ENVIRONMENT

GEO-ENGINEERING GIVING US THE TIME TO ACT?

Institution of MECHANICAL ENGINEERS

Improving the world through engineering

“”

AFTER DECADES OF FAILED MITIGATION, GEO-ENGINEERING MAY GIVE US THOSE EXTRA FEW YEARS TO TRANSITION TO A LOW CARBON WORLD AND PREVENT ANY ONE OF THE FUTURE CLIMATE CHANGE SCENARIOS WE ALL FEAR.

DR TIM FOX
HEAD OF ENVIRONMENT AND CLIMATE CHANGE
INSTITUTION OF MECHANICAL ENGINEERS

Our planet is getting hotter due to climate change. Governments from around the world continue to debate the best ways to mitigate these changes but with little real success. As time runs out to implement CO_2 emission reduction plans, could geo-engineering give us those few extra years we need?

This report by the Institution of Mechanical Engineers assesses three possible geo-engineering approaches and outlines a roadmap where mitigation, adaptation and geo-engineering all play their part in helping us avoid the consequences of dangerous climate change.

Published August 2009.

ENERGY

ENVIRONMENT

EDUCATION

TRANSPORT

CONTENTS

02 EXECUTIVE SUMMARY

05 COOLING THE PLANET

08 CASE STUDY ONE:
AIR CAPTURE—
ARTIFICIAL TREES

14 CASE STUDY TWO:
AIR CAPTURE—
ALGAE ON BUILDINGS

18 CASE STUDY THREE:
SOLAR RADIATION MANAGEMENT—
REFLECTIVE BUILDINGS

22 GEO-ENGINEERING
PRACTICAL ISSUES AND
ROADMAP TO COOLING THE PLANET

24 REFERENCES

EXECUTIVE SUMMARY

Irrespective of the many global agreements over the last 20 years calling for action and funding to abate climate change, our planet is still getting hotter. This is generally considered to be caused by human activities releasing so called 'greenhouse gases' into our atmosphere. The primary gas causing most concern is carbon dioxide (CO_2).

Many believe that we are fast approaching a critical point in dealing with climate change. The consensus is that we cannot allow global average temperature to rise by 2°C above pre-industrial levels. If we do – and many predict this will happen within the next few decades – dramatic changes to our climate may occur which could prove disastrous for human society in the long term.

For many years, governments have primarily focused on climate change mitigation, or in simple terms, reducing the amount of CO_2 each nation emits into the atmosphere. Indeed the UK Government recently released its Low Carbon Transition Plan, which the Institution welcomes as a positive plan of action for the next decade.

More recently, attention has broadened to include climate change adaptation. This approach sets out to ensure that critical assets, such as power generation, transport links, water supplies and the urban environment, are redesigned and rebuilt to protect against future changes in climate. This subject has recently been promoted by the Institution in its 2009 'Climate Change: Adapting to the Inevitable?' report.

However a third, but less explored avenue, is geo-engineering. This is where technology is used to remove CO_2 from the atmosphere, or where the planet is cooled by reflecting solar radiation back into space. Geo-engineering is not an encompassing solution to global warming. It is however, another potential component in our approach to climate change that could provide the world with extra time to decarbonise the global economy, a task which has yet to begin in earnest.

GEO-ENGINEERING OPTIONS

The Institution of Mechanical Engineers has undertaken an initial assessment of a range of potential geo-engineering options available under its 'Cooling the Planet' programme. Of the many options reviewed, the three most promising have been outlined in this report:

1. Artificial trees
Research is being undertaken into building machines which, like trees, can remove CO_2 from the atmosphere. This occurs when air passes through the device (the tree) and CO_2 sticks to a sorbent material (the leaves). The CO_2 is then removed and buried underground in the same way as conventional carbon capture and storage (CCS). At an estimated cost of $20,000 for each unit, the UK would require 100,000 'trees' (each absorbing ten tonnes of CO_2 per day) to capture the entire nation's non-stationary and dispersed emissions.

2. Algae-coated buildings
This approach uses strips of algae which are fitted to the outside of buildings. Algae naturally absorbs CO_2 through photosynthesis. The algae are then periodically harvested from building surfaces and used as biofuel in conjunction with a carbon sequestration solution. The advantage of this proposal is that no additional land is required therefore it will not affect existing and future food production or other important land uses.

3. Reflective buildings
Reducing the amount of solar radiation absorbed by the Earth's climate system has the potential to cool the planet. This can simply be achieved by making surfaces more reflective and thus lowering the heating effect the sun's rays have on us. Although this option may not be as effective as the other two proposals, it does have the additional benefit of reducing temperatures in urban heat islands – city centres can often be several degrees hotter than the surrounding environment.

ROADMAP FOR OUR FUTURE

The relative use of these technologies needs to be assessed. It is also important that these potential options are not seen as alternatives to climate change mitigation. Indeed, the Institution proposes a climate change roadmap over the next 75 to 100 years in which geo-engineering is an integrated supporting component in global climate mitigation and adaptation plans. Elements in such a roadmap would include the following:

- Funding for geo-engineering research is granted by Government. Any such research must be linked with existing mitigation and adaptation research
- Widespread implementation of artificial forests leveraging emerging CCS infrastructure for storage and purpose-built co-located renewable energy generation for power
- Parallel decarbonisation and expansion of global electricity generation capacity, including deployment of smart supergrids on a continental scale
- Parallel research and development of electric transportation technologies and technologies for decarbonisation of dispersed sources
- Possible 'emergency' deployment of Solar Radiation Management (SRM) subject to research outcomes and progress globally on mitigation
- Phased electrification of transportation sector and dispersed sources of CO_2 emissions
- Continued use of artificial trees to clean-up past emissions until atmospheric CO_2 concentration returns to a climatically acceptable level
- Decommissioning of geo-engineering solutions.

PLAN B OR A FULLY INTEGRATED COMPONENT?

Despite its potential, the UK Government considers geo-engineering as a low priority. Indeed, Joan Ruddock MP, then Under-Secretary of State at DECC stated in November 2008 "I regard [geo-engineering] as being somewhere down the list of priorities and potentially a Plan B". This position may well be because the Government does not wish attention to be diverted from its mitigation goals. However, two decades of failed global mitigation efforts should be a wake-up call. It could be geo-engineering that provides the global community with those extra years to introduce effective mitigation and adaptation strategies and, in the long term, remove some of the existing CO_2 from the atmosphere. As such, Plan B needs to be upgraded to become a fully integrated part of a comprehensive three-point approach embracing **M**itigation, **A**daptation and **G**eo-engineering; a 'MAG approach' to policy. If certain geo-engineering techniques require research and testing, we should not wait until it's too late for them to have lasting effect.

KEY FACTS

- Global efforts to mitigate climate change have so far been relatively ineffective
- The world is rapidly heading towards a 2°C increase in global temperatures
- We may need more time to reduce CO_2 emissions to acceptable levels
- Geo-engineering offers the world some extra time by removing CO_2 from the atmosphere or reflecting solar radiation back into space.

RESEARCH AND DEVELOPMENT

For geo-engineering to be considered, more research into its potential to reduce global warming needs to be undertaken. Furthermore, a realistic cost analysis and timescale of planetary wide implementation needs to be worked through. As the UK is already a leading nation in the science behind geo-engineering, we have the potential to assess, manufacture and deploy these technologies to the world. The Institution believes, along with the mitigation and adaptation industries, geo-engineering has the potential to create one million jobs by 2050 as outlined in our example roadmap on page 22. However, this will not occur without Government leadership and a commitment to initial research and development funding.

RECOMMENDATIONS

In response to these challenges, the Institution of Mechanical Engineers has developed the following recommendations for Government and other stakeholders:

1. Support geo-engineering research. The Institution of Mechanical Engineers calls upon the Government to support a national programme of geo-engineering feasibility research and development in an international context. As little as £10m could provide us with more reliable quantitative understanding of the effectiveness, risks and costs of geo-engineering, as well as the ethical, governance and moral perspectives associated with it. This needs to bring together climate scientists and modellers, engineers, economists, social scientists and philosophers. Given the urgency of our climate challenge, we should wait no longer.

2. Use the resources we already have. The UK is already a world leader in climate modelling and impact studies, as well as mitigation and adaptation research. The world-renowned Tyndall Centre, working with the Hadley Centre, is therefore ideally placed to lead, co-ordinate and deliver geo-engineering research. The centre's programmes are characteristically multi-disciplined in nature and therefore ideally suited to the task.

3. Pilot promising schemes. Schemes that show the most promise should be carried through to demonstrator phase to enable their relative potential to be accurately assessed and for the best schemes to become available for possible deployment. Such work requires investment in new modelling capabilities, tools and pilot-project scale engineering studies.

4. Adopt a realistic roadmap for decarbonisation of the global economy integrating geo-engineering. Building on knowledge acquired through a rigorous comprehensive technology assessment the Institution recommends that a comprehensive roadmap to implementation be devised for a global transition to a low-carbon future incorporating geo-engineering.

5. Maximise the commercial opportunities for UK plc. If the engineering industry sees Government policy moving research spend into geo-engineering, commercial companies are highly likely to start investing in their own research and initial feasibility assessments to try to second-guess the market opportunities which might arise out of the policy being pursued.

COOLING THE PLANET

WAKING UP TO REALITY

Despite continuous warnings from scientists about the consequences of global warming and the speed with which our climate is already changing, efforts worldwide to instigate effective widespread mitigation action have to date failed[1,2]. Since the UN Framework Convention on Climate Change was agreed in 1992, fossil fuel CO_2 emissions have continued to grow by more than 30%[3]. Furthermore, there is increasing recognition, even after recent further commitments by the G8 in Italy, that the reductions needed to limit a global mean temperature rise to below 2°C are not likely to be achieved[1,4,5]. Indeed many predict that this critical threshold will be passed well before 2050 and that the global mean temperature will rise by somewhere between 4°C and 6°C by the end of this century[1,2,5,6].

The global consequences of a rise between 4°C and 6°C will be severe. Although we may be able to adapt our built environment and physical infrastructure to be resilient to such climatic changes, as outlined in the Institution's recent Climate Change Adaptation report[2], the social, economic and political stresses may be too high for civilised society to cope with. For example, widespread food and water shortages would likely lead to the collapse of agricultural systems and market supply chains. When combined with sea-level rises and the increased prevalence of dangerous diseases, human displacement on a massive scale is likely to occur[1,7]. The only absolutely certain way to avoid such a future is to rapidly reduce greenhouse gas emissions from human activity to almost zero. The most significant task to achieve this is the decarbonisation of our global economy.

What this means is that every nation needs to transition from an economy underpinned by the use of fossil fuels for energy supply, to one in which all energy comes from either renewable or low-carbon sources. The only problem with that is, assuming we had all the technologies available, and a market hungry for their deployment, the process of global decarbonisation would take a very long time to physically achieve[2]. This is time we do not necessarily have.

Any move towards global decarbonisation will encounter several key barriers. To begin, many of the potential technologies are still a significant way from being ready for widespread deployment. This issue is exacerbated by skills gaps and shortages[8] of qualified engineers, technicians and equipment. For example, it is recognised that skills shortages is a critical issue for the implementation of the UK's new nuclear build programme – a significant component in the UK's decarbonisation strategy[9]. Thirdly, and maybe the most significant, markets around the world are simply not that interested. Green energy is expensive and the free market has consistently shown that the cheapest approach is to dig up fossil fuels and burn them.

The big question therefore is: if we haven't got enough time to decarbonise the global economy before the mean global temperature rise passes 2°C, is there something we can do to avoid dangerous climate change and a 4°C to 6°C outcome? Is there something we can do to buy us some time while we go about the business of a low-carbon transition, yet which doesn't distract us from that principal objective? The answer may be 'yes' and it is geo-engineering.

To explore this question in more detail, the Institution of Mechanical Engineers carried out a review of promising geo-engineering approaches, and made an initial engineering assessment of the feasibility of the most practical solutions. In this report the Institution presents the three most promising case studies and provides an engineer's view of the steps needed to make geo-engineering a reality.

COOLING THE PLANET

Global warming results from an increase in the amount of greenhouse gases present in the air which trap heat within our atmosphere. Therefore, if we can remove greenhouse gases from the air we can cool the planet. Alternatively, a similar outcome can be achieved by reflecting more sunlight back into space before it has a chance to heat up the atmosphere. To have any significant effect either of these approaches would need to be done on a large scale, in fact on a planetary scale, hence the term 'geo-engineering'.

The mechanisms to achieve a geo-engineering approach are conceptually straightforward. They may involve physical, chemical or biological interventions. For example, CO_2 removal from the air using chemical processes in machines[10], by stimulating plankton growth in the ocean[11], by planting trees for afforestation and reforestation[12] or by shading or reflecting sunlight[13]. There is in fact no shortage of ideas, most of which have been proposed by individuals from various disciplines within the scientific community[14]. However, there has been a lack of public funding for research in this area[9] and no systematic attempt to quantify their real potential through a national or international initiative. In particular there is a pressing need for a balanced assessment of the full range of proposals with regard to their climatic effectiveness, likely environmental and ecological impacts and possible unintended side-effects.

GOVERNMENT POLICY

The potential options for geo-engineering are rapidly gaining prominence both in the media[15] and among policymakers, particularly within the United States[16]. However the UK Government's current approach is ambivalent, as can be discerned from DECC, BIS and Defra, departments within whose sphere of interest the subject falls. All three seem to lack the sense of urgency appropriate to a technology that may offer a valuable addition to the portfolio of responses to climate change. Indeed, then Parliamentary Under-Secretary of State at DECC Joan Ruddock MP said in November 2008 that: "Scientists should probably not be looking at what I regard as being somewhere down the list of priorities and potentially the Plan B [geo-engineering], because we need all our energies directed at Plan A [mitigation and adaptation]."[9] A recent House of Commons Innovation, Universities, Science and Skills Committee review on the subject highlighted this failing and stated that: "Given the need for urgent action in addressing the challenge of climate change, we can see no reason for not considering geo-engineering technologies."[9]

Although the Government regards its priority as continuing to focus on emissions abatement[17], as outlined in its new national Low Carbon Transition Plan[18], it recognises that the challenge of significantly reducing greenhouse gas emissions is great and the risks associated with failing to do so are high. The Government therefore considers that a continued review and some further research on the potential of geo-engineering approaches are merited, particularly modelling studies[17]. However despite this position it has not, so far, undertaken any sizeable research into geo-engineering and has no current plans for public funding at an appropriate scale. Essentially the policy is simply to keep a watching brief.

"ENGINEERS ARE CRUCIAL TO THE CONVERSION OF GEO-ENGINEERING IDEAS AND CONCEPTS INTO PRACTICAL WORKING DEVICES AND MACHINES."

A key concern of the Government is the desire to avoid diverting public attention away from emissions reduction and a belief that most geo-engineering solutions would require global agreement and action[9]. So in the Government's view if the international political community fails to bring the world together to implement mitigation, it will be unlikely to succeed with the less-understood subject of geo-engineering.

At present, geo-engineering is barely visible to industry in the UK. However at this time, the UK leads the scientific world on our understanding of climate change impacts and modelling of future possible climates. Potentially there is an opportunity for UK plc to take a political and commercial lead in this area, to build on our existing scientific capability and exploit our engineering expertise.

But the current low level of business interest, and the inherent high financial risks involved with research and development, make it likely that Government funding would be needed in the early stages of concept testing, engineering assessment, pilot studies, 'picking winners' and scale-up. With the emergence of potentially winning technologies, forward-thinking industries will invest in R&D to prepare for a possible emerging market, both nationally and internationally.

CO_2 CAPTURE VS SOLAR RADIATION MANAGEMENT

There is growing consensus[14] that, in general, geo-engineering methods that remove CO_2 from the atmosphere involve less risk than those that act upon incoming solar (short-wave) radiation. Although measures based on the latter may be most effective in cooling the planet, they are potentially difficult to control and if failed or stopped would result in abrupt warming. In addition, they do not solve the issue of ocean acidification and may lead to undesirable changes to existing ecosystems together with residual regional climate changes. On the other hand, methods that remove CO_2 tackle the cause of the problem directly (humans emit CO_2 into the atmosphere, and the method removes it), are relatively more controllable and would not result in abrupt warming if stopped suddenly.

ENGINEERING GEO-ENGINEERING

Engineers are crucial to the conversion of geo-engineering ideas and concepts into practical working devices and machines. Promising schemes from a climate science point of view will require initial assessment of their technical feasibility. Geo-engineering solutions will need to be designed as low-carbon solutions, having a minimum carbon footprint in manufacture and deployment, consuming minimum energy in operation and emitting far less CO_2 than they remove or counteract. Most importantly they will need to be easy and quick to deploy, and avoid too much distraction of technical and financial resources from our primary objective of transitioning to a low-carbon economy.

In the process of making these initial assessments, it will be necessary for professional engineers to report on the availability of the required techniques, materials, manufacturing and construction processes. Furthermore, they will need to identify the risks associated with manufacture, installation, operation, maintenance and decommissioning, and to determine achievable efficiencies, costs and timescales for deployment. Given the lead times likely to be associated with the development of engineering schemes on this scale, from initial assessment to global deployment and operation, we desperately need to begin this initial assessment activity and instigate the necessary research.

To illustrate what initial engineering assessments of geo-engineering ideas might reveal, this report presents the findings from three case studies, selected from a group of assessments conducted by the Institution of Mechanical Engineers as part of its 'Cooling the Planet' programme[19]. The three examples were chosen for their apparent inherent practical nature from an initial review of promising approaches, as defined from the climate science point of view[14]. These case studies reveal what can be fleshed out when engineering feasibility is considered, and emphasise the need to urgently move forward with a comprehensive co-ordinated programme of assessment and research.

CASE STUDY ONE: AIR CAPTURE— ARTIFICIAL TREES

A number of scientists[10,14,20] have put forward ideas for devices that have become generally known as 'artificial trees'. In the same way as a tree stands in the open and removes CO_2 from the air through its leaves, an air capture device can collect CO_2 on its surfaces or 'artificial leaves'. In the artificial tree case, the CO_2 is caught on a sorbent material until it becomes saturated. It is then released through a cleaning process and secured from the atmosphere. Compared with natural trees however, an artificial tree covering an equivalent size footprint can be several thousand times more effective at removing CO_2.

The principal advantage of the air capture approach is that it addresses the reduction of atmospheric CO_2 irrespective of the source. It therefore tackles the difficult issue of non-stationary sources, such as those from the transportation sector, and relatively small dispersed sources that are difficult or not cost-effective to address through larger-scale mitigation technologies (eg emissions from domestic dwellings and small industrial plants). Some 50% of global CO_2 emissions are emitted from such non-stationary and dispersed sources, with about 20% derived from the transportation sector alone. Locating trees alongside motorways where CO_2 concentrations are particuarly high would help tackle the difficult issue of capturing emissions from millions of cars, vans and lorries each day.

Another key advantage of air capture is that it can address past emissions. With governments continually failing to meet global reduction targets, this point is becoming ever more important.

There are three main process steps in the operation of an artificial tree:

1. Capture of the CO_2 from the air to a filter medium
2. Removal of the captured CO_2 from the filter
3. Storage of the removed carbon

This case study focuses on an engineering assessment of the artificial tree concept proposed by Klaus Lackner from Columbia University[20].

SOME 100,000 ARTIFICIAL TREES WOULD BE SUFFICIENT TO CAPTURE THE WHOLE OF THE UK'S CURRENT NON-STATIONARY AND DISPERSED EMISSIONS.

HOW MANY TREES NEED PLANTING?

Early versions of Lackner's concept used sodium hydroxide as the sorbent material for the filter. This produced a residue of sodium carbonate from which the CO_2 was extracted. The cleaning process was, however, energy-intensive and made the cost calculation, in terms of both money and carbon (ie the amount of carbon likely to be emitted in the energy generation), unattractive. Further subsequent research by Lackner and his team has led to a proprietary sorbent material that can be washed in water vapour to remove the CO_2, dramatically reducing the energy consumption. This represents a major step forward in the practical feasibility in energy terms, as well as reducing potential toxicity issues significantly.

Since CO_2 is well mixed in the atmosphere, artificial trees can be positioned anywhere in the world. The rate an artificial tree can absorb CO_2 is largely a function of the area of the collector surfaces, and to a lesser degree the speed of the air blowing through the tree. The air speed does not have to be very high. Indeed it can be equivalent to a breeze. Even a completely stationary air flow will result in some CO_2 removal, but the effect would be dramatically reduced. This flexibility means that the units can be located together in groups, or artificial forests, and at close proximity to an appropriate storage area.

Air-capture units could, in theory, be deployed at various scales. At one end they could take the form of large goalpost-shaped structures with slats or a box-shaped extractor between them. At the other end, Lackner has proposed smaller sized units that more closely resemble a roadside cabin-type building than a 'tree'. For example, Lackner has estimated that a unit based on current technology, the size of a standard shipping container, operating 24 hours per day, would capture about one tonne of CO_2 per day, or 365 tonnes annually. That is roughly equal to the CO_2 emissions produced by 20 average automobile units in the USA. However, it is conceivable that with further research and development a single unit with a larger collector would be able to capture as much as ten times more CO_2. At a capture rate of ten tonnes per day some 100,000 units would be sufficient to capture the whole of the UK's current emissions from non-stationary and dispersed emissions. With a footprint of a standard 12-metre shipping container, and allowing room for access and infrastructure, the land required for such a solution would be about 600 hectares, or the equivalent of less than 10% of the area covered by the Firth of Forth in Scotland.

On a global scale, currently the world emits approximately 29 Gt/yr of CO_2. Of this total, about 14 Gt/yr is estimated to come from non-stationary and dispersed sources. With today's technology, it would take in the order of ten million artificial trees to collect 3.6 Gt/yr. However, with technological improvements, it should be possible to improve the trees capability in the order of ten. This would mean that five million trees would be able to comfortably capture all the non energy sector emissions for the planet. Five or ten million units might initially be perceived as a large number. But to put this in an industrial mass-production context, the world's production of cars and commercial vehicles is approximately 73 million per year.

STORING THE CARBON DIOXIDE

Several methods of CO_2 storage have been proposed[14]. The most feasible is geological confinement in depleted oil and gas reservoirs, deep unused saline formations and deep unmineable coal seams. This being the case, the storage requirement is the same as for conventional carbon capture and storage (CCS) technology currently under development. The limiting factor will therefore be the Earth's geological reserve capacity. Professor Nicholas Stern[7] states that estimates of storage space remain speculative and range from 1,700–11,000 $GtCO_2$. The IPCC[21] states that it is 'likely' that there is at least 2,000 $GtCO_2$ of storage capacity in geological formations, enough for at least 90 years at present emission rates.

Clearly if any of the stored CO_2 were to escape into the atmosphere, then the effectiveness of the process would be impaired. This however does not appear to be a problem. The 2005 IPPC report[21] on CCS states that it is 'likely' that more than 99% would still be present after 1,000 years. The safety and environmental risks associated with geological storage would be comparable to the risks of current activities such as natural gas storage.

Locating artificial forests close to storage sites where they can leverage emerging CCS infrastructure will lead to economies of scale for both applications. In addition, many of the world's depleted oil and gas reservoirs are positioned relatively remote from significant centres of human settlement (for example in the North Sea, Middle Eastern deserts and Siberia). This brings further potential advantages, as the trees are likely to be away from places where their deployment might give rise to aesthetic concerns, or competition for land use with food production or urban settlement. There may also be readily available sources of renewable energy to power the devices and storage processes. A North Sea location would, for example, yield wind power and a Middle East location might lend itself to the exploitation of solar energy. The other principal criteria for the site would be, in the case of Lackner's design, access to a water supply, which can be a source of saline water, for filter washing.

Some might question whether it would be better to use electricity generated from renewable sources at the site to power electric transportation and homes, rather than capturing the CO_2 that such non-stationary and dispersed sources emit. There are two points here. Firstly if artificial forests are located in proximity to storage sites, they are likely to be remote from populations that would use large amounts of electricity and therefore significant transmission losses might be expected. Secondly, air-capture units could most likely be designed, developed and deployed on a timescale significantly ahead of the implementation and delivery of a comprehensive programme of vehicle electrification and the full electrification of the built environment. Moreover, even when the latter has been achieved, it will still be necessary to continue to extract the CO_2 emitted by aircraft, ships and other remaining non-electric vehicles, as well as clean up past emissions.

COST OF AN ARTIFICIAL FOREST

The engineering and production of artificial trees will be completely dependent upon the implemented form of the units. However, in reality the technology involved is relatively straightforward and likely to be amenable to mass production. Deployment on the site is also likely to be relatively straightforward.

The manufacturing or building of artificial trees is likely to account for about 20% of the costs of using this approach to remove CO_2 from the atmosphere, Lackner estimates that once in production, the cabin-sized units would cost about $20,000 each. The main cost of the trees, however, is in the CO_2 recovery from the sorbent filter material, in terms of both energy and money. Lackner has shown that the cost of the recovery step in air capture is similar to that anticipated in a conventional post-combustion CCS process and that the long-term price of air capture could drop to as low as $30/tonne of CO_2.

With regard to the CO_2 balance of the device, Lackner's team has estimated that the emissions associated with operating each machine will be less than 5% of the CO_2 captured over the lifetime. That assumes energy being taken from a current grid mix whereas if the energy being used to power the devices were generated using renewable sources, this figure would decrease further.

KEY FACTS

- Artificial trees would be several thousand times more effective at removing CO_2 compared with natural trees
- Five to ten million 'trees' could remove the current global annual non-energy production CO_2 emissions
- Leveraging emerging CCS infrastructure will lead to economies of scale
- Each tree would cost about $20,000.

A NORTH SEA LOCATION WOULD BE ADVANTAGEOUS AS RENEWABLE ENERGY COULD POWER THE TREES AND EMPTY OIL WELLS COULD BE USED TO STORE CAPTURED CO_2.

CASE STUDY TWO: AIR CAPTURE—ALGAE ON BUILDINGS

An alternative approach to air capture involves the application of biological technology. Algae absorb carbon[22] through photosynthesis, and numerous studies indicate that they could significantly contribute to a reduction of atmospheric CO_2 levels[23]. The geo-engineering concept assessed in this case study involves the large-scale introduction of algae into the built environment, with the growth of biomass in the form of algae for energy and CO_2 sequestration. This is predicated upon the idea of integrating growth facilities into the fabric of urban developments, using the available vertical and horizontal surfaces as support for sealed vessels known as photobioreactors (PBRs). Furthermore, there is scope within this concept to integrate it as a retrofit proposal to existing building stock, giving increased opportunities for benefits to be achieved.

PBRs are designed to efficiently collect solar radiation and occupy minimal area. A closed-loop PBR system used on a domestic and small commercial scale would exist in the form of prefabricated packages or a self-installed plastic biotube that could contain the growth in a manageable form. A prefabricated PBR unit would be more accessible from the commercial point of view, and would be an ideal bolt-on solution for a retrofit scenario. As the scale increased the tubes and infrastructure required would get larger but the process remains much the same. The system itself, being closed, guards against infestations and would need CO_2 rich air and other mineral nutrients to be injected. In addition to providing a natural source of energy the algae growth infrastructure will act as a building insulator and as such potentially lead to reduced energy demand for heating.

The rate of algae growth, and thus CO_2 removal from the atmosphere, is influenced by several factors including temperature, light levels and nutrient availability. Different algal species have different requirements, especially in their response to light spectra[24] and levels of acidity and salinity. Increased CO_2 concentration tends to result in increase rate of growth as long as there is an abundance of other limiting nutrients.

ENERGY FROM ALGAE

Introducing PBRs into the built environment has the potential to not only sequest CO_2 from the atmosphere but also produce energy-yielding biofuel, as a beneficial side-effect. Using a closed-loop system where home-grown algae provide fuel to a generator or CHP engine and the engine exhaust CO_2 is fed back to the algae in combination with atmospheric air, ensures that there is little waste. The only major input required is solar – any oxygen produced will benefit the local environment. As algae can be grown in saline water or in waste water, it will not impact potable water supplies. In environments where water is critical, processing of the algae can be controlled to capture and recycle rainwater.

Algae would be harvested as fuel before they start to decay or die. This prevents the carbon being released back to the atmosphere during decomposition and allows it to be processed for energy directly. The occurrence of photosynthesis results in the production of carbohydrates and lipids as energy reserves, and these can account for 50% by weight. Algae have a high energy content with a value per unit mass, at 18.5 MJ/kg to 35 MJ/kg, which rivals coal (averages at 24 MJ/kg) and exceeds the energy density of wood, wastewater sludge and agricultural by-product.

Algae collected from the photobioreactor systems can be converted into energy by a number of pyrolysis processes. Pyrolysis involves the thermal degradation of organic materials with biochar resulting as a by-product. The production of biochar can not only contribute to a significant reduction of atmospheric CO_2 levels, but can also be implemented as a fertilisation mechanism. The value of adding organic char to soil is well known in the Amazon basin, where prehistoric civilisations intentionally incorporated char and created a soil called 'terra preta' which is still known today for its superior agricultural productivity. Given that most commercial fertilisers are currently derived directly from petroleum or through intensive fossil fuel-consuming production processes, the concept of using biochar as a fertiliser is very attractive.

Introducing algae into the built environment is a three-point solution primarily offering geo-engineering benefits but additionally paving the way for implementation of mitigation schemes in conjunction with CO_2 removal:

1. Atmospheric carbon absorption – direct removal (geo-engineering)
2. Removal of harmful emissions from urban exhaust gases and improved insulation (mitigation)
3. Biomass fuel source – based on the Bio-Energy with Carbon Storage (BECS) process, resulting in a carbon-negative energy source for the built environment (mitigation)

Mixed-use developments with an energy demand profile sufficient to merit running a CHP unit for more than 5,000hrs/yr, are ideally suited for a scheme such as this. The implementation of this concept is scalable, but larger processing plants and systems will benefit most from economies of scale. A combined energy centre for a development could contain and co-ordinate all processing and generation, or could be linked up to a district heating/cooling network. Integration with other renewable sources should be considered, as well as connection to a national grid in order to feed back any energy not used at the point/time of generation.

TECHNICAL BARRIERS

At this juncture, this geo-engineering solution is very much at a conceptual stage and has attracted little, if any, assessment of its technical feasibility. However, given its potential to not only remove carbon from the atmosphere but also help mitigate climate change in a more conventional fashion, it is worthy of further research.

The Institution's initial assessment suggests that the main technical limitation of the concept at this stage is the integration of PBRs into the built environment. Any such solution must be integrated with the architectural design, in both the case of new build and retrofitting, and should consider the full scale of the algae scheme and associated processing. There will be implications to building structure and fabric, as well as to site layout, accessibility, transfer to energy centre, and storage of algae prior to combustion.

PBRs themselves are a fledgling technology and at the moment are too expensive to be commercially viable. However, there has been some success with larger scale PBR development and many demonstration facilities are under way. In terms of final outcome, the concepts of biofuel-based energy generation and carbon sequestration as biochar are neither new nor technically restricted. Both processes are fully understood and are currently undertaken in several forms, suggesting that implementation on a large scale is a plausible outcome.

When considering the opportunity cost of this scheme, it potentially offers faster implementation and rate of return than many other geo-engineering ideas on a similar scale. High-level atmospheric or space-based schemes directed at decreasing incoming radiation have potentially very high capital cost as well as many inherent risks, some of which are either unknown or potentially uncontrollable. Due to the small scale of individual units, this idea has lower capital cost per installation as well as clearly understood impacts and side effects relating to the global environment.

KEY FACTS

- Algae photobioreactors can be fitted to new or existing buildings.
- The harvested algae have an energy content between 18.5MJ/kg and 35MJ/kg which rivals coal at 24MJ/kg
- A by-product of using algae as an energy source is bio-char, which can be used as an organic fertiliser.

“”

BY FITTING ALGAE UNITS TO THE SIDES OF BUILDINGS AND STRUCTURES, VALUABLE LAND RESOURSES NEEDED FOR FOOD PRODUCTION ARE NOT COMPROMISED.

CASE STUDY THREE: SOLAR RADIATION MANAGEMENT—REFLECTIVE BUILDINGS

An alternative to the direct removal of CO_2 from the atmosphere is the reduction of incoming solar radiation absorbed by the climate system – the so-called solar radiation management (SRM) approach. In geo-engineering terms, reflective building surfaces are usually classified as an urban land-based solar reflector in the SRM category and the effects are maxima constrained by the area of the surface type utilised. More than 50% of humans live in urban areas, and the figure continues to increase. So the question is whether the urban area, through surfaces such as roofs, building facades, pavements and roads, has the potential to help cool the planet?

Albedo enhancement methods through the use of reflective surfaces can potentially be extended to all areas of human settlement.

The potential effectiveness of increasing the reflective characteristics of urban surfaces has been assessed by a number of scientists[14]. Depending on the assumptions made in their calculations regarding the percentage of land area covered by an appropriate surface (between 0.051% and 0.174%) and the increase in albedo that might result from a change in material, they estimate such an approach could lead to a drop in global surface air temperatures in the range 0.01°C to 0.16°C. Regardless of which of these estimates is considered to be the most accurate it is clear from the results that, in the context of geo-engineering, urban albedo modification does not produce a large enough effect to contribute significantly to balancing global warming.

Large scale surface albedo changes might affect cloud cover and precipitation due to changes in the surface radiation balance, but whether this actually occurs, or whether it would arise due to urban surface modification is not clear from studies conducted to date[25]. There are not thought to be many direct negative ecological or environmental side effects, mainly because the changes are to controlled human environments.

URBAN HEAT ISLANDS

A positive use of this approach however, which would lead to some small contribution to cooling of the planet as a side-effect, might be in the reduction of the so-called 'urban heat island' effect. Urbanisation and community developments alter the Earth's surface causing localised micro-climate change across developed areas. Urban heat islands are created due to the dark roofs and paving absorbing the solar radiation and warming the air above them. For example, towns and cities including London, Birmingham and Edinburgh tend to be several degees hotter than their surrounding suburban and rural areas. Central Los Angeles registers temperatures which are typically 4°C higher than it's suburbs. The localised temperature increase causes discomfort, higher air-conditioning demand, and accelerates the formation of smog[26,27].

One way to limit this heat island effect is to use solar-reflective or high-albedo alternatives to traditional absorptive surfaces, thereby bringing about a drop in local temperature[27]. The implementation of a reflective buildings approach in this way has the opportunity to cool the urban environment, improving the air quality, and in addition reduce the cooling loads on individual buildings. This in turn would lead to a reduction in the energy consumption of buildings, and therefore also their associated CO_2 footprints. Such an outcome may be particularly valuable in hot climates and climates that will become hotter in the near future, as a result of the regional climate changes that are now inevitable as a consequence of past emissions[2,28].

The possibility that reducing urban albedo will indirectly contribute to a reduction in carbon emission has been investigated by The Lawrence Berkeley National Laboratory. It conducted a series of monitored building experiments in California and Florida, which showed that solar-reflective roofing can reduce annual cooling energy use by 10–60%[29]. The effect of these solar reflectors is likely to be much higher during summer periods than in the winter, and any anticipated increases in winter heating demand is likely to be negligible[30].

REFLECTIVE MATERIALS

The materials required for implementation of the approach are potentially simple, proven and generally available. White or other light-coloured paints are the obvious and easiest choice to increase urban albedo. However, as approximately 50% of the sun's radiation at the Earth's surface is near-infrared (NIR), significant albedo improvements can be made while retaining traditional colours. This would mean that the aesthetics of the building could remain the same while the efficiency improved[31]. Reflective surfaces can also extend the lifetime of building materials, by damping the daily temperature range, thus reducing excessive contraction and expansion, and by reducing the absorption of damaging ultraviolet. However, to ensure the effectiveness of the reflective material, their reflectivity must be maintained as it declines with age, and they need to be kept clean, as dirt and pollution lower reflectivity.

The composition of the materials can also be an important factor in making 'cool surfaces' more acceptable for use in suburban residential buildings. For example, light-coloured roofs, which generally are acknowledged as having the best solar-reflective properties, are not desirable or practical unless they are applied to flat or low-slope roofs that are not overlooked. Glare becomes a problem with light-coloured roofs when applied to steeper sloped roofs, and the adoption is not likely in housing, due to conventional aesthetic ideas. As mentioned before, more than half of the solar power that arrives on earth is within the invisible NIR range. This enables materials to be created that have fairly good solar reflectance, due to a combination of high NIR reflectance and lowered visual reflectance.

The material used for reflective roofing therefore depends upon the application. Commercial and flat-roofed buildings that are not overlooked are perfect candidates for the application of white, highly solar-reflective roofing materials. For suburban residential areas, reflective roofing in more aesthetically pleasing and less-glaring colours is more appropriate. Although the benefits of these will not be as great as the smooth white material of commercial buildings, the effects that they have will still make small contributions to the reflectance of solar energy and lead to a meaningful reduction of energy consumption.

For locations where the average temperatures mean that cooling loads far outweigh heating loads, reflective building surfaces can be exceptionally beneficial. In the USA, studies[32] have shown the potential for large cost savings through the use of reflective roofing materials. In areas where individuals may not have access to cooling systems, there is a direct benefit to the individual, as internal building temperatures are lowered and health risks related to heat exhaustion reduced[33].

For reflective materials to be adopted, governments and the public need to be made more aware of the possibilities, in terms of both cooling the urban environment and the financial gains that may be realised. Government adoption of the policy, as seen in California, would probably have the greatest influence. The introduction of legislation to encourage the use of the approach could be based on a number of ideas. Mandates, as used in California, forcing the construction industry to take on reflective surfaces could be used. Alternatively, there could be the implementation of government grants, but experience from building insulation initiatives has shown that typically these are less successful at stimulating adoption.

KEY FACTS

- This method may be more effective at reducing the 'urban heat island' effect
- Reflective roofing can reduce cooling energy use by up to 60%
- Issues of glare and aesthetics need to be considered
- Government adoption of a mandatory policy, as seen in California, would probably have greatest influence.

SOLAR-REFLECTIVE ROOFING CAN REDUCE ANNUAL COOLING ENERGY USE BY BETWEEN 10% AND 60%.

THE PRACTICAL ISSUES

The key practical issues to be addressed from an engineering perspective, are in the areas of ensuring that geo-engineering implementations:

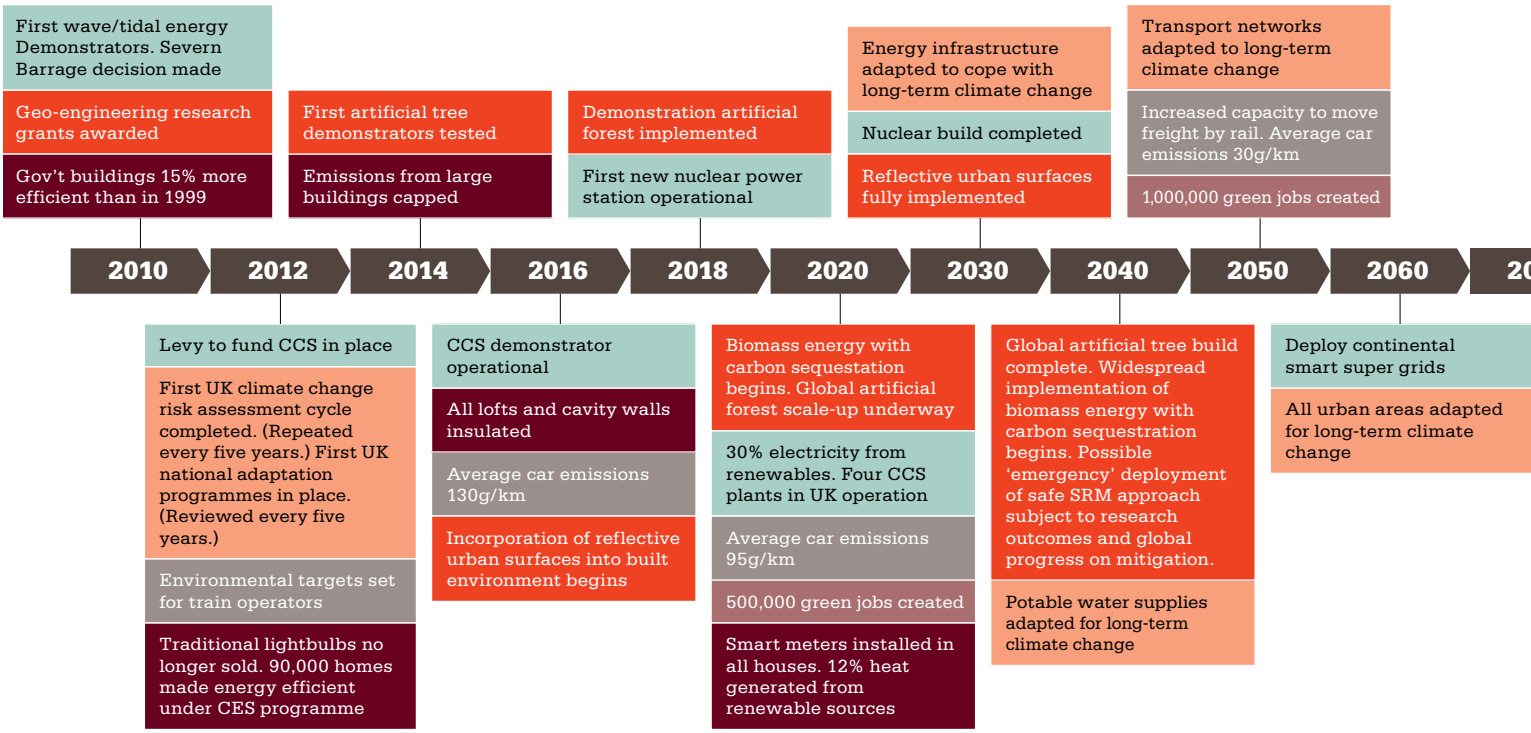
- are low-carbon solutions
- build on existing engineering knowledge and are relatively easy to design, deploy and operate (to avoid distraction of significant engineering resources from mitigation activity)
- can be achieved at low cost within a government low carbon policy framework

Judged against these criteria, the artificial trees concept is the front runner. The simplicity of design, reliance largely on current technical knowledge and existing proven technology components, amenability to mass production of units and relatively straightforward deployment, mean that engineering risks and costs should be low and the distraction from transitioning to a low-carbon economy minimal.

The initial engineering assessment of the algae-on-buildings idea, revealed a more complicated picture of an approach based on emerging technical knowledge and unproven components, still in the early stages of development. Difficult to rapidly deploy as an addendum to new and existing building stock, and probably requiring higher-level installation skills, the engineering risks and costs associated with this idea might be expected to be relatively higher. In this respect the solution needs more research effort to prove its feasibility and ensure it does not lead to a drain on resources that would be better focused on implementing the transition to a low-carbon economy.

Although relatively ineffective from a climate science point of view, the initial engineering assessment of the third idea, that of reflective building surfaces, revealed its potential for use in combating the localised issue of urban heat island effect. The benefits of the approach were seen to include a contribution towards mitigation, through the reduction in building cooling loads, and health improvements particularly in hot areas with relatively low levels of cooling capacity. Given that the approach is largely reliant on current technical knowledge and proven technology components, and relatively straightforward to deploy, the engineering risks and costs should be low and the distraction from transitioning to a low-carbon economy minimum.

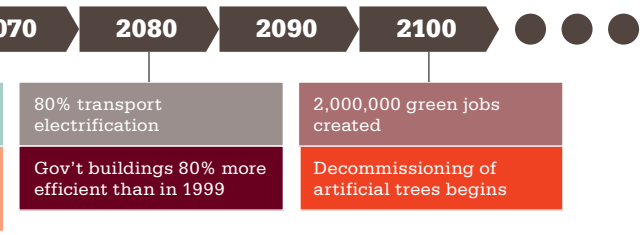
Figure 1: Example MAG (Mitigation, Adaptation and Geo-engineering) roadmap



WHAT NEEDS TO HAPPEN?

The case studies carried out by the Institution give an initial indication of the sort of work that needs to be done in the engineering assessment of promising geo-engineering approaches and is a first attempt at making a step in the right direction. However beyond such individual initiatives it is now crucial to instigate publicly funded national and international programmes to carry out assessment and research at the feasibility level so that the global community is technically informed of the real practical potential of geo-engineering. A £10–20 million UK contribution to such a programme, carried-out internationally for about £100 million, might be expected to advance the scientific and engineering assessment significantly[34]. This will not only allow nations to be informed participants in international discussions on the approach, or indeed discussions with individual entrepreneurs who wish to bring the approach forward, but also ensure feasibility and realistic expectations are built into global decision-making.

Secondly, given the lead times likely to be associated with the development of engineering schemes on this scale, it is important to urgently instigate research and assessment activity, so that the technical community can be prepared for the potential 'emergency' deployment of geo-engineering systems, should they be required to do so.



Key:

- Power (Mitigation)
- Buildings (Mitigation)
- Transport (Mitigation)
- Geo-engineering
- Adaptation
- Jobs (All)

ROADMAP TO COOLING THE PLANET

Building on knowledge acquired through a rigorous comprehensive technology assessment, the Institution recommends that a roadmap to implementation be devised for a global transition to a low-carbon future incorporating geo-engineering. Based on the Institution's initial assessment to date, such a roadmap might include the following elements over a 75 to 100-year timescale:

- Funding for geo-engineering research is granted by Government. Any such research must be linked with existing mitigation and adaptation research
- Widespread implementation of artificial forests, leveraging emerging CCS infrastructure for storage and purpose-built co-located renewable energy generation for power
- Parallel decarbonisation and expansion of global electricity generation capacity, including deployment of smart supergrids on a continental scale
- Parallel research and development of electric transportation technologies and technologies for decarbonisation of dispersed sources
- Possible 'emergency' deployment of Solar Radiation Management (SRM) subject to research outcomes and progress globally on mitigation
- Phased electrification of transportation sector and dispersed sources of CO_2 emissions
- Continued use of artificial trees to clean up past emissions until atmospheric CO_2 concentration returns to a climatically acceptable level
- Decommissioning of geo-engineering solutions

There is currently insufficient information to adequately support an informed debate on this topic, for formation of robust Government policy, or the laying out of a detailed roadmap. The Institution urges Government to empower the scientific and social sciences community to undertake a thorough, collaborative and rigorous research activity to provide guidance as to which approaches offer the most potential at lowest risk to the Earth system. This will allow the engineering profession to develop feasibility assessments without wasting precious time considering invalid approaches. And we appear to have precious little time to waste.

REFERENCES

1 **Richardson, K. et al., Synthesis Report: Global Risks, Challenges & Decisions** (International Scientific Congress, Copenhagen 2009, 10-12 March 2009, available at http://climatecongress.ku.dk/pdf/synthesisreport/).

2 **IMechE, Climate Change: Adapting to the Inevitable?** (Institution of Mechanical Engineers, London, 2009).

3 **Marland, G., Andres, R. J., and Boden, T. A., in Trends: A Compendium of Data on Global Change** (Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tenn., U.S.A., 2008).

4 **Pielke, R. A., The British Climate Change Act: A critical evaluation and proposed alternative approach**. Environmental Research Letters, Vol. 4, No. 2, (2009).

5 **Anderson, K. and Bows, A., Reframing the climate change challenge in light of post-2000 emission trends**. Phil. Trans. R. Soc. A 366, 3863 (2008).

6 www.guardian.co.uk/environment/2008/aug/06/climatechange.scienceofclimatechange

7 **Stern, N., Stern review on the economics of climate change** (Her Majesty's Treasury, Cambridge University Press 2006).

8 **CBI, Taking Stock, CBI Education and Skills Survey 2008** (CBI, 2008).

9 **House of Commons, IUSS Committee Fourth Report, Engineering: Turning ideas into reality** (HC50-1, 2009).

10 **Keith, D.W. et al., Climate strategy with CO_2 capture from the air**. Climate Change 74, 17 (2006).

11 **Lampitt, R.S. et al., Ocean fertilisation: a potential means of geo-engineering?** Phil. Trans. R. Soc. A 366, 3912 (2008).

12 **Read, P. and Parshotam, A., Holistic greenhouse gas management strategy** (Institute of Policy Studies Working Paper 07/1, Victoria University of Wellington, Wellington, New Zealand, 2007).

13 **Angel, R., 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 (46), 17184 (2006).

14 **Vaughan, N.E. and Lenton, T.M., A review of climate geoengineering proposals** (Submitted to Climatic Change).

15 www.guardian.co.uk/environment/manchester-report

16 http://americasclimatechoices.org/

17 **House of Commons, IUSS Committee Fifth Special Report of Session 2008-09, Engineering: Turning ideas into reality: Government response to the Committee's Fourth Report** (HC759, 2009).

18 **H.M. Government, The UK Low Carbon Transition Plan** (2009).

19 www.imeche.org/about/keythemes/environment/Climate+Change/Cooling+the+Planet+competition/

20 **K. S. Lackner, Carbon Dioxide Capture from Ambient Air. In "The Physics Perspective on Energy Supply and Climate Change – A Critical Assessment"**, Blum, W.; Keilhacker, M.; U. Platt; Roether, W., Eds. Springer Verlag: Bad Honnef (2009).

21 **IPCC, Carbon Dioxide Capture and Storage** (Cambridge University Press, Cambridge, 2005).

22 www.sciencedaily.com/releases/2006/01/060114152028.htm

23 **Jacob, L. et al., Rates of CO_2 removal by Aphanothece Microscopica Nageli in Tubular Photobioreactors** (Biochemical Engineering Laboratory, Universidade Estadual de Campinas, Sao Paulo, Brazil, 2007).

24 **Barsanti, L. & Gualtieri, B., Algae; Anatomy, Biochemistry and Biotechnology** (Taylor & Francis Group, CRP Press, Oxon, 2006).

25 **Hamwey, R. Active Amplification of the Terrestrial Albedo to Mitigate Climate Change: An Exploratory Study** Mitigation and Adaptation Strategies for Global Change, 12: 419 (2007).

26 **Rosenfeld, A., Romm, J., Akbari, H., & Lloyd, A., Paint the Town White -- and Green** (MITs Technology Review 1997).

27 **Taha, H., Urban Surface Modification as a Potential Ozone Air-Quality Improvement Strategy in California: A Mesoscale Modelling Study** Boundary-Layer Meteorol, 127:219 (2008).

28 **UKCIP, UKCP09 Climate Projections**. Available at http://ukcp09.defra.gov.uk/

29 **Bretz, S., Kooney, J., & Brown, R., Energy Star Roofing** (Energy End-Use Forecasting, 2009).

30 **Taha, H., Akbari, H., & Rosenfeld, A., Residential Cooling Loads and the Urban Heat Island: the Effects of Albedo** Building and Environment 23, 271 (1988).

31 **Bretz, S., Akbari, H., & Rosenfeld, A., Practical Issues for Using Solar Reflective Materials to Mitigate Urban Heat Islands** Atmospheric Environments, 2 (1), 95 (1997).

32 http://eetd.lbl.gov/Heatisland/CoolRoofs/

33 **Department of Health, HEATWAVE PLAN: 2009** (2009).

34 **Parliamentary Office of Science and Technology, POSTnote 327, Geo-engineering Research** (2009).

Institution of Mechanical Engineers

1 Birdcage Walk
Westminster
London
SW1H 9JJ

T 020 7304 6862
F 020 7222 8553

environment@imeche.org
www.imeche.org