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Review

Engineering geo-engineering

Timothy A. Fox[a]* and Lee Chapman[b]
[a] *Institution of Mechanical Engineers, London, SW1H 9JJ, UK*
[b] *School of Geography, Earth and Environmental Science, University of Birmingham, Birmingham, B15 2TT, UK*

ABSTRACT: This paper reviews the geo-engineering approach to tackling climate change. The failure of the 15th United Nations Framework Convention on Climate Change Conference of the Parties (COP15) to obtain a legally binding emissions reduction agreement makes the deployment of geo-engineering solutions an increasingly attractive proposition. This review looks at a variety of global and local approaches to geo-engineering covering solar radiation management and carbon cycle engineering and attempts to assess the feasibility of the technologies from an engineering perspective. However, despite the plethora of ideas generated by the science community, it still appears that much work remains to be done in the initial engineering assessment of these techniques and this is a major hurdle to overcome before any geo-engineering scheme can be fully considered. Hence, the paper concludes by calling for the instigation of national and international programmes of research at the feasibility level, to inform discussions regarding future possible deployment of small scale, local geo-engineering and adaptation measures. Copyright © 2011 Royal Meteorological Society

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1. Introduction

Since 1988 there have been warnings from scientists documenting the consequences of anthropogenic global warming (Hansen, 1988) and, in particular, the rapid speed in which the climate is changing (Richardson *et al.*, 2009). The traditional response to offset this warming is by means of mitigation, in particular targeted policies and technologies designed specifically to reduce greenhouse gas emissions such as CO_2 ('decarbonization'). Indeed, the mitigation of climate change is now very much a science in its own right and detailed sector-specific guidelines exist and are under constant review (e.g. IPCC, 2007). However, despite international agreements such as the 1997 Kyoto Protocol, focused on reducing greenhouse gas emissions, society as a whole has largely been slow to respond and there is a need to look for alternative solutions (Boyd, 2008a). The failure to act on CO_2 emissions is a major concern. The long residence time of CO_2 in the atmosphere means that the warming being recorded today is actually the result of emissions accumulated over the last century (Penner *et al.*, 1999) and that the full impact of emissions today may not be realized for a further 50–100 years. For this reason, the planet is already committed to experiencing some degree of climate change during the course of the current century.

As a first step, the international community is presently focused on implementing measures which will limit global temperature rises to 2 °C. Whilst this is not ideal, it is hypothesized that this target should prevent the most dangerous effects of climate change (Meinshausen *et al.*, 2009). However, the failure of the 2009 UNFCCC conference in Copenhagen (COP15) to achieve a legally binding global emissions reduction agreement has added to growing concern that in reality the mitigation actions required to meet this target are ultimately unrealistic. It is predicted that the 2 °C threshold could be exceeded before 2050, with a total rise in global mean temperature relative to pre-industrial levels more likely to be somewhere between 4 and 6 °C by the end of this century (Watson, 2001; Anderson and Bows, 2008; Richardson *et al.*, 2009; IMechE, 2009a). The consequences of such an increase in temperature have been postulated to be a possible collapse in world agricultural systems, increased conflict for primary resources and widespread human displacement (Stern, 2006; Richardson *et al.*, 2009).

In order to prevent predicted dangerous climate change, there is a need to continue mitigation efforts focused on decarbonizing the global economy. However, as COP15 has shown, the reality of all developed and developing nations multilaterally moving forward to embrace new carbon reduction technologies in order to develop a new economy, no longer underpinned by fossil fuel usage, seems highly unlikely in the short to

* Correspondence to: Timothy A. Fox, Institution of Mechanical Engineers, 1 Birdcage Walk, London, SW1H 9JJ, UK.
E-mail: t_fox@imeche.org

medium term (IMechE, 2009b, 2009c). The world does not necessarily have time to wait for decarbonization over the longer term. Therefore, do technological or engineering solutions exist that can provide society with the additional time needed to mitigate against climate change before mean global temperature increase beyond the 2 °C target? Some scientists believe that geo-engineering may be the answer and the UK Institution of Mechanical Engineers has proposed that implementation of a number of the more practical approaches may buy the time required, whilst not distracting the world from the principle objective of mitigation (IMechE, 2009d). Geo-engineering approaches are conceptually straightforward and often rely on a series of physical, chemical or biological interventions. The Royal Society recently published a comprehensive report on scientific and technical aspects of geo-engineering with the aim of informing climate policy (Royal Society, 2009). In their report, the scientific team assessed in detail a range of geo-engineering approaches. The report culminates in an appraisal of the various schemes with respect to effectiveness, affordability, safety and timeliness. This paper aims to build on that document by reviewing and ranking the current range of interventions from an engineering viewpoint, to ascertain the feasibility of implementing the various schemes at an appropriate scale.

2. Planetary solar radiation management

Solar radiation management (SRM) seeks to reduce the impact of climate change by providing a quick solution which offsets the rate of global warming by changing the reflectivity of the Earth or preventing radiation from reaching the Earth's surface (Teller *et al*., 1997). A number of conceptual solutions have been proposed that fall into two main categories.

2.1. Spaceborne solar reflectors

Ambitious proposals have been made that involve physical interventions to reflect a fraction of incoming solar radiation back into space before it enters the Earth system, effectively shading the planet (Mautner, 1991; NAS, 1992). A variety of climate control measures have been proposed, ranging from the use of thousands of small mirrors (e.g. Angel, 2006), the creation of an artificial planetary ring of particles or parasols (Pearson *et al*., 2006), the positioning of a large rotating lens between the Sun and the Earth (Teller *et al*., 1997) to the encasing of the entire planet with a polyvalent structure (Cathcart and Ćirković, 2006). Calculations have shown that to offset a doubled pre-industrial atmospheric concentration of CO_2 would require an approximate 2% decrease in solar radiation input (Royal Society, 2009). It is estimated that such a reduction could be achieved by placing 3 million km^2 of 'sunshade' in orbit at the L1 Lagrange point (Royal Society, 2009). From an engineering perspective this would be an unprecedented undertaking and, certainly if based on current technology, difficult to envisage deployment at scale on the grounds of energy consumption and carbon emissions alone. For example, it has been estimated that even if such a sunshade were in place today, which was large enough to counteract current global emissions, it would require the addition of $\sim$31 000 km^2 of shade *per annum* to keep pace with emissions growth, possibly equating to around 136 000 delivery vehicle launches *per* year (Vaughan and Lenton, 2011). This figure would reduce as emissions are brought under control, but the number of launches required in the short to medium term seriously undermines the feasibility of such an approach.

2.2. Aerosols

An alternative, and potentially cheaper, approach works on the injection of particles into the stratosphere which will form into reflective aerosols (Boyd, 2008a). This approach was investigated by scientists motivated by the atmospheric impact of the 1991 Pinatubo volcanic eruption where the emission of sulphur particles into the stratosphere led to decrease in northern hemisphere temperatures of 0.5–0.6 °C and a global reduction of about 0.4 °C (Stenchikov *et al*., 1998; Crutzen, 2006). The subsequent sulphate aerosols scatter sunlight back into space and it has therefore been proposed that placing sulphur particles into the stratosphere might be a plausible geo-engineering approach. Suggestions for aerosol deployment include aircraft based schemes, aviation fuel additives, rockets, artillery, balloons and tethered hoses with pumps (Crutzen, 2006; Boyd, 2008a). The amount of sulphur required to be delivered is dependent on a range of factors including particle size and location of injection, but estimates of between 1 and 5 Mt year^{-1} have been suggested and considered feasible (Royal Society, 2009). Approaches using aerosols are not limited to sulphur. For example, by seeding marine clouds with seawater droplets, it is proposed that cloud reflectance will increase causing a net cooling effect (Latham *et al*., 2008). However, research into this particular area of geo-engineering is still in its infancy (e.g. Rasch *et al*., 2009). Indeed, there are many as yet unanswered questions about the use of aerosols, regarding stratospheric chemistry, spatial and seasonal variability, ozone depletion and disruption to local weather patterns (Robock, 2008).

2.3. A tragedy of the commons?

Whilst there is no shortage of planetary scale SRM ideas, progress on their development has been hindered by cost, ethical, environmental and ecological concerns, as well as the absence of international discussion on how to proceed. The atmosphere is a global common, protected and owned by all (Thornes *et al*., 2010), hence multilateral international agreement would be required before the instigation of any large scale planetary geo-engineering approach. Consenus on modifying a common for the common good (if a common good actually exists – what is advantageous for one can often be detrimental to another) is highly unlikely, particularly when projects carry so many uncertainties needing to be explored. To date there is a lack of engagement by governments in the debate and no significant public funding for research in this area (POST, 2009). Hence, many ideas are simply that: there has been little systematic attempt to assess the engineering feasibility of planetary scale geo-engineering solutions, let alone rigorously quantify their effectiveness, balanced with any negative or unintended impacts (Boyd, 2008a; IMechE, 2009d). Lunt *et al*. (2008) provide a rare evaluation of the impacts of SRM. A global circulation model was used to model the installation of reflective mirrors in space and discovered that whilst SRM will cool the tropics, high latitudes would actually become warmer. Such radical changes to the climate of the planet largely rules out SRM as a valid approach.

3. Planetary carbon cycle engineering

There is a growing consensus that whilst SRM would provide the quickest means to cool the planet, methods of CO_2 sequestration provide the lowest risk solution (Vaughan and Lenton, 2011). For example, a sudden injection of sulphur into the stratosphere could have many unknown consequences and would be largely uncontrollable. Instead, carbon cycle engineering would provide a more controllable solution targeted at the root cause of anthropogenic global warming, namely increasing atmospheric concentrations of CO_2, and is the means by which carbon is captured and stored away from the atmosphere so that it cannot act as a greenhouse gas. Furthermore, this approach can help offset a major problem of increasing greenhouse gas concentrations; that of ocean acidification (Boyd, 2008a). However, carbon cycle engineering requires a longer time period than that of solar radiation management to be effective, and with the world currently emitting approximately 29 Gt year^{-1} of CO_2 (IMechE, 2009d), rapid large scale implementation would be required.

3.1. Marine sequestration

The ocean and atmosphere exchange carbon on a large scale ($\sim>$90 PgC year^{-1} in 1990s) and, although there are local and time dependent variations in the rate of transfer, the overall net effect globally is that the ocean acts as a sink. Indeed, about 25% of current global anthropogenic CO_2 emissions are estimated to be removed from the atmosphere through this mechanism annually (Canadell *et al*., 2007) which has led to a number of geo-engineering approaches being conceptually devised to enhance the process (Stephens and Keith, 2008). The ocean is the largest potential sink for CO_2 and if the geo-engineering projects are feasible then the ocean is more than capable of storing all the excess CO_2 from the atmosphere.

Enhancement of the ocean sink can be achieved by increasing alkalinity through the addition of carbonate minerals. In this method more CO_2 is absorbed due to the lowering of pH and practical proposals based on the use of limestone (calcium carbonate source) have been made (e.g. Kheshgi, 1995; Harvey, 2008). The added alkalinity neutralizes the acidity of the CO_2 and, therefore, prevents ocean acidification and its subsequent impact on marine fauna and ecosystems (Fabry *et al*., 2008). However, it is anticipated that large amounts of energy will be used in the quarrying, crushing and transportation of the limestone, leading to high lifecycle carbon emissions for the process. In addition, there are unanswered questions with respect to impacts on ocean chemistry and biology that challenge the potential feasibility of this technique.

An alternative approach to ocean sink enhancement through increased alkalinity is ocean fertilization, which exploits the biological carbon pump (a term used to identify the natural process by which carbon in biological material sinks to depth (Boyd, 2008b)). This mechanism is responsible for sinking $\sim$10 GtC year^{-1} out of the surface layer of the ocean. This concept recognizes that the carbon sink rate is generally set by the flux of incoming nutrients to the surface layer of the ocean and that adding those that are limiting in regions of deficiency can lead to enhanced export production (net increase in sinking flux) (Lampitt *et al*., 2008; Boyd, 2008b). In most cases it is nitrogen and/or phosphorus that are limiting: approximately 40% of the ocean surface is estimated to be low-nutrient low-chlorophyll. It has therefore been proposed that the addition of phosphate (Karl and Letelier, 2008; Lampitt *et al*., 2008) or nitrogen, the latter possibly in the form of urea (Young, 2007; Ocean Nourishment Corporation, 2009), would increase carbon uptake in these areas. Indeed, calculations have suggested that if the whole nitrogen deficit were removed in the global oceans, an additional 299 PgC could be stored in the deep ocean, but that this process might take 600 years to achieve (Vaughan and Lenton, 2011). However, it should be noted that to date fertilization experiments (e.g. iron fertilization) have shown only a small or insignificant increase in export production (Boyd *et al*., 2007).

Any attempt to geo-engineer the oceans runs into many of the same issues as SRM. The oceans are also a common and any significant changes to the chemistry of the oceans would be irreversible in the short to medium term (Chisholm *et al*., 2001). In summary, oceans fit into the planetary geo-engineering category and for this reason, any attempt to geo-engineer the marine environment is highly unlikely.

3.2. Terrestrial sequestration

Forestry is the third largest source of greenhouse gas emissions accounting for 17% of global emissions (Eliasch, 2008), with deforestation having contributed between 22 and 43% of the historic rise in CO_2 (Betts *et al*., 2008). Hence, in terms of mitigation approaches to climate change the forest sector is a key area to tackle and, indeed, the terrestrial environment offers carbon cycle engineering opportunities that could have an important role to play as part of the overall solution. Terrestrial sequestration is the process by which carbon is transferred from the atmosphere into soils or vegetation by natural processes operating in terrestrial ecosystems (Litynski *et al*., 2008). At a basic level, terrestrial sequestration can be increased by reforestation (Canadell and Raupach, 2008), thus offsetting lost forest with new growth and enhancing the terrestrial sink. With adequate investment, it is hoped that this approach will enable the forest sector to become carbon neutral by 2030 (Eliasch, 2008). Afforestation also has a role to play. In particular, great potential lies in the development of land currently devoid of both soil and vegetation such as reclaimed mine lands (e.g. Litynski *et al*., 2006; Shrestha and Lal, 2006).

Reforestation and afforestation will help to achieve greenhouse gas stabilization targets, which in turn should reduce the scale of any required geo-engineering solution. However, engineering has a role to play in optimizing sequestration in the terrestrial environment. CO_2 captured by vegetation is eventually released back into the atmosphere once the trees die and decay. One way in which the carbon can be sequestered longer term is by turning plant matter into biochar, a type of charcoal produced by the pyrolysis of biomass in the absence of oxygen (see Lehmann *et al*., 2006, for a detailed review). Biochar can then be added to soils, where it acts as a soil conditioner whilst enhancing the carbon content (Stephens and Keith, 2008). Although the exact timeframes are unclear, this process effectively sequesters the carbon in the soil for hundreds of years. However, whilst biochar can make a real difference to global carbon budgets (Lehmann, 2007), the general consensus is that soils are a finite sink (e.g. Freibauer *et al*., 2004). Indeed, large scale biochar production would require a significant rolling programme of deforestation and reforestation, which may or may not be feasible and further calculations and research are required before deployment (Lehmann, 2007).

4. Local scale geo-engineering

So far, with the exception of terrestrial sequestration, this review has largely dismissed the feasibility of planetary scale geo-engineering, particularly techniques which involve a significant modification to a common. When the scale of geo-engineering is no longer planetary, the technologies and solutions begin to merge with and complement climate change mitigation and adaptation approaches. Adaptation is defined by the IPCC Working Group 2 as

> *Adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities.*

Many adaptation measures are focused on providing localized cooling to ameliorate increasing heat and with 50% of the world's population now living in cities (United Nations, 2008), and predictions of up to 70% by 2050, it is sensible to focus adaptation measures in urban areas. Urban areas are especially sensitive to increased heat as they already experience increased warmth due to the urban heat island effect (see Arnfield, 2003 for a comprehensive review). Many adaptation techniques exist which focus on modifying the urban microclimate through urban greening (e.g. green roofs; Niachou *et al*., 2001) and improving airflow (Smith and Levermore, 2008), however, the most common techniques involve changing heat absorption and emission through modification of surface properties. Such adaptation measures reduce urban temperatures (Taha, 2008) which in turn reduce energy consumption by means of reduced air conditioning (IMechE, 2009d). This approach is effectively local-scale SRM.

4.1. Local scale SRM: terrestrial Albedo management

Although this review has highlighted the significant challenges in moving forward with planetary SRM as a geo-engineering solution to offset climate change, due to the planetary scale of implementation and potential for unforeseen climatic side-effects, SRM approaches may have a role to play in combating global warming as part of a portfolio of small scale localized geo-engineering/adaptation solutions.

One category of these solutions is solar reflectors (albedo enhancement; IMechE, 2009d). These provide a retrofit solution which could be used across the built environment (Hamwey, 2007). The effectiveness of this approach is well documented (e.g. Hamwey, 2007; Akbari *et al*., 2009; Vaughan and Lenton, 2011), with estimates of the order of 0.01 to 0.16 °C reduction in global average temperatures depending on the assumptions made in regard to the percentage of land available and increases in albedo that might result from a change in material (IMechE, 2009d). However, albedo management isn't limited to urban areas, this simple form of geo-engineering can be easily scaled up to other environments to reduce heat impacts. For example, reforestation and deforestation has a cooling effect in tropical and polar areas respectively (Mylne and Rowntree, 1992; Bonan, 2008). Furthermore, high albedo crop varieties/vegetation could also be grown wherever suitable which has the potential to offset 1 °C of warming (Ridgwell *et al*., 2009). Potential disadvantages of the approach are the potential interference with the surface radiation balance which may affect cloud cover and precipitation (Hamwey, 2007).

4.2. Local scale carbon cycle engineering

4.2.1. Carbon capture and storage (CCS)

CO_2 can be captured in real-time from large point sources (i.e. power stations) by a variety of techniques (White *et al*., 2003), however, although from an engineering perspective these are relatively straightforward, they are often costly both financially and in terms of the efficiency of the plant (Herzog and Golomb, 2004). Indeed, in the absence of a sufficiently high market price for carbon, or other suitable commercial incentivization, the challenge for this approach is largely economic rather than technical. Most methods involve capturing the CO_2 post combustion, just before release from the flue, by using wet scrubbing technologies, dry sorbents or cryogenics (see Wolsky *et al.*, 1994 for a full review). For example, monoethanolamine is a commonly used solvent which selectively absorbs CO_2 and effectively acts as a filter for the flue gases (Chakma *et al.*, 1995; Zeman and Lackner, 2004).

The efficiency of the capture process can be improved by using oxy-fuel combustion where the fossil fuel is burned in pure oxygen instead of air (Herzog and Golomb, 2004). This creates flue gases which can then be recycled to further improve combustion (Buhre *et al.*, 2005). Another way of improving efficiency is to use pre-combustion capture. This process involves gasifying coal to create carbon monoxide which can be reacted with water to produce carbon dioxide for capture and hydrogen for energy production (Herzog and Golomb, 2004). However, unlike post combustion capture, neither of these techniques are suitable for retrofitting.

Once captured, the CO_2 needs to be transported to a storage facility. Pipelines are the natural choice for transport and, whilst being safer and cheaper than road transport, such infrastructure still comes at significant cost (Skovholt, 1993). Indeed, the transportation of CO_2 by pipeline is already well established as the injection of CO_2 into oil fields is commonly used for enhanced oil recovery (Herzog and Golomb, 2004). Sinks have been proposed in marine and geological environments.

Deep ocean sequestration of CO_2 can be achieved by direct injection (Marchetti, 1977). The theory is to inject the CO_2 below the thermohaline layer where CO_2 becomes denser than seawater and thus remains in solution. However, it has been argued that the increases in density at even relatively shallow depths may be sufficient to transport the dissolved gas to suitable depths (Haugan and Drange, 1992). A number of techniques have been proposed to achieve this using ships and/or static pipelines (e.g. Liro *et al.*, 1992; Ozaki *et al.*, 1995). However, there are many concerns with this approach, in particular the continued increase in ocean acidity as a result of the increased levels of CO_2. Of course, this is already a significant problem, as seen by the bleaching of coral reefs (e.g. Hughes *et al.*, 2003) and this method will only intensify the problem (Robock, 2008). Furthermore, this approach, whilst capturing CO_2 locally, is once again interfering with a global common.

Other advanced (and more local) methods of CO_2 storage have been proposed, however, perhaps the most feasible is geological sequestration where CO_2 is transported and injected into underground saline formations, unused mines and depleted oil and gas reservoirs (White *et al.*, 2003; Vaughan and Lenton, 2011). Trapping mechanisms vary, but range from actual physical trapping to solubility and mineral trapping (Chow *et al.*, 2003). There is considerable potential for this approach which is essentially a permanent solution where potentially 11 000 Gt of CO_2 could be stored in this way (Stern, 2006). White *et al.* (2003) provide a comprehensive review of geological sequestration techniques in which they highlight the key issues pertaining to the integrity of the storage along with the physical and chemical processes involved in injecting CO_2 deep underground. Their general conclusion is that most risks can be mitigated and geological sequestration should be possible using existing technologies, but the high costs associated with the approach could prove commercially challenging. However, the implications of leakage from geologic reservoirs has led to other scientists being much more skeptical (e.g. Chow *et al.*, 2003). A catastrophic failure of a large reservoir would have a significant local effect (e.g. at Lake Nyos in Cameroon, a sudden catastrophic leakage of naturally sequestered CO_2 killed over 1700 people in 1986; Kling *et al.*, 1987) as well as the obvious, sudden implications for global climate. It has been demonstrated that an acceptable leakage rate would be around just 1%. This in itself is challenging and would require significant continuous monitoring to be in place for centuries after sequestration (Chow *et al.*, 2003).

4.2.2. Artificial trees

Assuming that engineering permits geological sequestration of carbon, there is potential to extend carbon capture technology at a local scale. Point source capture is an excellent technology for collecting 'new' CO_2, but in order to bring CO_2 levels down to a safe level in the atmosphere a technique may also be required to capture accumulations of past emissions. Implementation of such a technique might be considered to be a 'negative emissions' approach residing within the mitigation portfolio of approaches and in this area direct capture technologies have been proposed by a number of scientists (Keith *et al.*, 2006; Lackner, 2009). As discussed earlier, trees are the natural way for CO_2 sequestration and this has led to concepts for 'artificial trees' that capture CO_2 through solvent or adsorption based chemical processes. For example, Lackner (2009) propose the use of sorbent materials such as sodium hydroxide on artificial leaves. Once the leaves are saturated, the CO_2 is removed in a controlled process and stored elsewhere. It has been shown that this approach could be thousands of times more effective at removing CO_2 than a natural tree (IMechE, 2009d). A key advantage of this method is that it can capture CO_2 emissions regardless of the source, as CO_2 is well mixed in the atmosphere. Thus, trees can be located anywhere which makes the technology particularly suited to CO_2 capture from non-stationary sources (i.e. the transport sector; Lackner *et al.*, 2001). Alternatively they could be used to target the combined impact of small-scale dispersed sources which are too small to realistically utilize larger scale mitigation technologies; non-stationary and small-scale dispersed sources currently account for around 14 Gt year^{-1} of CO_2, some 50% of global CO_2 emissions (IMechE, 2009d) CO_2 capture is simply a function of the collector area and, to a lesser extent, the speed of airflow. The main disadvantage to this approach is the energy-intensive cleaning process which is subject to ongoing research (Lackner, 2009). With further technological development and process improvement it is estimated that 5 million trees, each with a footprint similar to that of a standard shipping container, would be sufficient to capture current CO_2 emissions annually from all non-stationary and small-scale dispersed sources (IMechE, 2009d).

4.2.3. *Algae*

Algae naturally absorb CO_2 through the process of photosynthesis and recent studies highlight the potential of algae as a geo-engineering solution (Jacob-Lopes *et al*., 2008). One new idea involves using algae as a geo-engineering approach in the built environment by growing it on building surfaces in sealed vessels (e.g. plastic bio-tubes to control the growth) known as photobioreactors (IMechE, 2009d). Photobioreactors present a retrofit geo-engineering solution which can be used in an urban environment, thus removing the conflict that occurs where a geo-engineering approach or mitigation solution leads to a loss in land areas for food growth. A further advantage of this approach is that the algae will act as an insulator, thus reducing energy demand for space heating.

A positive side-effect of photobioreactors is that they also can be used to produce biofuel (Chisti, 2008). A closed loop system is envisaged, ultimately driven by solar energy, where the thermal degradation of algae by pyrolysis fuels a combined heat and power station whose CO_2 emissions are automatically fed back into the algae (Patil *et al*., 2008) (incidentally a by-product of this process is biochar – see Section 3.2). At present, this geo-engineering solution is very much a conceptual idea, but a solution which enables negative emissions through capture of CO_2 from air and helps mitigate against future climate change by providing a renewable energy source is worthy of further investigation (IMechE, 2009d).

5. Discussion and conclusions

Geo-engineering provides an engineering challenge, transforming ideas rooted in climate science into actual working solutions. A number of practical, feasible and relatively environmentally benign geo-engineering approaches exist which have the potential to support the global transition to a low-carbon economy. However, few of the geo-engineering schemes discussed in this review are demonstrated or costed, and there is a need to instigate a series of national and international research programmes targeted at researching the feasibility of the various ideas. Geo-engineering research, development and demonstration (RD and D) is likely to be expensive. However, it is estimated that a 10 year UK programme at a cost of approximately £10 M *per annum* would be required to advance the science significantly (POST, 2009; Royal Society, 2009). Development must be true to the low carbon values and must have the ability to be quickly deployed as the world makes the transition to a low carbon economy. Unfortunately, the RD and D process will involve a significant lead-time and given the speed in which the climate is changing, there is an urgent need to instigate detailed engineering assessments.

Table I provides a summary of the various schemes discussed in this paper in an initial rank order of engineering feasibility. Any scheme that relies on international agreement (shown in italics) is currently considered highly unlikely to be deployed due to a lack of robust, multilateral government policy. Furthermore, the adverse environmental consequences of such schemes cannot really be fully quantified, and should a scheme suddenly fail, then the results could lead to relatively rapid warming or unforeseen ecological impacts, a modern-day tragedy of the commons (Robock, 2008; Boyd, 2008a). For these reasons, many of the larger scale ideas covered in this review will probably never see operational use. In the Royal Society (2009) review, the use of stratospheric aerosols and cloud seeding scored highly in effectiveness and affordability. However, whilst these solutions are easily engineered, the modification of a global common is still a major stumbling block. Hence, this paper concludes that there is a need for each nation to try and put its own 'house in order' by meeting mitigation targets and adaptation strategies. The implementation of smaller local-scale approaches, particularly carbon capture and storage and those that provide adaptation and negative emissions solutions (e.g. terrestrial albedo management and artificial trees) could contribute to achieving such goals. This conclusion may seem a little downbeat at the end of such a review as it is possible that geo-engineering has the potential to cool the planet in a controllable and effective manner. However, at this stage it is impossible to say with confidence whether the large-scale engineering is feasible or not, how long global solutions would take to deploy and what the price tag might be.

Table I. Initial ranking of engineering feasibility of schemes described in this paper for deployment at an appropriate scale (those in italics require international agreement).

↓ Decreasing engineering feasibility, from feasible (top) to unfeasible (bottom)	Reforestation/afforestation *Aerosols* *Carbon capture: marine sequestration* *Ocean fertilization*
	Carbon capture: geological sequestration *Increased ocean alkalinity* Biochar Albedo management Algae on buildings *Spaceborne solar reflectors*

References

Akbari H, Menon S, Rosenfeld A. 2009. Global cooling: increasing world-wide urban albedos to offset CO2. *Climatic Change* **94**: 275–286.

Anderson K, Bows A. 2008. Reframing the climate change challenge in light of post-2000 emission trends. *Philosophical Transactions of the Royal Society A* **366**: 3863–3882.

Angel R. 2006. Feasibility of cooling the earth with a cloud of small spacecraft near the inner Lagrange point (L1). *Proceedings of the National Academy of Sciences of the United States of America* **103**: 17184–17189.

Arnfield AJ. 2003. Two decades of urban climate research: a review of turbulence, exchanges of energy and water, and the urban heat island. *International Journal of Climatology* **23**: 1–26.

Betts R, Gornall J, Hughes J, Kaye N, McNeall D, Wiltshire A. 2008. *Forests and Emissions: A Contribution to the Eliasch Review*. UK Met Office: Exeter, United Kingdom; 55.

Bonan GB. 2008. Forests and climate change: forcings, feedbacks, and the climate benefits of forests. *Science* **320**: 1444–1449.

Boyd PW. 2008a. Ranking geo-engineering schemes. *Nature Geosciences* **1**: 722–724.

Boyd PW. 2008b. Implications of large-scale iron fertilization of the oceans: introduction and synthesis. *Marine Ecology Progress Series* **364**: 213–218.

Boyd PW, Jickells T, La CS, Blain S, Boyle EA, Buesseler KO, Coale KH, Cullen JJ, de Baar HJW, Follows M, Harvey M, Lancelot C, Levasseur M, Owens NPJ, Pollard R, Rivkin RB, Sarmiento J, Schoemann V, Smetacek V, Takeda S, Tsuda A, Turner S, Watson AJ. 2007. Mesoscale iron enrichment experiments 1993–2005: synthesis and future directions. *Science* **315**: 612–617.

Buhre BJP, Elliott LK, Sheng CD, Gupta RP, Wall TF. 2005. Oxy-fuel combustion technology for coal-fired power generation. *Progress in Energy and Combustion Science* **31**: 283–307.

Canadell JG, Le Quere C, Raupach MR, Field CB, Buitenhui ET, Ciais P, Conway TJ, Gillett NP, Houghton RA, Marland G. 2007. Contributions to accelerating atmospheric CO2 growth from economic activity, carbon intensity, and efficiency of natural sinks. *Proceedings of the National Academy of Sciences of the United States of America* **104**: 18866–18870.

Canadell JG, Raupach MR. 2008. Managing forests for climate change mitigation. *Science* **320**: 1456–1457.

Cathcart RB, Ćirković MM. 2006. Extreme climate control membrane structures. *Macro-Engineering*, Chapter 9. Springer: Dordrecht, the Netherlands; 151–174.

Chakma A, Mehrotra AK, Nielsen B. 1995. Comparison of chemical solvents for mitigating CO2 emissions from coal-fired power plants. *Heat Recovery Systems and CHP* **15**: 231–240.

Chisholm SW, Falkowski PG, Cullen JJ. 2001. Dis-crediting ocean fertilization. *Science* **294**: 309–310.

Chisti Y. 2008. Biodiesel from microalgae beats bioethanol. *Trends in Biotechnology* **26**: 126–131.

Chow JC, Watson JG, Hezog A, Benson SM, Hidy GM, Gunter WD, Penkala SJ, White CM. 2003. Separation and capture of CO2 from large stationary sources and sequestration in geological formations. *Journal of Air and Waste Management Association* **53**: 1172–1182.

Crutzen PJ. 2006. Albedo enhancement by stratospheric sulphur injections: a contribution to resolve a policy dilemma? *Climatic Change* **77**: 211–219.

Eliasch J. 2008. *Climate Change: Financing Global Forests*. Office of Climate Change: London, United Kingdom; 250.

Fabry VJ, Seibel BA, Feely RA, Orr JC. 2008. Impacts of ocean acidification on marine fauna and ecosystem processes. *Journal of Marine Science* **65**: 414–432.

Freibauer A, Rounsevell MDA, Smith P, Verhagen J. 2004. Carbon sequestration in agricultural soils of Europe. *Geoderma* **122**: 1–23.

Hamwey RM. 2007. Active amplification of the terrestrial albedo to mitigate climate change: an exploratory study. *Mitigation and Adaptation Strategies for Global Change* **12**: 419–439.

Hansen JE. 1988. The Greenhouse Effect: Impacts on Current Global Temperature and Regional Heat Waves. Statement to United States Senate, Committee on Energy and Natural Resources. June 23, 1988.

Harvey LDD. 2008. Mitigating the atmospheric CO2 increase and ocean acidification by adding limestone powder to upwelling regions. *Journal of Geophysical Research* **113**: 21.

Haugan PM, Drange H. 1992. Sequestration of CO2 in the deep ocean by shallow injection. *Nature* **357**: 318–320.

Herzog H, Golomb D. 2004. Carbon capture and storage from fossil fuel use. In *Encyclopedia of Energy*, Cleveland CJ (ed.). Elsevier Science: New York, NY; 277–287.

Hughes TP, Baird AH, Bellwood DR, Card M, Connolly SR, Folke C, Grosbery R, Hoegh-Guldberg O, Jackson JBC, Kleypas J, Lough JM, Marshall P, Nyström M, Palumbi SR, Pandolfi JM, Rosen B, Roughgarden J. 2003. Climate change, human impacts, and the resilience of coral reefs. *Science* **301**: 929–933.

IMechE. 2009a. *Climate Change: Adapting to the Inevitable?* Institution of Mechanical Engineers: London, United Kingdom; 30.

IMechE. 2009b. *UK 2050 Energy Plan: Making our Commitment a Reality*. Institution of Mechanical Engineers: London, United Kingdom; 32.

IMechE. 2009c. *Climate Change: Have we lost the Battle?* Institution of Mechanical Engineers: London, United Kingdom; 24.

IMechE. 2009d. *Geo-engineering: Giving us the time to Act?* Institution of Mechanical Engineers: London, United Kingdom; 27.

IPCC. 2007. *Climate Change 2007: Mitigation*, Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press: Cambridge, United Kingdom and New York, NY.

Jacob-Lopes E, Scoparo CHG, Franco TT. 2008. Rates of CO2 removal by Aphanothece microscopica Nageli in tubular photobioreactors. *Chemical Engineering and Processing* **47**: 1365–1373.

Karl DM, Letelier RM. 2008. Nitrogen fixation-enhanced carbon sequestration in low nitrate, low chlorophyll seascapes. *Marine Ecology Progress Series* **364**: 257–268.

Keith DW, Ha-Duong M, Stolaroff JK. 2006. Climate strategy with CO2 capture from the air. *Climatic Change* **74**: 17–45.

Kheshgi HS. 1995. Sequestering atmospheric carbon dioxide by increasing ocean alkalinity. *Energy* **20**: 915–922.

Kling GW, Clark MA, Wagner GN, Compton HR, Humphrey AM, Devine JD, Evans WC, Lockwood JP, Tuttle ML, Koenigsberg EJ. 1987. The 1986 Lake Nyos Gas Disaster in Cameroon, West Africa. *Science* **236**: 169–175.

Lackner KS. 2009. Capture of carbon dioxide from ambient air. *European Physics Journal Special Topics* **176**: 93–106.

Lackner KS, Grimes P, Ziock HJ. 2001. Capturing carbon dioxide from air. *Proceedings on the First National Conference on Carbon Sequestration*, 14–17 May 2001, Washington, DC.

Lampitt RS, Achterberg EP, Anderson TR, Hughes JA, Iglesias-Rodriguez MD, Kelly-Gerreyn BA, Lucas M, Popova EE, Sanders R, Shepherd JG, Smythe-Wright D, Yool A. 2008. Ocean fertilisation: a potential means of geoengineering? *Philosophical Transactions of the Royal Society A* **366**: 3919–3945.

Latham J, Rasch P, Chen CC, Kettles L, Gadian A, Gettelman A, Morisson H, Bower K, Choularton T. 2008. Global temperature stabilization via controlled albedo enhancement of low-level maritime clouds. *Philosophical Transactions of the Royal Society A* **366**: 3969–3987.

Lehmann J. 2007. A handful of carbon. *Nature* **447**: 143–144.

Lehmann J, Gaunt J, Rondon M. 2006. Bio-char sequestration in terrestrial ecosystems – a review. *Earth and Environmental Science* **11**: 395–419.

Liro C, Adams E, Herzog H. 1992. Modeling the release of CO2 in the deep ocean. *Energy Conversion Management* **33**: 667–674.

Litynski JT, Plasynski S, McIlvried HG, Mahoney C, Srivastava RD. 2008. The United States Department of Energy's Regional carbon sequestration partnerships program validation phase. *Environmental International* **34**: 127–138.

Lunt DJ, Ridgwell A, Valdes PJ, Seale A. 2008. "Sunshade World": a fully coupled GCM evaluation of the climatic impacts of geoengineering. *Geophysical Research Letters* **35**: L12710, DOI: 10.1029/2008GL033674

Marchetti C. 1977. Geo-engineering and CO2 problem. *Climate Change* **1**: 59–68.

Mautner M. 1991. A space-based solar screen against climate warming. *Journal of the British Interplanetary Society* **44**: 135–138.

Meinshausen M, Meinshausen N, Hare W, Raper SCB, Frieler K, Knutti R, Frame DJ, Allen MR. 2009. Greenhouse-gas emission targets for limiting global warming to 2 °C. *Nature* **458**: 1158–1162.

Mylne MF, Rowntree PR. 1992. Modelling the effects of albedo change associated with tropical deforestation. *Climatic Change* **21**: 317–343.

NAS. 1992. *Policy Implications of Greenhouse Warming: Mitigation, Adaptation, and the Science Base*. National Academy of Sciences, National Academy Press: Washington, DC; 944.

Niachou A, Papakonstantinou K, Santamouris M, Tsangrassoulis A, Mihalakakou G. 2001. Analysis of the green roof thermal properties and investigation of its energy performance. *Energy and Buildings* **33**: 719–729.

Ocean Nourishment Corporation. 2009. The Technology. http://www.oceannourishment.com/technology.asp. (Accessed 13 May 2010).

Ozaki M, Sonoda K, Fujioka Y, Tsukamoto O, Komatsu M. 1995. Sending CO2 into deep ocean with a hanging pipe from floating platform. *Energy Conversion Management* **36**: 475–478.

Patil V, Tran LQ, Giselrød HR. 2008. Towards sustainable production of biofuels from microalgae. *International Journal of Molecular Science* **9**: 1188–1195.

Pearson J, Oldson J, Levin E. 2006. Earth rings for planetary environment control. *Acta Astronautica* **58**: 44–57.

Penner JE, Lister DH, Griggs DJ, Dokken DJ, McFarland M. 1999. *IPCC Special Report: Aviation and the Global Atmosphere*. Cambridge University Press: Cambridge, United Kingdom; 373.

POST 2009. *Geo-Engineering Research*, Postnote 327. Parliamentary Office of Science and Technology: London, United Kingdom; 4.

Rasch PJ, Latham J, Chen CC. 2009. Geoengineering by cloud seeding: influence on sea ice and climate system. *Environmental Research Letters* **4**: 045112, DOI: 10.1088/1748-9326/4/4/045112

Richardson K, Steffen W, Schellnhuber HJ, Alcamo J, Barker T, Kammen DM, Leemans R, Liverman D, Munasinghe M, Osman-Elasha B, Stern N, Waever O. 2009. Synthesis report: climate change. *Global Risks, Challenges and Decisions. International Scientific Congress*, 10–12 March 2009, Copenhagen, Denmark; 39.

Ridgwell A, Singarayer JS, Hetherington AM, Valdes PJ. 2009. Tackling regional climate change by leaf albedo bio-geoengineering. *Current Biology* **19**: 146–150.

Robock A. 2008. 20 reasons why geo-engineering may be a bad idea. *Bulletin of the Atomic Scientists* **64**: 14–18.

Royal Society. 2009. *Geo-Engineering the Climate; Science, Governance and Uncertainty*. The Royal Society: London, Copenhagen; 98.

Shrestha RK, Lal R. 2006. Ecosystem carbon budgeting and soil carbon sequestration in reclaimed mine soil. *Environmental International* **32**: 781–796.

Skovholt O. 1993. CO2 transportation systems. *Energy Conversion and Management* **34**: 1095–1103.

Smith CL, Levermore GJ. 2008. Designing urban spaces and buildings to improve sustainability and quality of life in a warmer world. *Energy Policy* **36**: 4558–4562.

Stenchikov GL, Kirchner I, Robock A, Graf HF, Antuna JC, Grainger RG, Lambert A, Thomason L. 1998. Radiative forcing from the 1991 mount Pinatubo volcanic eruption. *Journal of Geophysical Research-Atmospheres* **103**(D12): 13837–13857.

Stephens JC, Keith DW. 2008. Assessing geochemical carbon management. *Climatic Change* **90**: 217–242.

Stern N. 2006. *The Economics of Climate Change: The Stern Review*. Cambridge University Press: Cambridge, UK; 713.

Taha H. 2008. Urban surface modification as a potential ozone air-quality improvement strategy in California: a mesoscale modelling study. *Boundary-Layer Meteorology* **127**: 219–239.

Teller E, Wood L, Hyde R. 1997. *Global Warming and Ice Ages: I. Prospects for Physics Based Modulation of Global Change*. UCRL-231636/UCRL JC 128715. Lawrence Livermore National Laboratory: Livermore, CA.

Thornes JE, Bloss W, Bouzarovski S, Cai X, Chapman L, Clark J, Dessai S, Du S, van der Horst D, Kendall M, Kidd C, Randalls S. 2010. Communicating the value of atmospheric services. *Meteorological Applications* **17**: 243–251.

United Nations. 2008. *World Urbanization Prospects: The 2007 Revision*. United Nations: New York, NY; 244.

Vaughan NE, Lenton TM. 2011. A review of climate geo-engineering proposals. *Climatic Change* (submitted).

Watson RT. 2001. *IPCC Special Report: Climate Change 2001: Synthesis Report*. Cambridge University Press: Cambridge, United Kingdom; 398.

White CM, Strazisar BR, Granite EJ, Hoffman JS, Pennline HW. 2003. Separation and capture of CO2 from large stationary sources and sequestration in geological formations–coalbeds and deep saline aquifers. *Journal of Air and Waste Management Association* **53**: 645–715.

Wolsky AM, Daniels EJ, Jody BJ. 1994. CO2 capture from the flue gas of conventional fossil-fuel-fired power plants. *Environmental Progress* **13**: 214–219.

Young E. 2007. Can ‘fertilising’ the ocean combat climate change? *New Scientist* **2621**: 42–45.

Zeman FS, Lackner KS. 2004. Capturing carbon dioxide directly from the atmosphere. *World Resource Review* **16**: 157–171.

