

# **Briefing Paper on Proposed Greenhouse Gas Removal Techniques for the Global Calculator Project**

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## **Executive Summary**

This paper lays out information about proposed technologies to remove greenhouse gases from the atmosphere in the context of the Global Calculator Project<sup>1</sup>. These have been posited as a means by which it may be possible to avoid global mean temperature rises exceeding the 2°C threshold of “dangerous” climate change. Indeed such proposed technologies are already assumed in IPCC scenarios that avoid this threshold and are also assumed within policy pronouncements by senior UNFCCC figures (“Global greenhouse gas emissions need to peak this decade, and get to zero net emissions by the second half of this century” Christiana Figueres (Executive Secretary of UNFCCC, 8 November 2013)). But as is made clear in the UNEP Emissions Gap Report (2012) “To achieve such negative emissions is simple in analytical models but in real life implies a need to apply new and often unproven technologies or technology combinations at significant scale”(p3).

## **Structure of this paper**

This briefing paper<sup>2</sup> provides a brief summary of seven categories of proposed Greenhouse Gas Removal (GGR) techniques - five categories of techniques to remove carbon dioxide from the atmosphere – biochar, ocean fertilisation, enhanced weathering – terrestrial, enhanced weathering – oceanic and direct air capture – one category of techniques to remove other greenhouse gases and one category that considers combinations of the preceding techniques. These summaries will explain what the proposed techniques are, what constraints such techniques face and what the current state of development of these techniques is. Excluded from this briefing paper are sections on afforestation, BECCS and land use management, which while also proposed methods of removing carbon dioxide from the atmosphere are covered elsewhere in the Global Carbon Calculator Project. The paper concludes with suggestions for further reading.

Before we summarise the proposed techniques, it is important to reflect on the validity of the analysis in this space. In an area such as this, there is a great desire to characterise in numbers the range of techniques so as to try to gain an understanding of the relative ranking of the proposed techniques and the overall potential of the basket of such

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<sup>1</sup> The Global Calculator Project is led by the UK Department of Energy and Climate Change (DECC), and co-funded by the EIT Climate-KIC, involving a number of partner institutions worldwide. Imperial College London is responsible for modelling the Land, Food and Bioenergy Sector, and the GGR approach, which was prepared in collaboration with the University of Oxford. See more at: [www.globalcalculator.org](http://www.globalcalculator.org)

<sup>2</sup> This paper was originally prepared for the Global Calculator’s Workshop on Greenhouse Gas Removals hosted by Imperial College London on 10<sup>th</sup> Feb 2014, as described in the workshop notes. The current version includes minor updates by 11<sup>th</sup> July 2014, as a supporting document to the Global Calculator’s webtool.

techniques. Experts are sought to conduct analysis and lend insight into a complicated space and to deliver quantifiable answers. An expert called upon to provide such answers who arrives at the conclusion that no meaningful quantification can be made will often find their conclusion dismissed if another, perhaps less conservative though no more proficient expert, delivers numbers, regardless of the validity of those numbers. A parallel example would be to ask a pollster to predict the outcome of a national election based on a survey of three voters. Sometimes the answer “I don’t know” is more valid than an answer professing knowledge.

Much of the analysis to date has focused on the purely technical aspects of deployability – addressing the question “what are the physical limitations of these proposed techniques?” For techniques that involve the use of land-based photosynthesis (afforestation, biochar, BECCS and land use management) there is a clear physical constraint – land area – while for others there is no such physical constraint (direct air capture and enhanced weathering – oceanic). This can lead to two contrasting risks – either those techniques that are constrained are downplayed relative to the unconstrained techniques, or constraints on those previously unconstrained techniques are developed to avoid such an analytical skew.

The focus on what a particular technique can physically deliver in terms of removing greenhouse gases from the atmosphere is misplaced – it needs to be recognised that the scale and rate of deployability requires a socio-techno-economic analysis. This is extremely complex and often in order to arrive at a conclusion, the simpler technical analysis is performed, with the hope and expectation that this will provide an adequate proxy on which to base policy decisions. A counter-example can reveal why this can be extremely misleading:

If the question was asked as to how the UK could cut emissions of greenhouse gas emissions by 20% in a year, then a technical-only analysis might identify that shutting down a large number of power stations could achieve this aim. Technically it is easy to achieve this, but the results of such a course of action would be widespread power cuts which would be disastrous in terms of human welfare, the economy and social order. The (correct) analysis of it being technically possible does not determine whether it would be deployable in the real world.

That is not to say that we could not at some later date, with further research, arrive at a valid conclusion, just that the level of information that we possess at the moment is such that we cannot profess any confidence in such projections and to do so would be misleading.

Discussion about such technologies is characterised by ignorance (a lack of basic information from which to draw meaningful conclusions), uncertainty (a lack of clarity as to how deployable such techniques may be), narrowness (many of the assessments of such techniques focus exclusively or preponderantly on the technical aspects and show little

regard for the broader societal interactions and governance challenges), inconsistent assessment bases (the different assumptions used in different assessments debases comparison), proponent bias (many estimates emanate from those involved in developing a particular proposed technique), hype (some analyses make unsupported claims as to the efficacy of particular proposed processes) and pessimism (some analyses preclude consideration of any technological advances beyond what is already well understood and thereby limit the role such techniques may play).

They are also characterised by necessity. Projections indicate that the large-scale deployment of such negative emissions technologies may be necessary in order to avoid a 2°C rise in global mean temperatures and as that is the threshold that has been set by policymakers, then it is necessary to develop analysis of such techniques. In a subversion of the well-known adage “Necessity is the mother of invention” we are not inventing the technology – we are simply inventing the numbers. Therefore, the GGR levers in the Global Calculator Project simply present a large range of speculative trajectories<sup>3</sup> by 2050 in order to illustrate the potential impacts of negative emissions technologies on the global CO<sub>2</sub> concentration. Thus, this approach should not be used as a reference for policymaking or business decisions, given the current uncertainties and potential risks associated with these technologies.

## **Direct Air Capture**

### **What it is:**

Direct Air Capture (DAC) involves using chemical processes to directly capture carbon dioxide from ambient air. Typically this will involve using an alkaline material (such as sodium hydroxide) which reacts with carbon dioxide or a material which adsorbs the carbon dioxide. Further treatment will release the carbon dioxide in pure form and will regenerate the sorbent for repeated use. The pure carbon dioxide is then ready for geological sequestration. The process results in carbon dioxide being transferred from the atmosphere – where it is causing climate change and ocean acidification – to long-term storage underground in suitable geological formations.

DAC differs from Carbon Capture and Storage (CCS) as DAC involves capturing carbon dioxide from ambient air (~0.04% concentration) while CCS involves capturing carbon dioxide from large stationary sources, such as power plants or cement plants (4-30% concentration). The back-end of both processes is the same – geological storage.

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<sup>3</sup> Adapted from Note 447 of the UK Parliamentary Office of Science and Technology – POST (2013), which is available at: <http://www.parliament.uk/business/publications/research/briefing-papers/POST-PN-447>

### **What the key constraints facing this technique are likely to be:**

- The amount of energy that is required to run such systems (any process that demixes carbon dioxide from the very dilute 0.04% present in ambient air to the >99% purity required for geological sequestration will require energy)
- The volume of air that needs to be treated. Given the low initial concentration of carbon dioxide in ambient air, it is necessary to treat 1.4 million cubic metres of air to remove a single tonne of carbon dioxide (assuming all carbon dioxide is stripped out in a single pass). These volumes indicate that the scale of the machinery is likely to be large with significant resource implications.
- Many, but not all, such techniques have a significant water requirement.
- It is unlikely, except for some niche markets, that DAC from ambient air is likely to be cost competitive with CCS, as the starting concentration of the carbon dioxide feedstock is so much lower. It would make economic sense to first exhaust all potential CCS opportunities before applying DAC. The exception to this analysis would be if large quantities of 'stranded energy' were available in locations close to geological storage sites – in those circumstances the increased energy and capital costs associated with extracting carbon dioxide from a lower concentration source could be counterbalanced by lower energy costs and lower sequestration costs.
- DAC will compete with geological storage space with CCS from large stationary plants.
- DAC will require a carbon price to be deployed on a large scale. There are some niche markets (for example using carbon dioxide for enhanced oil and gas recovery, or for developing jet fuels for aircraft carriers, where the alternative fuel supply comes with a high economic and strategic price), where a carbon price is not required, but a carbon price would be required for it to be deployed at a scale that would have a material impact on the atmospheric carbon dioxide concentration.

### **What is the state of development of this technique:**

- There are about a dozen proposed DAC technologies – not all of them in the public domain – which have been demonstrated at small scales. Technically the process works – it can be demonstrated that carbon dioxide can be removed from air in the way envisaged. Indeed, the removal of carbon dioxide from ambient air in submarines and spacecraft has been practised for decades. The real question is about the carbon balance of the systems (is more carbon dioxide emitted during the life-cycle of the technology than is removed by the process) and the economics. Analysis by American Physical Society indicates costs greater than USD600 per tonne of carbon dioxide removed (see further reading section). This is hotly contested by leading proponents who believe that a long-term cost goal of less than USD100 per tonne of carbon dioxide is achievable. In either case, this price is significantly higher than the current carbon price.

## **Ocean Fertilisation**

### **What it is:**

Ocean Fertilisation (OF) involves enhancing the biological capacity of the oceans to draw down more carbon dioxide from the atmosphere. Photosynthesising organisms incorporate carbon dioxide that originates in the atmosphere into themselves as they grow and multiply. Some of this carbon will eventually end up in the deep ocean where it will be effectively stored away from the atmosphere for a sufficiently long period of time that it no longer has an impact on the climate.

Some parts of the ocean are deficient in micronutrients such as iron, the absence of which limits the growth of photosynthesising organisms. By enhancing the iron level in those parts of the ocean, more photosynthesis can occur and more carbon can be transported from the atmosphere to the deep ocean.

### **What the key constraints facing this technique are likely to be:**

- OF is physically constrained by the area of ocean that is deficient in micronutrients and the effect that relieving that constraint would have on the net transfer of carbon from the atmosphere to the deep oceans. Once iron is no longer a constraint photosynthetic activity can increase up to the point that the next constraining factor limits growth – this is typically the availability of nitrate in ocean waters. Thus there is a finite potential increase in the photosynthetic capacity of the oceans.
- Some proponents of OF have suggested that it may be possible to boost macronutrients such as nitrate as a means of enhancing photosynthetic capacity. While that may be possible, the quantity of material that is required to boost photosynthesis by a given amount is far higher for macronutrients than for micronutrients and such an approach is dismissed by most assessments as being impractical.
- Serious environmental concerns have been raised about OF. The introduction of micronutrients into the ocean will alter the ecology of the oceans, favouring certain types of organisms at the expense of other organisms that thrive in low-iron waters. In addition, increased photosynthetic activity could lead to increased ocean acidification and a decrease in dissolved oxygen in the ocean.
- The efficacy of the process has been challenged. It is not sufficient for photosynthetic activity to increase – it is also necessary that carbon is transferred from the atmosphere to the deep ocean for the technique to have a positive impact on the climate. Some of the studies (see further reading section) show that a large fraction of the carbon removed from the atmosphere in the initial photosynthetic bloom is released back into the atmosphere as the algae die or enter the food chain, rather than transiting to the deep ocean.

- The governance issues relating to OF are complicated. Rules established by the London Convention/London Protocol (LC/LP) restrict activities to small-scale scientific experiments, while the Convention on Biological Diversity also seeks to restrict such activities.

**What is the state of development of this technique:**

- A small number of OF experiments have been undertaken – most with approval of national research establishments, but some without such approval. Those experiments that have been undertaken without approval have been highly controversial and have created a backlash against the technique as a whole.
- The results of the officially approved OF experiments have indicated, at least in some instances, that there has been net carbon drawdown, but there are still many unanswered questions as to the long-term effects of this technique on both carbon removal and ecological consequences.

**Enhanced Weathering – Oceanic**

**What it is:**

Enhanced Weathering – Oceanic (EW-O) seeks to enhance the chemical capacity of the oceans to draw down carbon dioxide, by the introduction of alkaline materials that increase the pH of the ocean and allow more carbon to be stored as Dissolved Inorganic Carbon (DIC) in the ocean.

Various proposed methods have been suggested to enhance ocean alkalinity – adding limestone (calcium carbonate), hydrated lime (calcium hydroxide) or finely ground olivine (magnesium silicate) or by electrolysis of seawater. These techniques differ widely in application, but all have the same net effect – enhancing the amount of DIC in the ocean.

**What the key constraints facing this technique are likely to be:**

- The addition of large quantities of alkaline material to the ocean is likely to perturb natural ecosystems. The increase in pH will favour those organisms that thrive at the perturbed level over those organisms that would thrive at the pre-existing level. This is a similar argument to the perturbation of OF, but differs in that the current pH is itself perturbed from historic norms, and so the addition of alkaline materials could be expected to restore the pH. What would not however be restored is the calcium and magnesium ion concentrations – these would increase (though very marginally).
- The process for obtaining alkaline materials is likely to be costly both in economic and energy terms. There are few naturally occurring deposits of alkaline materials that could be added to the ocean to have the intended effect, but it may be possible to manufacture such materials.

- To have a material impact on the concentration of carbon dioxide in the atmosphere would require a massive mining, mineral processing and distribution industry.
- The application of EW-O would involve perturbing a global commons which creates governance challenges. An amendment (currently in progress) to the LC/LP would permit small scale research activities, but deployment would require further amendments.

**What is the state of development of this technique:**

- EW-O has been studied in the laboratory and has been modelled, but it has not been researched in the open environment. The processes required to generate alkaline materials are well established and practised at an industrial scale, but the application of alkaline materials to the ocean has not been undertaken.
- The principles of how DIC behaves in the ocean in response to increased pH is well understood. What are not well understood – and cannot be established without experimentation – are the impacts on the environment – both positive and negative – of increasing ocean pH.

**Enhanced Weathering – Terrestrial**

**What it is:**

As minerals weather they absorb carbon dioxide. The natural weathering of silicate minerals results in the formation of carbonate minerals which acts to remove carbon dioxide from the atmosphere. These weathering reactions tend to occur very slowly and have a small beneficial impact on carbon dioxide levels in the atmosphere. Enhanced Weathering – Terrestrial (EW-T) seeks to accelerate this natural weathering process.

The main way in which it is proposed that weathering can be accelerated is by grinding appropriate minerals (such as olivine (magnesium silicate)) into a fine dust which, due to the resultingly higher surface-area-to-volume ratio will react more quickly than they would naturally.

**What the key constraints facing this technique are likely to be:**

- The energy and cost requirements for grinding appropriate minerals sufficiently to enhance weathering are high.
- The particle size to which such minerals need to be ground to in order to enable a material increase in the rate of weathering is often (depending on the mineral) smaller than 10 microns in diameter - a size which can cause harm to health.
- There is an upper limit as to the amount of carbon dioxide that can be sequestered via this method. This is determined not by the reaction of the magnesium silicate in dilute carbonic acid (rainwater), but by the saturation state of silicic acid that is produced when the magnesium silicate reacts.

- The weathering of large quantities of ground olivine will lead to the introduction of trace metals present in the olivine, a change of pH and potentially changes to soil structure (which may be positive or negative). The places currently identified as most suitable for enhanced weathering (tropical areas that have high rainfall and high temperatures) are also some of the most important areas for biodiversity globally.
- While EW-T would occur on territory under the jurisdiction of individual states, runoff from EW-T could have transboundary effects by altering the pH of river systems and potentially enhancing the saturation state of silicic acid in coastal waters.

**What is the state of development of this technique:**

- EW-T has been studied in the laboratory and has been modelled, but it has had little research in the open environment. Proponents of EW-T have sold some ground olivine as a soil additive, whilst marketing it as a means of removing carbon dioxide from the atmosphere. Technical and theoretical modelling of the particle sizes indicate that while there would be some carbon dioxide drawdown, it is far less than has been claimed.

**Biochar**

**What it is:**

Heating biomass in an oxygen-deficient environment results in incomplete combustion and the production of a char, which has a high carbon content. If this char is buried then carbon in the char is sequestered away from the atmosphere. Plants, in growing, remove carbon dioxide from the atmosphere and the charring process transforms a proportion of the carbon in the biomass into a recalcitrant form which is resistant to being re-released back into the atmosphere.

The addition of biochar to soils can often have co-benefits in terms of enhancing soil quality and crop yields.

**What the key constraints facing this technique are likely to be:**

- The proportion of recalcitrant carbon in a biochar is a function of many factors: the biomass feedstock, the method of producing the biochar and the characteristics of the soil into which the biochar is placed. The longevity of the stored carbon is also a function of these factors.
- The availability of biomass to produce the biochar.
- Biochar dust poses a potential hazard to human health.
- The addition of biochar to soils alters the property of the soil. As previously mentioned, in many cases it can lead to enhanced crop yields, for example, due to changes in the soil cation-exchange capacity (CEC) and water retention. However, it



can also lead to increased production of methane, and cause impacts on the soil biological diversity.

- The addition of large amounts of biochar to soils may result in reduced albedo, thereby counteracting some of the benefit of removing carbon dioxide.
- If a land area into which biochar has been added is affected by fire (e.g. fire use as an agronomical practice, accidental fire, or even an increase of fire occurrences as a potential result of a warming climate), then the carbon stored may be released back into the atmosphere.

#### **What is the state of development of this technique:**

- Biochar is already routinely produced for use as charcoal and as a soil improver. As such, large-scale production is already practised. What is less well-established is the long-term characterisation of the behaviour of biochar as a means of storing carbon away from the atmosphere.

#### **Other Greenhouse Gases**

##### **What it is:**

The focus to date has been on proposed techniques which seek to remove carbon dioxide from the atmosphere as it is the predominant greenhouse gas. But there are moves to examine whether it may be possible to remove other greenhouse gases from the atmosphere (such as N<sub>2</sub>O, methane and tropospheric ozone) from the atmosphere.

At first sight, this looks improbable – the concentrations of these gases is measured in parts per billion – how are we meant to extract such gases when we struggle to remove carbon dioxide which is present at (only) parts per million? The answer lies in two properties of these trace greenhouse gases: firstly, it is not necessary to store these gases in the way that it is necessary to store carbon dioxide – the oxidation or decomposition of these gases is sufficient to remove their greenhouse forcing potential – and secondly, the oxidation or decomposition of these gases is thermodynamically favourable, so if appropriate catalysts are developed there is no requirement to provide energy. Compare this with capturing carbon dioxide, where the imperative to store the carbon dioxide necessitates the demixing of carbon dioxide from the very low concentration in ambient air, which requires the expenditure of energy.

##### **What the key constraints facing this technique are likely to be:**

- As previously mentioned, the low concentration of these gases in ambient air requires the processing of very large volumes of air to remove a set quantity of these gases. This places energy and cost burdens on such processes.
- Materials able to catalyse the oxidation and decomposition of these gases exist, but only at higher than ambient temperatures and concentrations. Conceptually, catalyst

that are activated by UV light would be able to operate at ambient conditions, but they have yet to be developed.

- Addressing other greenhouse gases will not solve the whole problem – at best it may provide one or two decades of ‘breathing space’ of a delay in temperature increases. Such a delay may be useful in developing adaptation measures or decarbonising the economy.

**What is the state of development of this technique:**

- Very early stage – conceptual work only

**Combinations of Techniques**

**What it is:**

Analysis of proposed techniques has tended to examine them in isolation and as a result overlapping constraints and synergies are often missed. For example, DAC, BECCS and CCS all share a common constraint with regard to geological storage of carbon dioxide, and Afforestation, BECCS, Biochar and Land Use Management are commonly constrained by photosynthetically active land area. Any examination of the overall potential of a basket of Greenhouse Gas Removal techniques must recognise such shared constraints. Other constraints shared by most proposed techniques include non-physical resources such as capital, political will and engineering expertise and physical resources such as steel, cement and shipping.

Synergies may exist between techniques – for example one proposed method of EW-O involves reacting a gas stream with 5% carbon dioxide with limestone and seawater. Such a concentration of carbon dioxide does not exist at ambient conditions, but can be derived from either an adapted DAC system or an adapted BECCS system. The cost of generating a pure carbon dioxide, suitable for geological sequestration, is avoided potentially increasing the economic viability of such a combination.

**What the key constraints facing this technique are likely to be:**

- Neither overlaps, nor synergies between techniques have been adequately assessed. This could lead to either significantly overestimating or underestimating the potential of a basket of greenhouse gas technologies.

**What is the state of development of this technique:**

- Very early stage – conceptual work only

## **Further Reading**

### **Reviews**

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