2 into sediments deeper than 3000 metres water depth and underlying several hundred metres of sediment column. This combines the useful effects of geological storage, combined with large volumes of ocean storage, and suitable geochemistry.[25] When CO_2 is injected into the ocean deeper than 3000 m it sinks due to density. The overlying pore fluid forms a less dense cap to prevent buoyancy migration. This zone is also below the pressure temperature conditions for CO_2 hydrate formation, ensuring a second category of seal. Carbon dioxide that is injected beneath this zone gradually dissolves into ambient pore water and becomes denser, and sinks.[25,26]

Cost, feasibility: no costs are available for this method. Costs are likely to be high. CO_2 needs to be transported offshore by tanker, because injection sites will need to be laterally extensive. Advanced drill ships will be needed to hold the drill riser static whilst injection occurs. Physical conditions of the target sediments may not be helpful, due to small grain size and intrinsically poor permeability, leading to bad injection rates.

Tonnage: as suitable sediments are widespread on all Atlantic type continental margins, the potential storage volumes are extremely large – greater than 2000 years of current USA CO_2 production.

9 Discussion

It is clear that many and diverse opportunities for storing carbon exist (see Table 1). However the practical difficulties of re-capturing feral fossil carbon are immense. The experience of CCS is salutary.[82,83] Since the mid 1990's the ambition to develop CCS has been expressed by the governments of many industrial countries. However, even working within the present electricity generation system, the conversion from "established" to "clean" methods of operating has stalled, to run at only 10% of the build rate required to achieve climate sustainability. There are regulations to draft; territorial claims to make; regulators to create; licensing allocations to decide; pipelines to convert or build; expensive injection boreholes to drill; and monitoring and verification to enact. And that is all before tackling "who pays". So, by the mid 2010's, not a single UK project has been built, and only a small handful are operating globally. Slow, tortuous progress is normal, even for a technology which is conceptually easy to understand and is highly favoured by governments. What is the chance, then, that innovations such as biochar, or soil recarbonisation, will progress any faster? The message from other innovative technologies is clear: establishing acceptability can take 15 years from university to industry then scale-up of deployment usually takes a long time – several decades. Exceptions exist and are usually framed as responses to crises, emergencies, or wartime.

A fundamental blockage exists with money. Who pays for the common good is not politically a vote winning formula. There are different ways of analyzing this problem. On one hand, the UK claims only 2% of global emissions (although the embedded emissions in imports are roughly double that, and the UK stock market influences an additional 25% of global GHG production). On the other hand, the UK, being first to industrialise, has accumulated a historic debt of carbon emission, which places UK citizens

Table 1 Summary of CDR methods.

CDR method	*Description*	*Estimated potential (Gt CO_2 yr^{-1})*	*Estimated cumulative potential (Gt CO_2)*	*Residence time of removed CO_2 (years)*	*Vulnerability of removed CO_2*[a]	*Abatement measurement*
Biomass based processes						
Afforestation	Increasing forest cover	1.5–3	300–500 (ref. 69)	$10–10^2$	High	Complex but in development for *e.g.* REDD
Wetland enhancement	Increasing peat land C uptake	<0.5	unknown	$10–10^3$	High	Difficult: C fraction retention and time period subject to many factors
Biochar	Charred biomass with high stable C fraction dug into soils or buried	<3.5	500	$10–10^3$	Med	Difficult: C fraction retention and time period subject to many factors
BECCS – ethanol	Biomass fermentation with CCS	<2 (unknown)	unknown	$>10^5$	Low (if geological)	Measurable
BECCS – electricity generation	Biomass burning with CCS	2.5–5	350 (ref. 70)	$>10^5$	Low (if geological)	Measureable
Biomass burial	Burial of waste or purpose biomass	<2	unknown	$1–10^2$	Med	Difficult: C fraction retention and time period subject to many factors
Biomass use	Biomass in construction	<1	unknown	$10–10^2$	Med	Measureable
Algae	Air or flue-gas capture with CO2 storage or biofuel creation	unknown	unknown	$>10^5$ (if geological storage)	Low (if geological)	Measureable
Chemical processes						
Direct Air Capture – solid adsorption	Artificial trees	unknown	unknown	$>10^5$ (if geological storage)	Low (if geological)	Measureable
Direct Air Capture – alkaline solutions	Adsorption by sodium hydroxide	unknown	unknown	$>10^5$ (if geological storage)	Low (if geological)	Measureable

Estimated cost $\$\ t^{-1}\ CO_2$[b]	*Resource requirement*[c]	*Primary limitations*	*Control-reversibility: low, med, high*[d]	*Deployment speed (years)*	*Technology readiness level (1–9)*[e]	*Side effects and impacts*	*Research challenges*
\$20–100	LA***** NR*** MR* EI* LS**	Land-use competition	High-high	$>10^1$	6–7	Albedo change, hydrological effect, societal landscape use change	
\$20+	LA*** NR*** MR* EI* LS**	Land-use competition and water	High-high	$>10^1$	5	Land-use competition, possible CH_4 emissions, Ecosystem benefits.	
\$30–40	LA**** NR***** MR** EI* LS***	Biomass availability	High-low	$>10^1$	5	Land-use competition, Improved soil fertility, possible carcinogenic dust, albedo change	
\$25+ (unknown)	LA**** NR***** MR*** EI** LS****	Biomass availability	High-med	$>10^1$	6	Land use competition, water demand	
\$100–200	LA**** NR***** MR*** EI* LS****	Biomass availability, CO_2 storage availability	High-med	$>10^1$	4–5	Land use competition, water demand	
Unknown (low)	LA*** NR***** MR* EI* LS**	Biomass availability, suitable land	High-unknown	10^1	4–5	Local environmental change	
Unknown (low)	LA**** NR***** MR* EI* LS***	Demand	High-med	10^1	7–9	Societal	
unknown	LA*** NR*** MR*** EI** LS****	Nutrient	High-high	unknown	2–5	unknown	
\$100–500+ (unknown)	LA*** NR* MR**** EI**** LS****	Land area, CO_2 storage availability, energy	High-high	unknown	2–4	Land-use	
\$100–500+ (unknown)	LA*** NR* MR**** EI***** LS****	Land area, CO_2 storage availability, energy	High-high	unknown	2–4	Land-use	

Table 1 Continued.

CDR method	*Description*	*Estimated potential (Gt CO_2 yr^{-1})*	*Estimated cumulative potential (Gt CO_2)*	*Residence time of removed CO_2 (years)*	*Vulnerability of removed CO_2*[a]	*Abatement measurement*
Accelerated weathering	Pulverised silicate dispersal	0.1–3.5	400	$>10^5$	Low	Complex
Magnesium oxide cement	Negative emissions cement	<0.5	unknown	10^2–10^3	Med	Measurable

[a] The vulnerability of the removed CO_2 is ranked: high, medium and low, with respect to possible future climatic, environmental or societal impacts. Afforestation is ranked has ‘high’ as it may be subject to drought, disease or changed societal demand. Geological CO_2 (appropriately sealed) by contrast is ranked ‘low’.

[b] Cost estimates are highly subjective and are to a large extent based on current costs of resources and materials that may not remain valid.

[c] Resource demands are qualitatively assessed on a scale of * to ***** (highest) according to following categories: LA: land area; NR: natural resource demand (*e.g.* water, biomass, mined substance); MR: manufactured resource (*e.g.* steel, synthetic chemicals); EI: energy input (net); and LS: logistical scale (distribution, transportation).

amongst the most polluting global nations per capita – and it could be suggested that the UK should now, immediately, devote several percent GDP into cleaning up its historic legacy of carbon emission on which most of its present wealth is founded. Who pays to scrub CO_2 from the common global air is the type of question on which it is particularly difficult to convince sceptical voters.

The climate calculator is clear. To avoid the 2 °C rise in average sea and land temperature predicted by climate modeling requires actions to drastically cut emissions, and then to keep within a budget of total carbon emissions.[5] That budget, of one trillion tonnes of carbon, expires in February 2044 if humans persist in their established behaviour. So a combined approach is needed to enforce a reduction in emissions rates, combined with a firm cap.

So, what happens to the basic arithmetic? We know the total carbon per year emitted. We also know the total commercially exploitable carbon in economic reserves, and in the technically potential resources. And, from the analysis undertaken in this paper, we can estimate the total carbon storage resource. The numbers do not match. Our known resource of combustible carbon is far greater than the immediate storage ability.

That means changes, for example, the development of energy storage batteries which could store energy for a day, or even a week, as well as an improved understanding of how to reduce rebound behaviour where CO_2 savings in one sector may sometimes be transferred and expended in a different sector. This leads to the perennial Jevons paradox,[84] which suggests

Estimated cost $\$\ t^{-1}$ CO_2[b]	*Resource requirement*[c]	*Primary limitations*	*Control-reversibility: low, med, high*[d]	*Deployment speed (years)*	*Technology readiness level (1–9)*[e]	*Side effects and impacts*	*Research challenges*
\$25 + (unknown)	LA*** NR**** MR*** EI*** LS*****	Logistics of application	High-low	unknown	2–3	pH increase of land	
unknown	LA* NR**** MR** EI*** LS***	Demand	High-med	unknown	2–4	Mining of Mg	

[d] Controllability and reversibility are ranked: high, medium and low. Since afforestation can be ceased and felled, it is ranked 'high' both for control and reversibility.

[e] The stage of technology development is assessed on a scale of 1–9: 1 (scientific principle identified) to > 9 (proven and deployed system).[71]

that if energy efficiency increases, then energy consumption also increases. However, there are more specific studies which show that Jevons "rebound" does not always form a paradox, especially if the price, or other rationing, of energy increases at the same time as efficiency increases.

For the global carbon budget, there are several ways to react to the unfortunate mismatch. You can pretend nothing is wrong and carry on as before. You can make encouraging noises, then develop and deploy CCS and CDR components enroute to a real operation.[83] Or, you can mediate a rapid transfer across to low carbon emissions, which ultimately means getting out of fossil carbon utilisation as the main basis for energy supply. The latter would require a fundamental change to the behaviour of industrial societies, where taxing the dis-benefits of fossil carbon for a reduction in its use has never been on the agenda. Nevertheless, the evidence in this analysis suggests that sustainable carbon dioxide reduction or stabilisation can not be achieved by replacing continuing, or historical (from air), emissions of carbon into the ground. Leaving fossil carbon in the ground, unburned, is today a radical statement, but this may yet become the least expensive, and lowest risk, option.

10 Conclusions

1) Many methods of carbon dioxide reduction (CDR) exist (see Table 1). All of these have significant uncertainty in their global potential and poorly constrained costs.

2) All methods of CDR will require global industries to arise and deploy new logistical systems. Previous examples of industrial step changes have taken many years from invention to industrialisation, and several decades to full-scale deployment. CDR will not be rapid.
3) Rational life-cycle analysis of CDR methods has not usually been undertaken, based on carbon, energy, or resources.
4) The different CDR methods are sometimes in conflict, particularly for a finite supply of biomass, where rival uses include food production and long-term ecosystem maintenance.
5) Even though CO_2 storage capacities of all methods are very uncertain, it is clear that CDR alone is very unlikely to achieve net reduction of atmospheric carbon, because CDR cannot balance the projected release rate of fossil carbon, even with all standard mitigation efforts and fuel switching included.
6) Leaving fossil carbon in the ground, unburned, is the best option for humanity to move beyond hydrocarbon for long-term sustainability. To make this transition, new and competitively costed energy sources need to develop, and older carbon emitting activities need to be penalized. Both of those need courage by governments, which can arise from leadership, or from pressure by citizens.

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